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U. S. GEOLOGICAL SURVEY CIRCULAR 930–N

U. S. DEPARTMENT OF THE INTERIOR
March 3, 1849

International Strategic Minerals Inventory Summary Report—Rare-Earth Oxides

Prepared as a cooperative effort among earth-science and mineral-resource agencies of Australia, Canada, the Federal Republic of Germany, the Republic of South Africa, the United Kingdom, and the United States of America

Geologic Time Scale

Age			Million years before present
Holocene	Quaternary	CENOZOIC	0.01
Pleistocene			2
Pliocene	Tertiary		5
Miocene			24
Oligocene			38
Eocene			55
Paleocene			63
Late Cretaceous	Cretaceous	MESOZOIC	96
Early Cretaceous			138
Jurassic			205
Triassic			~240
Permian		PALEOZOIC	290
Pennsylvanian	Carboniferous		~330
Mississippian			360
Devonian			410
Silurian			435
Ordovician			500
Cambrian			~570
PRECAMBRIAN	Late Proterozoic	PROTEROZOIC	900
	Middle Proterozoic		1600
	Early Proterozoic		2500
		ARCHEAN	

International Strategic Minerals Inventory Summary Report—Rare-Earth Oxides

By Wayne D. Jackson and Grey Christiansen

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FOREWORD

Earth-science and mineral-resource agencies from several countries started the International Strategic Minerals Inventory in order to cooperatively gather information about major sources of strategic raw materials. This circular summarizes inventory information about major deposits of rare-earth oxides, one of the mineral commodities selected for the inventory.

The report was prepared by Wayne D. Jackson and Grey Christiansen of the U.S. Bureau of Mines (USBM). It was edited by David M. Sutphin and transcribed by Dorothy J. Manley of the U.S. Geological Survey (USGS). Rare-earth oxide inventory information was compiled by Wayne D. Jackson, Grey Christiansen (chief compiler); Ian R. McLeod (retired), Bureau of Mineral Resources, Australia; Roy R. Towner, Australian Bureau of Agricultural and Resource Economics; Aert Driessen, Australian Bureau of Resource Sciences (BRS); Andrew J. Sozanski and Yannis Lepinis, Energy, Mines & Resources (EMR), Canada, Mineral Policy Sector (MPS); W. David Sinclair, EMR, Geological Survey of Canada; and Andrew E. Grosz, USGS. Additional contributions were made by Antony B.T. Werner, EMR, MPS; Erik Hammerbeck, Geological Survey of the Republic of South Africa; Richard N. Crockett (retired), British Geological Survey; Gordon C. Battey, BRS; Ulrich H. Krauss, Bundesanstalt für Geowissenschaften und Rohstoffe, Federal Republic of Germany; Richard J. Fantel and James B. Hedrick, USBM; and Peter J. Modreski, USGS.

Robert M. Hirsch

Acting Director

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INTERNATIONAL STRATEGIC MINERALS INVENTORY SUMMARY REPORT

RARE-EARTH OXIDES

By Wayne D. Jackson[1] and Grey Christiansen[1]

Abstract

Bastnaesite, monazite, and xenotime are currently the most important rare-earth minerals. Bastnaesite occurs as a primary mineral in carbonatites. Monazite and xenotime also can be found in primary deposits but are recovered principally from heavy-mineral placers that are mined for titanium or tin. Each of these minerals has a different composition of the 15 rare-earth elements.

World resources of economically exploitable rare-earth oxides (REO) are estimated at 93.4 million metric tons in place, composed of 93 percent in primary deposits and 7 percent in placers. The average mineral composition is 83 percent bastnaesite, 13 percent monazite, and 4 percent of 10 other minerals. Annual global production is about 67,000 metric tons of which 41 percent is from placers and 59 percent is from primary deposits; mining methods consist of open pits (94 percent) and dredging (6 percent). This output could be doubled if the operations that do not currently recover rare earths would do so.

Resources are more than sufficient to meet the demand for the predictable future. About 52 percent of the world's REO resources are located in China. Ranking of other countries is as follows: Namibia (22 percent), the United States (15 percent), Australia (6 percent), and India (3 percent); the remainder is in several other countries. Conversely, 38 percent of the production is in China, 33 percent in the United States, 12 percent in Australia, and 5 percent each in Malaysia and India. Several other countries, including Brazil, Canada, South Africa, Sri Lanka, and Thailand, make up the remainder.

Markets for rare earths are mainly in the metallurgical, magnet, ceramic, electronic, chemical, and optical industries. Rare earths improve the physical and rolling properties of iron and steel and add corrosion resistance and strength to structural members at high temperatures. Samarium and neodymium are used in lightweight, powerful magnets for electric motors. Cerium and yttrium increase the density and heat resistance of sintered ceramics. Yttrium and gadolinium contribute to the efficiency of electronic switches and sensors. Cerium improves the effectiveness of catalysts in the petroleum and automotive industries. Cerium oxides speed glass melting and are used to polish glass by chemical, rather than mechanical, means. Cerium, europium, terbium, and yttrium, as phosphoric compounds, promote the vivid colors of television screens. Consumption of rare earths is expected to grow by about 2.6 percent per year.

PART I—OVERVIEW

INTRODUCTION

The reliability of future supplies of so-called strategic minerals is of concern to many nations. This widespread concern led to duplication of effort in the gathering of information on the world's major sources of strategic mineral materials. With the aim of pooling such information, a cooperative program named International Strategic Minerals Inventory (ISMI) was started in 1981 by government officials of the United States, Canada, and the Federal Republic of Germany. They were subsequently joined by the Republic of South Africa, Australia, and the United Kingdom.

The objective of ISMI reports is to make publicly available, in convenient form, nonproprietary data and characteristics of major deposits of strategic mineral commodities for policy considerations in regard to short-term, medium-term, and long-term world supply. This report provides a summary statement of the data compiled and an overview of the supply aspects of rare-earth

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oxides in a format designed to benefit policy analysts and geologists. Knowledge of the geologic aspects of mineral resources is essential in order to discover and develop mineral deposits. However, technical, financial, and political decisions also must be made, and often transportation and marketing systems must be developed before ore can be mined and processed and the products transported to the consumer. The technical, financial, and political aspects of mineral-resource developments are not specifically addressed in this report. The report addresses the primary stages in the supply process for rare-earth oxides and includes only peripheral considerations of rare-earth oxide demand.

The term "strategic minerals" is imprecise. It generally refers to mineral ores and derivative products that come largely or entirely from foreign sources, that are difficult to replace or substitute, and that are important to a nation's economy, in particular to its defense industry. In general, the term relates to a nation's perception of vulnerability to supply disruptions and to its concern to safeguard its industries from the disruptions of a possible loss of supplies.

Because a mineral that is strategic to one country may not be necessarily strategic to another, no definitive list of strategic minerals can be prepared. The ISMI Working Group decided to commence with commodity studies on chromium, manganese, nickel, and phosphate. All of these studies, plus those of platinum-group metals, cobalt, titanium, graphite, lithium, tin, vanadium, zirconium, and niobium (columbium) and tantalum have now been published. Additional studies on rare-earth oxides (this report) and tungsten have been subsequently undertaken.

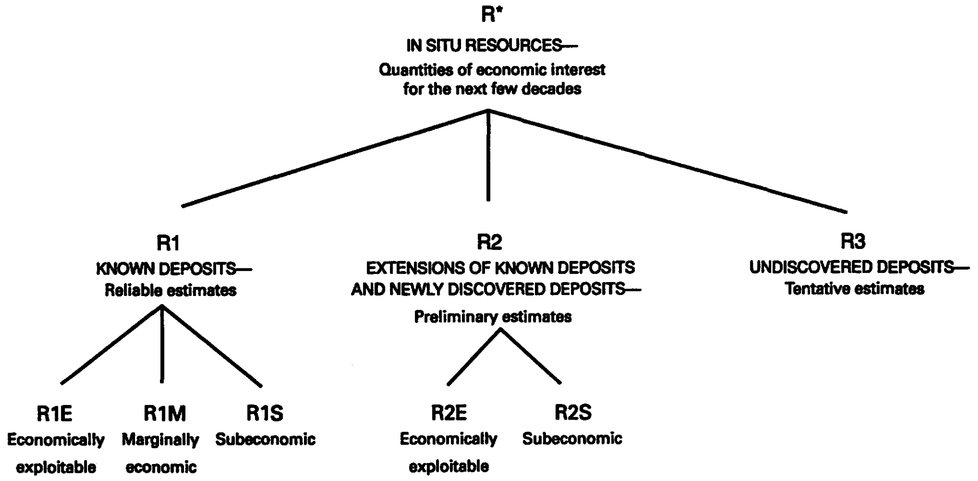
The data in the ISMI rare-earth oxides inventory were collected from October 1989 to June 1990. This report was submitted for review and publication in December 1990. The information used was the best available to the various agencies of the countries that contributed to the preparation of this report. These agencies were the Bureau of Mines and the Geological Survey of the U.S. Department of the Interior; the Geological Survey of Canada and the Mineral Policy Sector of the Canadian Department of Energy, Mines & Resources; the Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany; the Geological Survey and the Minerals Bureau of the Department of Mineral and Energy Affairs of South Africa; the Bureau of Resource Sciences of the Australian Department of Primary Industries and Energy; and the British Geological Survey, a component of the Natural Environment Research Council of the United Kingdom.

No geologic definition of a deposit or district is used for compiling records for this report. Deposits and districts are selected for the inventory on the basis of their present or expected future contribution to world supply. Records for all deposits compiled by ISMI participants meet this general "major deposit" criterion and are included in the inventory. No information is provided on deposits that were once significant but whose resources are now considered to have been depleted. Some records refer to districts that contain several deposits; these deposits are grouped because they are too small to be listed individually or because published data are available only for the deposits as a group.

The ISMI record collection and this report on rare-earth oxides have adopted the international classification system for mineral resources recommended by the United Nations Group of Experts on Definitions and Terminology for Mineral Resources (United Nations Economic and Social Council, 1979; Schanz, 1980). The terms, definitions, and resource categories of this system were established in 1979 to facilitate international exchange of mineral-resource data; the Group of Experts sought a system that would be compatible with the several systems already in use in several countries. Figure 1 shows the United Nations (U.N.) resource classification used here. This report focuses on category R1, which includes reliable estimates of tonnages and grades of known deposits. The familiar term "reserves," which many would consider to be equivalent to r1E or R1E, has been interpreted inconsistently and thus has been deliberately avoided in the U.N. classification.

It should be noted that, generally, until a deposit has been extensively explored or mined, its size and grade are imperfectly defined. In many cases, deposit size will prove to be significantly larger, sometimes even several times larger, than was established when the decision to mine was made. Experts with a sound knowledge of a deposit and its geologic setting might infer that the deposit extends beyond the bounds reliably established up to that time. Tonnage estimates for such inferred extensions fall into category R2. For major deposits, ISMI records show R2 estimates in the few cases for which they are readily available. Category R3, postulated but undiscovered resources, is not dealt with in this report.

The term "ore" in tables 21 and 22 (Part II) refers to mineralized rock or sands that contain an economic quantity of minerals, of which the rare-earth oxides may be of primary or secondary value. In those cases of primary value, the rare-earth oxides occur mainly as bastnaesite or monazite in igneous intrusions. In those



***The capital "R" denotes resources *in situ*; a lower case "r" expresses the corresponding *recoverable* resources for each category and subcategory. Thus, r1E is the recoverable equivalent of R1E. This report deals only with R1 and R2, not with R3.**

FIGURE 1. United Nations resource categories used in this report (modified from Schanz, 1980, p. 313).

cases of secondary value, the primary mineral of economic interest is usually titanium-bearing ilmenite or rutile deposited in black mineral sands, with the rare-earth oxides occurring in associated monazite or xenotime.

Not all companies or countries report resource data in the same way. In this report, all resource data are quoted as being in place. Mining recovery from an ore body depends on individual conditions and may vary considerably. For placer deposits, over 90 percent of the ore is generally recovered; for open-pit primary deposits, mining recovery is generally in the order of 75 to 90 percent. After mining, up to about 5 percent of the economic mineral content of alluvial ore may be lost in the mineral processing (concentration and separation stages). The metallurgical recovery rates of hard-rock ore depend very much on grain size and ease of liberation.

The World Bank economic classification of countries (World Bank, 1986, p. 180–181), which is based primarily on gross national product per capita, has been used in this and other ISMI reports to illustrate distribution of resources and production according to economic groupings of countries. This classification was chosen because it relies primarily on objective economic criteria and does not contain political bloc labels that might be perceived differently by different countries.

DEFINITION AND BACKGROUND OF RARE EARTHS

The term "rare earths" is a misnomer. They were originally called rare because they were discovered in isolated monazite crystals in certain types of granite. "Earth" is an old chemical name for oxides and refers to the fact that the metals always occurred in the oxide form (Martin, 1985).

Rare earths are not really rare in the Earth's crust. Cerium, the most abundant of the rare earths (crustal abundance=70 parts per million (ppm)), is more plentiful than nickel (58 ppm) or copper (47 ppm). Neodymium (37 ppm), yttrium (29 ppm), and lanthanum (29 ppm) are more plentiful than cobalt (18 ppm) or lead (16 ppm). Praseodymium (9 ppm), samarium (8 ppm), gadolinium (8 ppm), dysprosium (5 ppm), and erbium (3.3 ppm) are each more plentiful than tin (2.5 ppm). Ytterbium (330 parts per billion (ppb)) and thulium (270 ppb), the least abundant of the rare earths, are each more plentiful than mercury (83 ppb) or silver (70 ppb).

Rare earths are universally described as those 15 chemically similar elements in the periodic table that range from lanthanum through lutetium, which have atomic numbers 57 through 71, inclusively (table 1). Commonly, yttrium (no. 39) is included because it is invariably physically associated with this group. Scandium (no. 21) and thorium (no. 90) are sometimes considered as a part of the rare-earth series but are not included in the scope of this report. Since lanthanum is the first name in the rare-earths list, the whole group is sometimes referred to as the "lanthanides." The upper half of this series is termed the "light" or "cerium" subgroup, and the lower half is called the "heavy" or "yttrium" subgroup. An unusual property of the rare earths is that those elements having even atomic numbers are more abundant than their odd-numbered neighbors.

TABLE 1.—*Rare-earth elements and selected properties*

[ppm, parts per million. —, does not have a stable isotope and is not found in nature. Sources: Pincock, Allen and Holt, 1988, p. 1.2; Wellmer and others, 1988, p. 116]

Element	Chemical symbol	Atomic number	Valence	Atomic weight	Crustal abundance (ppm)	Oxides
Light rare earths (cerium group)						
Lanthanum	La	57	3	138.92	29.00	La_2O_3
Cerium	Ce	58	3,4	140.13	70.00	CeO_2
Praseodymium	Pr	59	3,4	140.92	9.00	Pr_6O_{11}
Neodymium	Nd	60	3	144.27	37.00	Nd_2O_3
Promethium	Pm	61	3	145.00	—	none
Samarium	Sm	62	2,3	150.43	8.00	Sm_2O_3
Europium	Eu	63	2,3	152.00	1.30	Eu_2O_3
Gadolinium	Gd	64	3	156.90	8.00	Gd_2O_3
Heavy rare earths (yttrium group)						
Terbium	Tb	65	3,4	159.20	2.50	Tb_4O_7
Dysprosium	Dy	66	3	162.46	5.00	Dy_2O_3
Holmium	Ho	67	3	164.94	1.70	Ho_2O_3
Erbium	Er	68	3	167.20	3.30	Er_2O_3
Thulium	Tm	69	3	169.40	.27	Tm_2O_3
Ytterbium	Yb	70	2,3	173.04	.33	Yb_2O_3
Lutetium	Lu	71	3	174.99	.80	Lu_2O_3
Yttrium	Y	39	3	88.92	29.00	Y_2O_3

Thus, given the choice, an even-numbered element should be selected for specific applications because it would be more available (Kilbourn, 1988).

The rare earths do not occur naturally as metallic elements. Their strong affinity for oxygen causes them to form mostly as oxides, although other combinations are possible. An exception is promethium, which does not have a stable isotope and is not found in nature. Because of their reactivity, it is difficult to refine the rare earths to a pure form. Due to their chemical similarity, it is even more difficult to separate them into individual elements or compounds.

APPLICATIONS

The rare-earths industry began in 1883 when the incandescent gas mantle was developed. By 1891, this mantle, composed of 1 percent ceria (CeO_2) and 99 percent thoria (ThO_2), was in commercial production (Neary and Highley, 1983). At the turn of the century, manufacturers started using a complex alloy of rare-earth metals, so-called "mischmetal," as the main ingredient in lighter flints. By the late 1940's, rare earths were employed in the formulation of ductile iron. A major surge in demand for rare earths in the late 1960's and early 1970's came with their use as additives in high-strength low-alloy steels and in oil refinery catalysts.

Present and potential applications of the rare earths include metallurgy, magnets, ceramics, and electronics and chemical, optical, medical, nuclear, and other uses. In the following paragraphs, a short description of the main markets for each element is given (Hong Kong Correspondent, 1990), followed by an expanded discussion of the markets (Business Opportunity Report, 1989). Table 2 shows the major uses of the rare earths by industry.

Uses for individual rare earths.—Lanthanum's primary use is in ceramic glazes and optical glass, such as camera lenses. Cerium, the chief constituent of mischmetal, is used in the steel industry. It improves the strength and ductility of aluminum alloys and raises the high-temperature properties of magnesium alloys. Other uses of cerium are as radiation shielding in cathode-ray tube face plates, petroleum refinery catalysts, ceramic capacitors, and heat-resistant jet engines.

Praseodymium is a constituent of ceramic tiles and capacitors and permanent magnets. When mixed with neodymium, the combination is known as didymium, which is used in glassmaker's goggles.

Europium, one of the scarcest of these elements, is employed in colored lamps and cathode-ray tubes. The oxide provides the red phosphor for color television. It is also an essential constituent of control rods in nuclear reactors because of its propensity for absorbing neutrons. When irradiated, thulium produces an isotope that emits X-rays and is used in portable X-ray machines.

Yttrium is used as a deoxidizer in stainless steel, in super-alloys for aircraft engines, in rechargeable

TABLE 2.—*Major uses of individual rare-earth elements*

[Simplified from Pincock, Allen and Holt, Inc., 1988]

Industry	Mixed REE	Rare-earth element															
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
Metallurgy																	
Ferrous	X	X	X														X
Nonferrous	X	X	X	X	X			X									X
Magnets	X	X	X	X	X		X		X		X						X
Ceramic	X	X	X	X									X				X
Electronic	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X
Chemical (metallurgical catalysts)	X	X	X		X		X		X		X				X		X
Catalysts	X	X	X		X		X		X						X		
Optical (including glasses)	X	X	X	X	X	X	X	X	X	X		X	X	X			X
Medical							X	X	X	X				X			X
Pharmaceuticals		X	X		X				X								
Nuclear																	
Fuel			X														
Control and shielding			X				X	X	X		X	X					X
Miscellaneous																	
Farming	X																
Hydrogen storage		X	X	X	X												
Cryogenics		X															
Batteries		X			X												X

batteries, and as a radioactive isotope used in pain killers. It can be forged, either cold or hot, deforms easier at temperatures above 800 °C, and is highly susceptible to oxidation, requiring that work be conducted in an inert atmosphere.

Of the other rare-earth elements, samarium is used mainly in permanent magnets and in glass lasers; gadolinium is an essential component of solid-state lasers and computer memory chips; terbium is used in cathode-ray tubes and in magneto-optical computer memories; and, dysprosium is employed in permanent magnets and in nuclear reactor control rods. Holmium also is used to control nuclear reactions; erbium forms a pink glaze on ceramics; lutetium has no known practical uses; and ytterbium is similar to lutetium but has a higher magnetic susceptibility.

Metallurgy.—One of the major applications of rare earths is in metallurgical alloys. One of the oldest of these alloys is mischmetal, which is made from bastnaesite concentrates. Mischmetal is used to improve the physical and rolling properties of iron and steel, a market currently in a decline, and in high-strength low-alloy steels. It is also a constituent of pyrophoric alloys, which give tracer shells their distinctive fiery trail.

A galvanizing zinc alloy, which offers much better protection to underlying steel than does the normal zinc cover, is made with 5 percent aluminum and small amounts of lanthanum and cerium. The contribution of the rare earths to metallurgy is fluidity, wettability, and the elimination of intergranular corrosion.

It is expected that there will be increased substitution of rare earths for toxic materials, such as chromates, zinc, cadmium, and nitrates, in aqueous corrosion protection coatings. The corrosion resistance of REO coatings approaches that of chromates. They have excellent adhesion and can be applied easily in 30 to 90 seconds at slightly above room temperature.

Selected rare earths improve the life of nickel and cobalt alloys that protect structural materials subject to intense cyclic heat and oxidation. Their additions cause the protective alloy to adhere much more strongly to the underlying metal, as for example in jet-engine exhaust nozzles. Use of these alloys in reaction vessels and heat exchangers permits chemical activity at higher temperatures, thus improving operating efficiencies.

Yttrium oxide is mechanically milled into nickel-chromium and iron-chromium alloys to improve high-temperature strength and creep resistance and to fight cyclic corrosive oxidation due to high heat and water vapor. Following mechanical alloying, the combined powders are compressed and sintered to required shapes.

A new aluminum alloy, composed of aluminum, iron, and cerium, is under development as a replacement for titanium compounds in specific applications in the temperature range of 93 to 316 °C. Cerium contributes required corrosion resistance at elevated temperatures. A similar alloy of titanium and erbium also is being tested. Addition of rare earths to cast iron improves the ductility of the metal by reducing the size of the graphite grains and by improving the dispersion of smaller grains throughout the matrix. Rare earths are also used to control deleterious elements in ductile iron.

Two magnesium alloys are being developed for use in high-performance engines for aircraft, space rockets, and satellites. The first contains 4 percent zinc and 1 percent mischmetal and can be used in applications encountering temperatures as high as 159 °C. The second alloy, which contains 5.5 percent yttrium, 3.5 percent other rare earths, and 0.5 percent zirconium, is stable at temperatures as high as 282 °C.

Magnets.—Rare earths appear to be achieving their fastest growth in the magnet industry. In the late 1960's, samarium, alloyed with cobalt, was first used in magnets. However, the relative scarcity and cost of samarium, coupled with cobalt supply problems encountered in 1978, led to a search for other materials. This resulted in development in 1982 of the neodymium-iron-boron magnet.

Samarium-based magnets are supplied in two grades: (1) 35 percent samarium and 65 percent cobalt or (2) 24 percent samarium and 20 percent zirconium plus iron, copper, and cobalt. Samarium-cobalt magnets impart a high remanence and have exceptional resistance to demagnetization. Major uses are in applications in which space is at a premium and cost is not crucial, as in lightweight electronic equipment.

Neodymium-based magnets also come in two grades: (1) 35 percent neodymium, 64 percent iron, and 1 percent boron or (2) 28 percent neodymium, 7 percent dysprosium, 40 percent iron, and 25 percent aluminum and boron. Their primary advantages are lower cost and better magnetic properties than samarium-cobalt magnets. However, compared to the samarium variety, these magnets have poor temperature and corrosion susceptibility.

For computers in which rotating disks are impractical, magnetic "bubble" memories that have no moving parts are used. The so-called bubble is a micron-sized magnetic spot, in a thin rare-earth orthoferrite layer, that can be switched off or on by a laser. As manufactured, the REO-alloy layer has a positive magnetism. In use, a moveable laser beam heats a bubble above a critical temperature to temporarily destroy its magnetism; upon cooling, the magnetism is restored, but in the reverse direction.

Gadolinium compounds can be employed in magnetic refrigeration. The underlying principle is that a gadolinium-based solid heats up in a strong magnetic field and cools when removed from that field. The system works at room temperature, but the greatest prospects may be in cryogenic applications.

Ceramics.—For the purpose of this report, ceramics are considered to be silicon compounds of sintered fine powders. They are physically hard, have high mechanical and heat strength, and resist thermal shock and corrosion but tend to be brittle. An unusual property, depending upon composition, is that ceramics can be either insulators or conductors of electricity. The main contributions of rare-earth additives are to increase the density and heat resistance of the sinter.

Ceria, yttria, and some other rare-earth oxides are used as a sintering aid due to their facility to eliminate weakening voids. As an example, during firing of silicon nitride, the elements form a Si-Y-O-N liquid phase. Upon cooling, the nitride grains regrow, and a yttrium oxynitride cools into a microcrystalline intergranular bond between the grains, which resists crack development. The resultant silicon nitride ceramic is used in hot-zone engine parts and high-speed cutting tools.

Yttria has a major use in the stabilization of high-temperature zirconia. This product forms one of the best high-temperature, high-strength and thermal-shock resistant refractory compositions that is stable under many conditions of oxidation and reduction at elevated temperatures. Consequently, it has high thermal-insulation properties and is used as a barrier coating to protect hot parts in jet engines. Because of inherent oxygen defects, yttria has an electrical resistivity that allows it to be used as an oxygen sensor in automobile exhaust systems. It is also employed in medicine for hip replacement parts and in dentistry for tooth fillings.

The rare earths have lately been receiving extraordinary attention in superconductivity research, which has involved ceramics composed of barium, copper, and oxygen. Why the rare earths contribute to this property is not fully known, and experiments continue with assorted compounds to improve superconductivity at higher temperatures. Once the critical current densities become commercial, the ceramics can be used for power generation and transmission, electromagnets, super computers, magnetic levitation (high-speed trains), and the supercollider.

Electronics.—Rare-earth materials are used in electronic devices that convert energy from one form to another. In some cases, both input and output are electricity, but the output variance is determined by another energy type, such as thermal or radiation. The rare earths in these materials are added to manmade garnet crystals: yttrium-iron, yttrium-aluminum, and gadolinium-gallium. Examples of these energy converters are diverse. The oxygen sensor, described earlier, produces a specific voltage corresponding to a certain oxygen input. Phosphors change electricity to luminescence. Window glass is now being made containing lead lanthanum zirconate titanate (PLZT), which can be switched electrically from transparent to opaque.

Chemical.—Rare earths contribute to the effectiveness of catalysts, which are used to modify chemical reactions while remaining unaltered themselves. The two major applications of these catalysts are in the petroleum and auto industries.

In oil refining, catalysts are used to increase the yield of gasolines extracted from the heavier oil fractions by a process called "cracking." Particularly in production of leaded gasolines, the catalyst is composed of a porous zeolite, which has as much as 5 percent rare earths lining its cavities. The rare earths create a strong electrostatic field, inducing surface acidity, to protect the zeolite against the high temperatures involved in regeneration by burning off accumulated carbon. Selection of a particular rare earth is based entirely on cost, as all of them are effective. Since 1985, oil refineries have been phasing out leaded gasolines and phasing in higher octane varieties. Since rare earths tend to lower octane rating, their growth rate is declining in this industry.

In automobiles, catalytic converters have been used since the 1970's to alter hydrocarbons, carbon monoxide, and nitrous oxides in engine exhausts to water, carbon dioxide, and nitrogen. The catalysts are composed of alumina and small amounts of precious metals and are activated by cerium, which is about 5 percent by weight. The cerium is used to give oxidation resistance at high exhaust temperatures, to stabilize palladium and rhodium dispersions, to minimize the interaction of rhodium with the alumina, and to enhance the oxidizing ability of the system. Testing is underway regarding substitution of lanthanum-enriched palladium for more expensive rhodium.

Optical.—The optics industry is usually interpreted as ranging from glasses through lasers and fiber optics to phosphors and fluorescent lights. Through the use of rare earths in these products, communications and vision are improved. Addition of small amounts of cerium oxide, for example, accelerates the melting of glass, and addition of neodymium and praseodymium gives glass its red or green color. If decolorizing is necessary due to iron contained in the glass, cerium is added to oxidize the iron. Cerium is also used in glass bottles to absorb ultraviolet light and thus protects the product and prevents browning of the glass due to radiation. Addition of lanthanum to camera lenses contributes a high refractive index and low dispersion. Praseodymium is used for vacuum-deposited antireflective coatings on lenses and as a constituent in tinted-glass filters for selective light absorption.

Special REO compounds, containing from 50 to 90 percent cerium oxide (the remainder are other light rare-earth elements), are used to polish glass surfaces without abrading. Other polishing agents, such as rouge, silica, and zirconia, are slow, dirty, and leave minute scratches. REO compounds are much faster, cleaner, and offer a superior finish. Polishing with REO is mostly a chemical reaction, whereby the hydroxyl ions in the agent interact with sodium ions in the glass to form a thin, softer hydrated layer that is removed or reformed.

Rare earths are used as activators in laser lenses and crystals. Neodymium is the most popular rare earth for the purpose, especially when combined with yttrium-aluminum-garnet. Researchers in California have experimented with a rare-earth laser in the "welding" of animal skin as a replacement for suturing. A promethium laser is undergoing testing for underwater communications and for contacting submarines and other submerged receivers.

Glass fibers containing rare earths can transmit data over exceptionally long distances without booster stations. The glass for these fibers, which may be composed of fluorides of lanthanum, zircon, barium, aluminum, sodium, and hafnium, is formed by chemical-vapor deposition, rather than through a melt, to minimize impurities.

Color for television and computer screens is made possible through the use of three phosphors: a europium-yttrium compound for red; a terbium-fluoride-zinc-sulfide for green; and, a cerium-strontium-sulfide for blue. When activated by photons, these phosphors emit the luminescence that makes the screen so attractive. A typical 19-inch (48 cm) television screen contains 5 grams of yttrium oxide and 0.5 grams of europium oxide. The TV faceplate contains neodymium oxide, which blocks ambient light from ruining the picture. In health care, terbium, thulium, and europium are used in X-ray phosphors to convert X-rays into visible light, which then strikes photographic film. The advantages of rare-earth phosphors over calcium-tungstate phosphor are reduced radiation exposure for the patient and staff, less silver in the film, and a sharper picture because of reduced patient movement within a shorter time interval.

Addition of rare earths to the phosphors in fluorescent lights makes the light seem more natural. Europium and terbium act as activators, and yttrium, lanthanum, or gadolinium as hosts. The resultant light is stronger and results in a savings of about 25 percent in capital and operating costs. The general mix of rare earths in the mineral monazite, when converted to fluorides and added to the core of carbon arcs, dramatically increases and whitens arc intensity. Yttrium, in a tantalum jacket, is used in high-pressure mercury-vapor lamps to absorb hydrogen gas, which is gradually released during operations and increases the ignition voltage and, thus, reduces the lighting efficiency.

Medical.—Rare-earth compounds have several uses in the medical profession. Cerium oxalate is prescribed for seasickness and morning sickness. Neodymium isonikotinate helps in the treatment of thrombosis. A gadolinium radioisotope is employed to diagnose and measure osteoporosis.

Nuclear.—The nuclear industry takes advantage of rare earths because of their ability to absorb neutrons and to remain stable at high temperatures. Yttrium metal is used in the tubes for molten-salt reactors. Cerium and yttrium hydrides are constituents of neutron moderators. Europium can be utilized in control rods.

Miscellaneous.—The Chinese have been experimenting with the use of rare earths as fertilizer. Crop yields have increased from 5 percent to 20 percent, and no harm to people or animals is indicated.

Lanthanide intermetallics can absorb and desorb large amounts of hydrogen at convenient temperatures and pressures. Thus, lanthanum pentoxide plus hydrogen will form a lanthanum nickel hydride in an exothermic reaction. Heating of the hydride will reverse the reaction, releasing hydrogen. Additions of cerium, praseodymium, and neodymium to the alloy allow the reaction to be tailored to specific requirements. Applications of these alloys are for hydrogen storage, catalysts, hydrogen purification, thermal compression, waste-heat engines, heat pumps, refrigeration, and batteries.

Refrigeration processes can cool cryogenic equipment to almost 33 °K (−240 °C) without the use of electricity. Lanthanum nickel hydride in a chamber is heated to about 377 °K (104 °C), which releases stored hydrogen gas. The gas passes through a heat exchanger, and is then allowed to expand. The expansion creates a considerable cooling effect and produces some liquid hydrogen. The gas is conducted to another chamber, where it is absorbed by more lanthanum pentoxide to form the hydride. The cycle is then repeated, using the new hydride, until the cooling chamber attains the target temperature.

Two types of hydrogen-based rechargeable batteries contain rare-earth elements. Both offer long life, high energy and power density, effective protection from over- and under-charging, and contain no toxic metals. The first type uses electrodes composed of lanthanum, neodymium, nickel, cobalt, and silica. The second battery type is composed of a nickel-oxide anode, a lanthanum-nickel-tin cathode, and a separator of polyamide resin containing caustic potash. When an electrical load is applied, the cathode releases the contained hydrogen, which consists of protons and electrons: the protons pass through the separator to the anode, and the electrons generate electrical current.

MINERALOGY AND GEOLOGY

Rare earths are mined and treated in their oxide form, known as rare-earth oxides (REO). More than 95 percent of REO occur in three minerals: bastnaesite ($CeFCO_3$), monazite $(Ce,Th,Y)PO_4$, and xenotime (YPO_4). Bastnaesite, found in vein deposits, contact metamorphic zones, and pegmatites, is also a rare accessory mineral in igneous rocks, most importantly in carbonatites and related veins. It contains approximately 70 percent REO, mostly of the lighter elements, and is mined in California and China as a primary ore.

Monazite and xenotime concentrations occur in placers as heavy mineral sands. Beach-sand placers are the most important source of heavy minerals; alluvial, stream, and aeolian deposits are much less significant. Monazite, a rare-earth thorium phosphate (sometimes as much as 10 percent ThO_2) containing about 70 percent REO, mostly of the lighter elements, is recovered as a byproduct in the mining of titanium placers in Australia, Brazil, India, Sri Lanka, South Africa, and the United States. Xenotime, a yttrium phosphate containing about 67 percent REO, mostly of the heavier elements, is recovered mainly from tin placers in Malaysia, although recently some production has come from Australian heavy-mineral sands. A listing of typical rare-earth-element distributions within these three minerals is shown in table 3.

Cerium is by far the most abundant rare-earth element in most bastnaesite and monazite, accounting for almost 50 percent of the rare-earth content of each mineral. Lanthanum and neodymium make up most of the remainder. Bastnaesite contains less than 1 percent of the heavy rare-earth elements, whereas monazite has almost 3 percent. The most abundant element in xenotime is yttrium, which is about 60 percent of the total. The lighter elements make up about 15 percent of xenotime, and the heavier elements make up 85 percent. Individual rare-earth element percentages vary for the same mineral found in different locations.

The types of rare earths contained in each mineral recovered are crucial to the success of a mining and beneficiating operation. Bastnaesite, which essentially

TABLE 3.—*Typical rare-earth-element distribution of the three major source minerals*

[N.r., not reported, values extremely variable, ranging from a trace to a significant number, depending upon the sample location. Figures may not add to totals shown due to rounding. Source: Business Opportunity Report, 1989, p. 28]

Element[1]	Mineral (percent of REO content)		
	Bastnaesite	Monazite	Xenotime
Light rare earths			
Lanthanum	32.0	23.0	[2]10.6
Cerium	49.5	46.5	
Praseodymium	4.2	5.1	
Neodymium	13.0	18.4	
Samarium	.8	2.3	1.2
Europium	.11	.07	.01
Gadolinium	.15	1.7	3.6
Subtotal	99.76	97.07	15.41
Heavy rare earths			
Terbium	.12	.16	1.0
Dysprosium		.52	7.5
Holmium		.09	2.0
Erbium		.13	6.2
Thulium	.02	.013	1.27
Ytterbium		.061	6.0
Lutetium		.006	.63
Yttrium	.10	1.95	59.99
Subtotal	.24	2.93	84.59
Total	100.00	100.00	100.00

[1] Promethium is not shown because it does not occur in the minerals listed.

[2] Percent of lanthanum, cerium, praseodymium, and neodymium in xenotime is extremely variable, but the total percentage for these four elements averages 10.6.

TABLE 4.—*Chemical formula, major REO group, and percent REO of the major rare-earth minerals*

[The letter "R" in the formulas represents rare earths. —, no data. Source: Business Opportunity Report, 1989, p. 24; Fleischer and Mandarino, 1991; A.N. Mariano, unpub. data, 1990]

Mineral	Chemical formula	Major REO designation	Percent REO
Allanite	$(R,Ca)_2(Al,Fe,Mn,Mg)_3(SiO_4)_3OH$	light	5–20
Apatite	$(Ca,R)_5((P,Si)O_4)_3(F,Cl,OH)$	light	0–12
Bastnaesite	$RFCO_3$	light	60–70
Brannerite	$(U,Ca,Y,Ce)(Ti,Fe)_2O_6$	heavy	12
Cerite	$(Ce,Ca)_{10}(SiO_4)_6(OH,F)_5$	—	70
Eudialyte	$((Ca,R)_2Na_4)(Fe,Mn,Y)ZrSi_8(OH,Cl)_2$	either	—
Euxenite	$(R,Ca,U,Th)(Nb,Ta,Ti)_2O_6$	heavy	14–43
Fergusonite	$(R,Ca,U,Th)(Nb,Ta,Ti)O_4$	—	46
Florencite	$RAl_3(PO_4)_2(OH)_6$	—	32
Fluocerite	RF_3	—	70
Gadolinite	$Be_2FeR_2Si_2O_{10}$	heavy	48
Loparite	$(R,Ca)(Ti,Nb)_2O_6$	light	≤30
Monazite	$(R,Th)PO_4$	light	50–78
Parisite	$CaR_2(CO_3)_3F_2$	—	60
Perovskite	$(Ca,R)TiO_3$	light	—
Pyrochlore	$(Ca,Na,R)_2Nb_2O_6F$	—	variable
Samarskite	$(Y,Ce,U,Fe^{+3})_3(Nb,Ta,Ti)_5O_{16}$	—	22
Xenotime	RPO_4	heavy	54–65
Zircon	$(Zr,Th,R)SiO_4$	either	—

contains all light rare-earth elements, cannot supply any of the heavier elements needed by industry. In contrast, xenotime, which contains predominantly heavy rare-earth elements, can furnish very few of the light elements. Monazite has a slightly better balance but is burdened with a major problem in that recovery of a few specific elements also requires production of other undesired rare-earth elements, which must be stored, discarded, or sold at a low price.

Rare-earth minerals

As shown in table 4, there are a number of minerals that are, or could be, of importance in the economic recovery of REO. Because some of these minerals are mined for primary products other than rare earths, the REO tailings are stockpiled or discarded.

Allanite.—This rare-earth-bearing member of the epidote group occurs in igneous, hydrothermal, and metamorphic environments. Normally limited to about 5 percent REO, allanite is usually too scattered in the rock to be of economic significance. There are, however, three deposits that have potential for allanite mining—the Mary Kathleen uranium tailings in Queensland, Australia; the Alice Springs prospect in the Northern Territory, Australia (1 million metric tons; 4 percent allanite, 20 percent REO); and the Hall Mountain Group in Idaho, United States.

Apatite.—Apatite, a calcium fluorophosphate, is found in carbonatites, alkaline igneous rocks, and some sediments. Currently, apatite is mined at certain locations as a source for phosphate fertilizers. At specific sites, such as the Kola peninsula in the former Soviet Union, the REO content may be high enough to warrant recovery as a byproduct. Potential REO projects based upon apatite are Phalaborwa in South Africa (124 million metric tons; 1.5 percent apatite, 7 percent REO) and the Mineville dumps in New York State, United States (16 million metric tons; 17 percent apatite, 6 percent REO).

Bastnaesite.—Exploitable deposits of bastnaesite, a fluorocarbonate of the cerium group, have been found as veins and disseminations in a complex of carbonate-silicate rocks, occurring with and related to alkaline intrusives (as in California), in quartz veins that cut micaceous schists and quartzite (as in Burundi), and in fluorite-bearing veins and breccia fillings in Permian sandstone (as in New Mexico). It is a primary source of light REO at Bayan Obo in China (800 million metric tons; 6 percent REO) and at Mountain Pass in California, United States (3.3 million metric tons; 7.7 percent REO). Bastnaesite is also the main REO mineral at Brockman in Australia, Poços de Caldas in Brazil, Thor Lake in Canada, and Karonge in Burundi. The chemical susceptibility of bastnaesite to weathering causes the REO to dissolve and combine with available phosphates.

Brannerite.—Brannerite, which can be an ore of uranium, occurs in pegmatites and conglomerates. The major economic location for brannerite is at Elliot Lake, Canada, where uranium is the primary product and where REO (as yttrium) is an occasional byproduct.

Eudialyte.—Eudialyte, a silicate, occurs in nepheline syenite (as at the Ilimaussaq deposit in Greenland) and in peralkaline granite (as at Pajarito in New Mexico, United States). Grades are 0.9 percent and 0.18 percent REO, respectively. Eudialyte tends to form as coarse-grained euhedral crystals, which are easily dissolved in acids.

Euxenite, fergusonite, florencite, gadolinite, and loparite.—Euxenite and fergusonite, complex oxides containing niobium and tantalum, are potential sources of REO. Florencite, an aluminum phosphate, is found in the weathered zone of carbonatites; by itself, this mineral can be relatively high in REO but is not known to occur in economic tonnages. Gadolinite, a beryllium iron silicate found in granite, granitic pegmatite, and placers, tends to be enriched in the heavy rare-earth elements. Loparite is basically an ore of niobium in which REO can be valuable byproducts. In the former Soviet Union, loparite contains as much as 30 percent REO.

Monazite.—A thorium-bearing phosphate, monazite originates in granites and carbonatites and contains mostly the light REO elements. In scattered locations, monazite content in the rock can be high enough to constitute an ore. However, due to its chemical and physical stability throughout the weathering cycle, most recoverable monazite is found in placers. It is often a byproduct of titanium mining (as in Australia). The thorium, which is radioactive, presents a handling and disposal danger during the beneficiation process. Some countries, such as Brazil, that wish to stockpile radioactive material, mandate that any thorium be removed before the material can be exported.

Perovskite.—Perovskite is known mainly as a possible titanium ore having REO byproduct potential. A major prospect containing perovskite is at Powderhorn in Colorado, United States, where the rock contains 0.36 percent REO.

Xenotime.—A yttrium phosphate, xenotime originates in igneous and metamorphic rocks and in pegmatites. It becomes concentrated in tin-bearing placers, most of which are dredged for tin offshore of Malaysia and Thailand. Xenotime is the only major REO mineral that is composed mostly of the heavy REO elements.

Types of rare-earth deposits

REO minerals occur in a variety of geological environments. In general, they are found in hard rock deposits or in placer sands and are of primary or secondary origin, respectively. Composition of the REO minerals is strongly influenced by the presence of carbonates and phosphates.

The predominant sources of REO are carbonatites—deep-seated magmas rich in carbon dioxide and low in silica that intruded the Earth's crust and solidified. Magmas forming closer to the surface commonly lose their carbon dioxide and other volatile agents and do not carry rare earths. Rare earths in carbonatites consist almost entirely of the light rare-earth elements contained in minerals such as bastnaesite, allanite, and apatite. Monazite, if present, contains a maximum amount of REO and a minimum amount of calcium and thorium.

Pegmatites, a hard-rock source of REO, begin as granitic magmas formed by remelting of crustal material. As the magma cools, crystals, incorporating heavy rare-earth elements, form. The liquid residue, relatively rich in the lighter REO elements, then crystallizes. Monazite and allanite in pegmatites tend to be richer in the heavy rare earths than when found in other rocks (A.N. Mariano, unpub. data, 1990). However, because monazite is likely to have more calcium and thorium, its overall REO content is reduced.

Hydrothermal solutions, developed through the interaction of hot underground water with crustal material, can carry rare-earth elements. Since the light rare-earth elements are less soluble than the heavier elements, they tend to settle out first, leaving the heavy elements more concentrated in the liquid. Thus, hydro-

TABLE 5.—*Distribution of rare-earth oxide deposits, mineral types, and production status of mines in those deposits, by country*

Country	No. of deposits	Deposit type		Mineral			Production status		
		Placer	Hard rock	Monazite	Bastnaesite	Other[1]	Non-producer[2]	Producer	REO concentrates[3]
Argentina	1	1	0	1	0	0	1	0	0
Australia	35	28	7	30	2	3	21	14	11
Brazil	16	14	2	14	1	1	12	4	2
Burundi	2	0	2	0	2	0	2	0	0
Canada	5	0	5	0	1	4	2	3	1
China	4	3	1	3	1	0	0	4	4
Egypt	1	1	0	1	0	0	1	0	0
Gabon	1	0	1	0	0	1	1	0	0
Greenland	1	0	1	0	0	1	1	0	0
India	5	5	0	5	0	0	1	4	4
Kenya	1	0	1	1	0	0	1	0	0
Malawi	1	0	1	1	0	0	1	0	0
Mauritania	1	0	1	1	0	0	1	0	0
Mozambique	1	1	0	1	0	0	1	0	0
Namibia	1	0	1	0	1	0	1	0	0
New Zealand	2	2	0	2	0	0	2	0	0
South Africa	3	1	2	2	0	1	0	3	1
Sri Lanka	1	1	0	1	0	0	0	1	1
United States	40	13	27	32	3	5	32	8	2
Uruguay	1	1	0	1	0	0	1	0	0
Total	123	71	52	96	11	16	82	41	26

[1] Includes allanite, anatase, apatite, brannerite, davidite, eudialyte, florencite, gadolinite, perovskite, and xenotime.

[2] Mines or deposits known or assumed to have no production.

[3] Number of mines or deposits of the known producers that generate REO concentrates for each country.

thermal deposits tend to contain minerals such as xenotime, which are enriched in the heavy rare earths.

Deep chemical weathering of carbonatites causes the dissolution of calcite, dolomite, and apatite. The REO released by this activity have an affinity for the phosphate radical and will form supergene monazite. Extreme lateritic weathering will convert pyrochlore to florencite and convert perovskite to anatase. In general, the light rare-earth minerals are converted to heavy rare-earth minerals.

Placers may contain recoverable amounts of REO minerals, such as monazite, xenotime, and anatase. These minerals have a high specific gravity, are chemically inert, and are stable during the erosion and transportation cycles of weathering. The major locations for placers are rivers, deltas, and coastlines. Along the coast, heavy minerals are concentrated by a combination of tidal action, longshore currents, waves, winds, and natural traps, such as a cape. Most of the placers being mined are recent beaches and dunes along coastlines; some are older deposits that have become stranded due to land elevation or ocean withdrawal. Mining of the placers is usually for a primary product such as ilmenite, rutile, tin, or gold; REO minerals, if recovered, are commonly byproducts.

Minor amounts of REO minerals are commonly associated with phosphate and uranium deposits. No phosphate operation recovers REO minerals. A few uranium mines in Canada, however, occasionally recover REO in brannerite.

DISTRIBUTION OF REO DEPOSITS

The ISMI rare-earth inventory covers 123 REO deposits in 20 countries. Of these deposits, most are in the United States (40), followed by Australia (35), Brazil (16), Canada and India (5 each), China (4), and 18 in 14 other countries. Table 5 shows the relative numbers, by country, for placer and hard-rock deposits, mineral types, and production status of REO-mineral concentrates.

As a simplification, the deposits are categorized either as placers or as hard-rock deposits. A total of 71 (58 percent) of these deposits are placers, and the remaining 52 (42 percent) are hard-rock deposits. The placers occur mostly in recent or ancient shorelines and less frequently along present or former riverbanks. Monazite is the predominant REO mineral in placers, except for Malaysia in which xenotime prevails; however, no Malaysian deposits are in the ISMI REO inventory. Countries having major placer deposits are Australia (28), Brazil (14), the United States (13), India (5), China (3), and New Zealand (2); Argentina, Egypt, Mozambique, South Africa, Sri Lanka, and Uruguay have 1 each.

The hard-rock deposits are derived mainly from magmatic activity. The exception is in Canada, where REO are associated with secondary uranium. The United States has the most hard-rock deposits (27), followed by Australia (7) and Canada (5); Brazil, Burundi, and South Africa have 2 each, and 7 countries have 1 each.

Monazite is the major REO mineral at 96 (78 percent) of the deposits, and bastnaesite is predominant at 11 (9 percent) sites. The leading minerals at the 16 (13 percent) remaining properties are allanite (3), brannerite (3), apatite (2), and eudialyte (2); anatase, davidite, florencite, gadolinite, perovskite, and xenotime are limited to individual properties.

In the United States, there are 32 monazite and 3 bastnaesite deposits, of which 8 are in actual operation, including only 2 (1 monazite and 1 bastnaesite) that are producing REO mineral concentrates. Australia has 30 monazite and 2 bastnaesite properties and 3 properties having other REO minerals; 14 are operating, of which 11 are producing monazite concentrates. Brazil hosts 14 monazite deposits, 1 bastnaesite deposit, and 1 deposit with other REO minerals; 4 are known to be operating, and 2 of these are making monazite concentrates; the status of the other 12 projects is not known. All five of the properties in India are monazite based, of which four are operating and producing monazite concentrates. In China, there are three monazite deposits and one bastnaesite deposit, all of which are operating and producing REO concentrates. Canada has three brannerite mines currently working, and one is producing REO concentrate. All three mines in South Africa are operating, but only Richards Bay is recovering a monazite byproduct. Sri Lanka has one operating monazite property, which produces a monazite concentrate. The map in figure 2 displays the names, locations, deposit type, and the size range of the world's major REO deposits and districts.

Australia.—In Australia, 27 of the 35 REO deposits are placers on, or close to, the west and east coasts—15 in Western Australia, 7 in Queensland, and 5 in New South Wales. Some operations on the east coast, such as Fraser Island, Moreton Island, and Munmorah, have been closed by the government because of environmental concerns; none of the west coast operations have been shut down for similar reasons, but incipient projects must undergo strict regulations, especially with regard to wetlands. The remaining eight deposits are inland—three in Western Australia, two in South Australia, and one each in the Northern Territory, Queensland, and Victoria. WIM–150, in Victoria, is the only far-inland placer. A planned operation at Port Pirie, in South Australia, proposes new plants for the processing of stockpiled REO-rich uranium tailings and for extracting rare earths from foreign and domestic monazite concentrate (Hammond, 1990).

Brazil.—Data regarding Brazilian projects are incomplete. There are numerous beach-sand deposits, which, contrary to placers in most other countries, are mined principally for the thorium content of the monazite. Two of the more interesting REO deposits are São Gonçala de Sapucaí and Tapira. The former will be the first inland REO placer to be dredged in the country. It is located on the Sapucaí River in Minas Gerais, and mining was scheduled to start in 1991 (Mining Journal, 1990a). At Tapira, which is an existing phosphate mine based on apatite in the same state, anatase-bearing overburden is currently stockpiled but will be mined and treated for recovery of titanium and REO (O'Driscoll, 1989).

Canada.—As market conditions warrant, REO are also extracted as a byproduct of uranium mining at Elliot Lake (Skillings Mining Review, 1990). There are indications, based upon beryllium content, that production could also come from Strange Lake, a deposit on the Quebec-Labrador border. Pyrochlore, fluorite, and REO would be byproducts (Engineering and Mining Journal, 1990).

China.—China undoubtedly has more REO deposits than the four reported. However, these four properties are among the world's largest resources, and their combined output strongly affects global supply. Bayan Obo is primarily an iron-ore mine, which has rare-earth minerals occurring both in separate bastnaesite zones and in the ferruginous material. REO production so far, and in the foreseeable future, is strictly from the bastnaesite zones; REO in the iron ore becomes locked in slag during the steel-making process and is not recoverable by current extractive procedures (L.J. Drew, USGS, unpub. data, 1990). The other three deposits are beach-river placers, which are worked by hand sluices. Ion-absorption clays are another undetailed resource.

India.—India has five major REO placer deposits, of which four are in production, all in coastal areas. The fifth placer, unworked, is inland, remote from necessary infrastructure. The federal or state governments own these projects and recover almost all of the minerals in the sands—ilmenite, rutile, zircon, garnet, sillimanite, leucoxene, magnetite, and monazite. Thorium is extracted from the monazite. Resources on the coastal placers of India and Sri Lanka may be underestimated because the beach sands are replenished by annual monsoons.

Mozambique.—A new (1992) REO placer operation is scheduled at Congolone, which is on the coast, 15 km north of Angoche. A complete infrastructure, including port and town, will be established. The consortium consists of Kenmare, the Mozambique government (25 percent free interest), and the Yugoslavia Geological Survey (Mining Journal, 1989).

New Zealand.—Two placer projects are in the pilot-plant stage in New Zealand. Important byproducts will be gold, cassiterite, magnetite, zircon, and monazite. Main products will be titania slag and pig iron (Industrial Minerals, 1990a).

South Africa.—South Africa has three major mines that contain REO minerals in the ore. Recently closed down, Buffalo Fluorspar produced three grades of fluorspar but did not recover the associated monazite. At the Phalaborwa Complex, Palabora Mining Company operates a large copper mine that has byproducts of sulfuric acid, uranium, precious-metal slimes, zircon, and vermiculite. Foskor runs a separate nearby apatite mine. REO are not extracted from the apatite, which is recovered for fertilizer manufacture. Richards Bay is a major beach-dredging operation producing ilmenite and byproduct zircon and monazite concentrates.

United States.—REO deposits are scattered across the United States, from inland California to the lower east coast. In Idaho, most properties are phosphate deposits, which are mined for fertilizer; inherent monazite is not recovered. Mountain Pass, in California near Las Vegas, Nev., is a major bastnaesite operation. The only other domestic rare-earth mine is at Green Cove Springs in Florida, where monazite is a byproduct of beach-sand dredging. Some of the coastal and inland placers are unlikely to be mined due to environmental problems. The map in figure 3 shows the World Bank (1986) economic class of each country that contains a major REO deposit.

REO RESOURCES

Total in-place resources in the world's major rare-earth oxide deposits are reported in terms of deposit type, mineralogy, and resource category. Amounts for recoverable ore resources, REO minerals, and REO will vary with the type and efficiency of mining and beneficiation. Table 6 summarizes the resources in the world's major REO deposits.

Based upon available data from 106 deposits, worldwide R1E REO ore resources amount to 20.6 billion metric tons, composed of 85 percent placer and 15 percent hard rock. The mineral mix consists of 90 percent monazite, 6 percent bastnaesite, and 4 percent other REO minerals.

REO minerals at 85 deposits amount to 36.9 million metric tons, comprising 33 percent in placers and 67 percent in hard rock. Composition is split into 79 percent monazite, 9 percent bastnaesite, and 12 percent other REO minerals.

Exclusive of ore and mineral statistics, REO at 103 properties amount to 93.4 million metric tons, of which 7 percent are in placer and 93 percent are in hard rock. The overall mineral composition is 20 percent monazite, 77 percent bastnaesite, and 3 percent other REO minerals.

As is apparent from the table and the discussion, monazite in placers is the predominant type of REO ore in terms of resource tonnage. With respect to REO content, bastnaesite is much more important. However, both mineral varieties are necessary to supply a complete range of light and heavy rare earths.

The category of "other resources" is based upon a much smaller set of records and consists mostly of poorly drilled areas contiguous to known properties. Whether they would ever be mined depends upon the exhaustion of the existing property and the market demand at the time.

REO ore resources, REO minerals, and REO data have been recast in terms of countries and their continents in tables 7, 8, and 9, respectively. Only R1E resources are shown since the other resource categories are not critical to this presentation.

With respect to R1E resources (table 7 and fig. 4), Australia possesses the largest resource at 8.6 billion metric tons, of which 94 percent occurs in placer sands and 95 percent is associated with monazite. Second in terms of tonnage is South Africa, with 5.2 billion metric tons, of which 97 percent occurs in placer sands and 98 percent is associated with monazite. The United States is third and has 3.3 billion metric tons of 63 percent placer sands and 90 percent monazite.

The United States is the leader in REO mineral resources (table 8); of 22.3 million metric tons, 97 percent are in hard-rock deposits and 73 percent are monazite. Australia is second at 5.2 million metric tons, consisting of 97 percent in placers and 99 percent

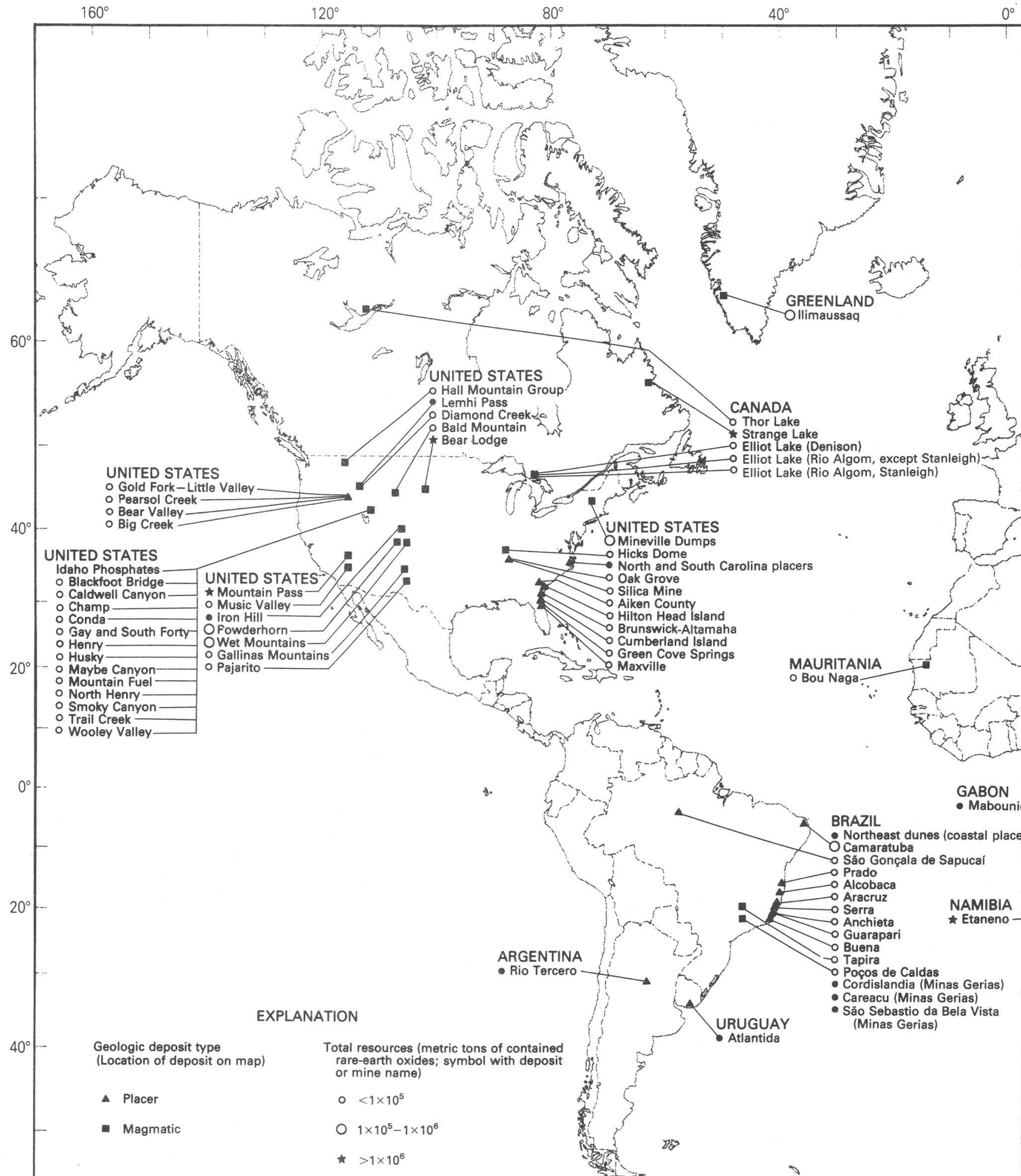
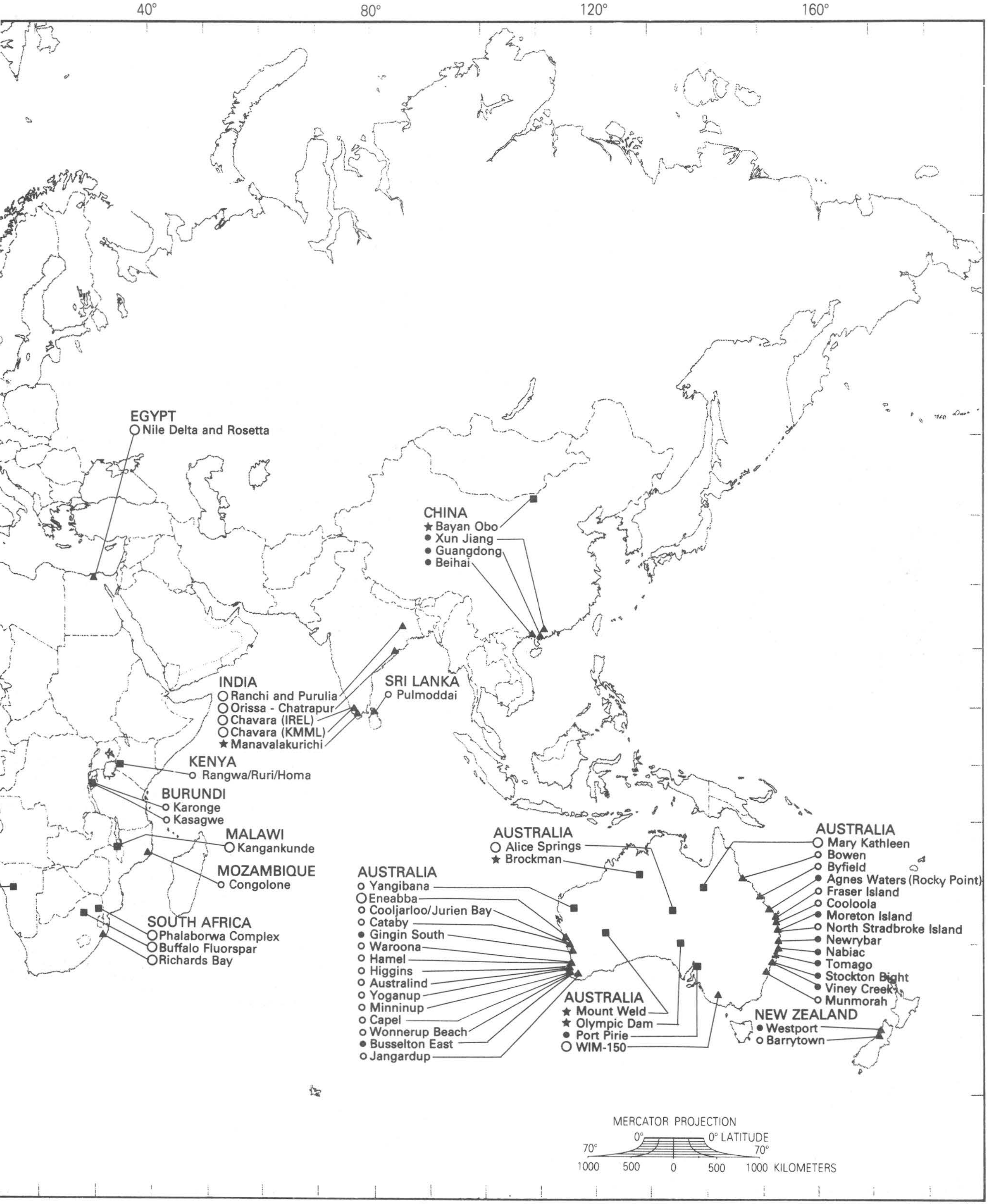


FIGURE 2. Location, geologic deposit type, and total resources of the world's major rare-earth oxide deposits and districts.



Locations and names are from tables 21 and 22 in Part II.

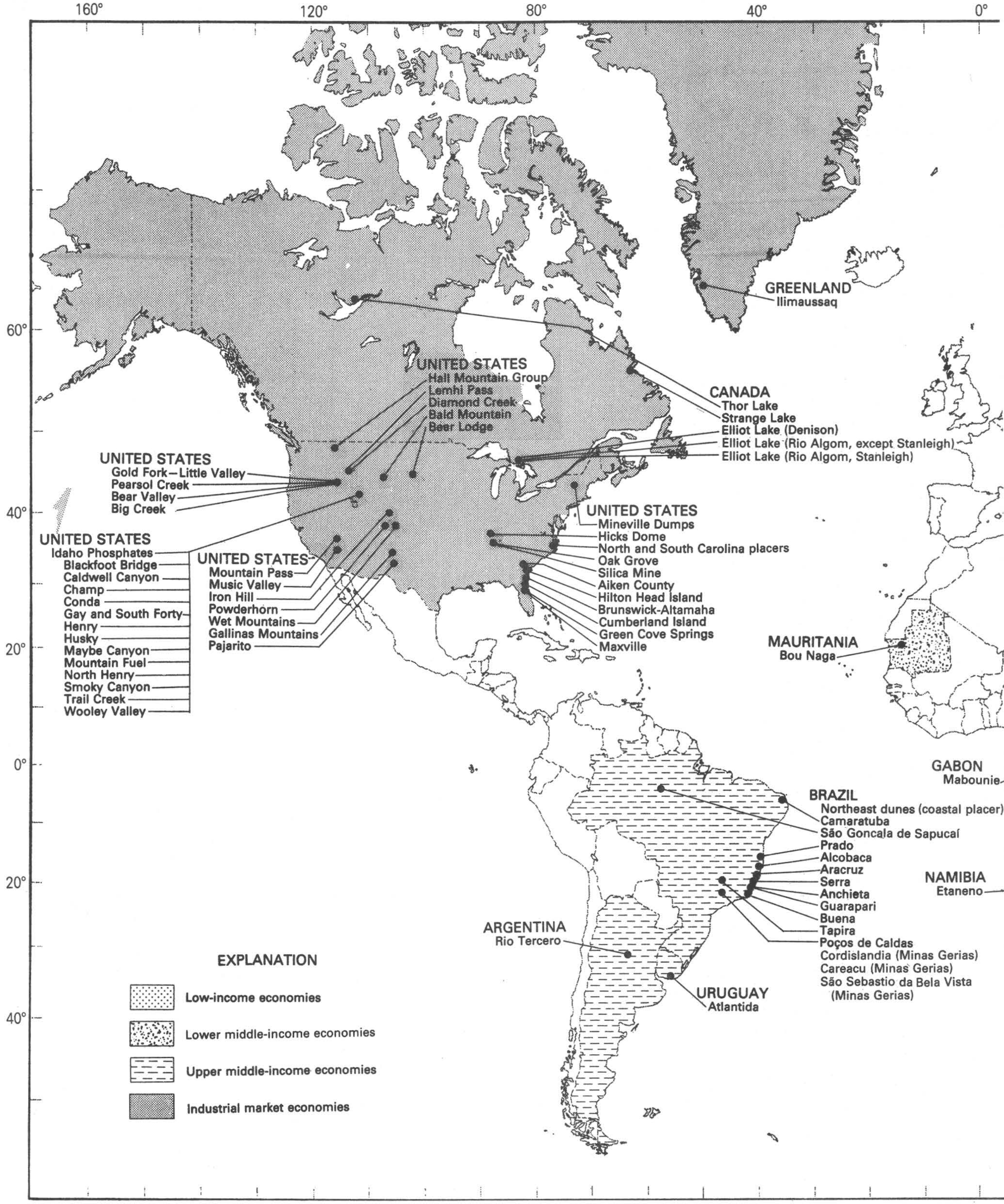
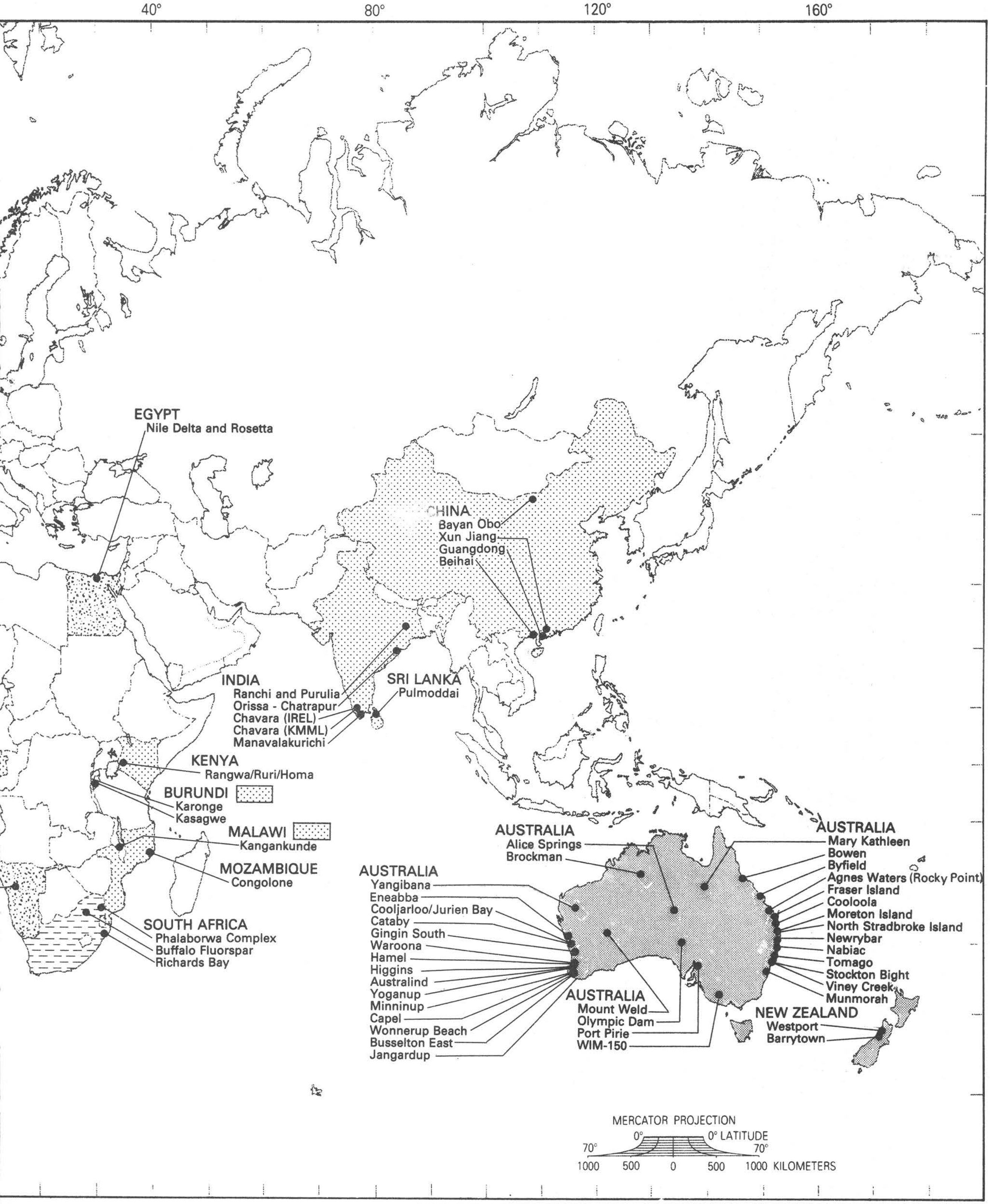


FIGURE 3. World Bank (1986) economic classification of countries containing major rare-earth oxide deposits and districts.



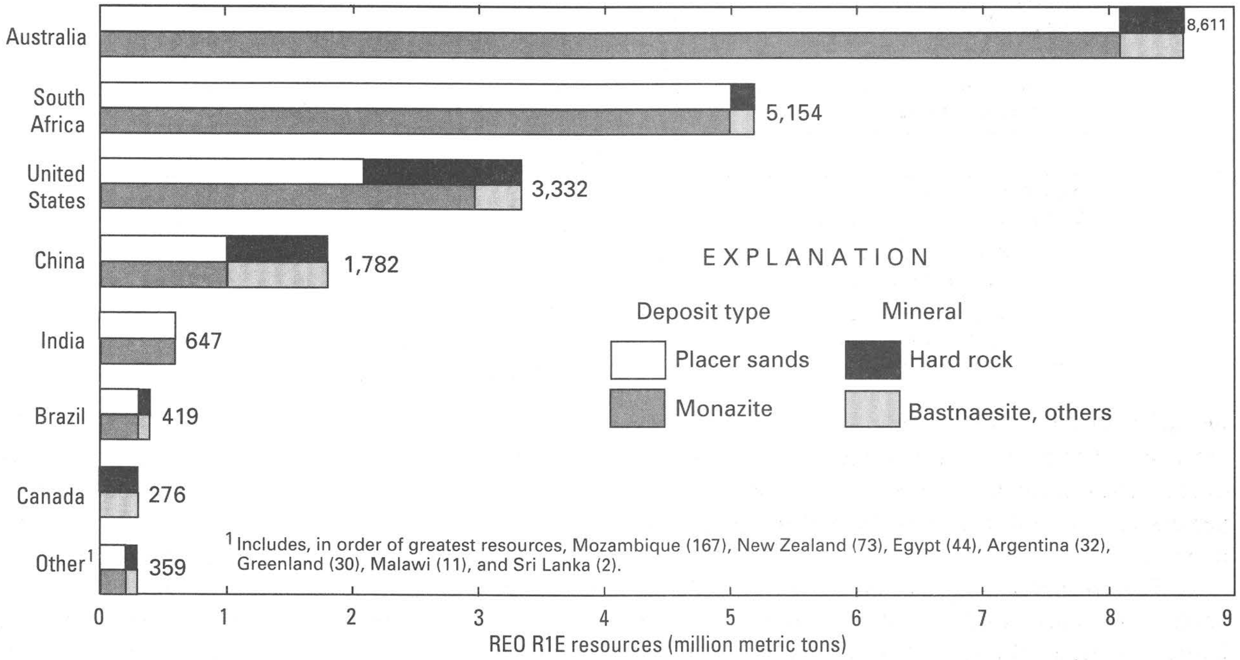
Locations and names are from tables 21 and 22 in Part II.

TABLE 6.—*Rare-earth oxide resources in the world's major rare-earth oxide deposits, by geologic deposit type and resource category*

[Percentages shown are weighted by the tonnages, not by the number of records. Figures may not add to totals shown due to rounding. N.r., not reported]

Deposit type	Mineral	R1E Number of deposits	R1E Million metric tons[1]	R1E Percent	Other resources Number of deposits	Other resources Million metric tons[1]	Other resources Percent
			REO ore resources				
Placer	Monazite	59	17,421	85	14	7,278	61
Hard rock	Monazite	21	991	5	14	1,270	11
	Bastnaesite	10	1,302	6	5	2,815	23
	Other	16	866	4	6	662	6
	Total	106	20,580	100	39	12,025	100
			REO minerals				
Placer	Monazite	57	12.132	33	12	5.534	20
Hard rock	Monazite	20	16.806	46	10	2.725	10
	Bastnaesite	4	3.381	9	3	18.829	70
	Other	4	4.556	12	1	N.r.	N.r.
	Total	85	36.875	100	26	27.088	100
			REO				
Placer	Monazite	57	6.732	7	10	3.230	13
Hard rock	Monazite	21	11.605	12	13	1.987	8
	Bastnaesite	11	72.118	77	5	18.936	76
	Other	14	2.959	3	6	.894	4
	Total	103	93.414	100	34	25.047	100

[1] Although this report is based upon 123 global REO deposits, individual project resource tonnages are not always available for the three main categories of ore (placer, hard rock), minerals (for example, monazite and bastnaesite), and rare-earth oxides. As a consequence, the tonnages for each category must stand alone and should not be compared with the tonnages for other categories.



[1] Includes, in order of greatest resources, Mozambique (167), New Zealand (73), Egypt (44), Argentina (32), Greenland (30), Malawi (11), and Sri Lanka (2).

FIGURE 4. Rare-earth oxide ore resources, by country, deposit type, and mineral type (see also table 7).

Table 7.—*Tonnages of rare-earth oxide ore-grade material in R1E resources, by continent and country, deposit type, and mineral*

[N.r., not reported. Figures may not add to totals shown due to rounding. See also figure 4]

Country	Deposit type (million metric tons)			Mineral (percent of R1E resource)	
	Placers	Hard rock	Total	Monazite	Bastnaesite and others
Africa					
Burundi	N.r.	N.r.	N.r.	N.r.	100
Egypt	44	N.r.	44	100	N.r.
Kenya	N.r.	N.r.	N.r.	100	N.r.
Malawi	N.r.	11	11	100	N.r.
Mauritania	N.r.	N.r.	N.r.	100	N.r.
Mozambique	167	N.r.	167	100	N.r.
Namibia	N.r.	N.r.	N.r.	N.r.	N.r.
South Africa	4,980	174	5,154	98	2
Subtotal	5,191	185	5,376		
Percent of total				98	2
Asia					
China	982	800	1,782	55	45
India	647	N.r.	647	100	N.r.
Sri Lanka	2	N.r.	2	100	N.r.
Subtotal	1,631	800	2,431		
Percent of total				67	33
Australasia					
Australia	8,135	476	8,611	95	5
New Zealand	73	N.r.	73	100	N.r.
Subtotal	8,208	476	8,684		
Percent of total				95	5
North America					
Canada	N.r.	276	276	N.r.	100
Greenland	N.r.	30	30	N.r.	100
United States	2,091	1,241	3,332	90	10
Subtotal	2,091	1,547	3,638		
Percent of total				82	18
South America					
Argentina	32	N.r.	32	100	N.r.
Brazil	267	152	419	64	36
Subtotal	299	152	451		
Percent of total				62	38
Total	17,420	3,160	20,580		
Percent of world total				85	15

monazite. In third place is India at 4.7 million metric tons, with 100 percent each in placers and monazite. South Africa is fourth; of 3.5 million metric tons, 67 percent are in hard-rock deposits and 47 percent are monazite.

The country having the largest amount of REO (table 9) is China, which has 48 million metric tons in bastnaesite (L.J. Drew, USGS, unpub. data, 1990). Second is Namibia, which has 20 million metric tons of REO, also in bastnaesite (Murray, unpub. data, 1989). The United States is third; of 14 million metric tons of REO, 73 percent is monazite. Australia is fourth; of 5.7 million metric tons of REO, 69 percent is in monazite.

Distribution of REO resources in the R1E category, by economic class of country, is shown in figure 5 (for selected countries) and table 10. Most of these resources are in the low-income economy countries, with a total of 51 million metric tons of REO. The ratio

TABLE 8.—*Tonnages of rare-earth-oxide-bearing minerals in R1E resources, by continent and country, deposit type, and mineral*

[N.r., not reported. Figures may not add to totals shown due to rounding]

Country	Deposit type (thousand metric tons)			Mineral (percent of R1E resource)	
	Placers	Hard rock	Total	Monazite	Bastnaesite and others
		Africa			
Burundi	N.r.	4	4	N.r.	100
Egypt	222	N.r.	222	100	N.r.
Kenya	N.r.	24	24	100	N.r.
Malawi	N.r.	550	550	100	N.r.
Mauritania	N.r.	8	8	100	N.r.
Mozambique	11	N.r.	11	100	N.r.
Namibia	N.r.	N.r.	N.r.	N.r.	N.r.
South Africa	1,145	2,358	3,503	47	53
Subtotal	1,378	2,944	4,322		
Percent of total				57	43
		Asia			
China	N.r.	N.r.	N.r.	N.r.	N.r.
India	4,654	N.r.	4,654	100	N.r.
Sri Lanka	2	N.r.	2	100	N.r.
Subtotal	4,656		4,657		
Percent of total				100	N.r.
		Australasia			
Australia	5,068	148	5,216	99	1
New Zealand	1	N.r.	1	100	N.r.
Subtotal	5,069	148	5,217		
Percent of total				99	1
		North America			
Canada	N.r.	N.r.	N.r.	N.r.	N.r.
Greenland	N.r.	N.r.	N.r.	N.r.	N.r.
United States	647	21,651	22,297	73	27
Subtotal	647	21,651	22,297		
Percent of total				73	27
		South America			
Argentina	5	N.r.	5	100	N.r.
Brazil	376	N.r.	376	100	N.r.
Subtotal	382		382		
Percent of total				100	N.r.
Total	12,132	24,743	36,875		
Percent of world total				78	22

between placers and hard-rock deposits is 5:95. Approximately 96 percent of the deposits are composed of bastnaesite or minerals other than monazite. China has a major influence on these numbers since it has 48 million metric tons of hard-rock-deposit bastnaesite.

The industrial-market economy countries are second in tonnage; 21.0 million metric tons are composed of 15 percent in placers and 85 percent in hard rock deposits. Monazite accounts for 67 percent of the REO minerals. In this economic class, the United States contains the largest resource, 14.0 million metric tons, followed by Australia, which has 5.7 million metric tons.

Lower middle-income economy countries are third in tonnage, which is 20.1 million metric tons, composed of 1 percent in placers and 99 percent in hard-rock deposits. About 99 percent of the REO is contained in bastnaesite and minerals other than monazite. Most of

Table 9.—*Tonnages of rare-earth oxides in R1E resources, by continent and country, deposit type, and mineral*

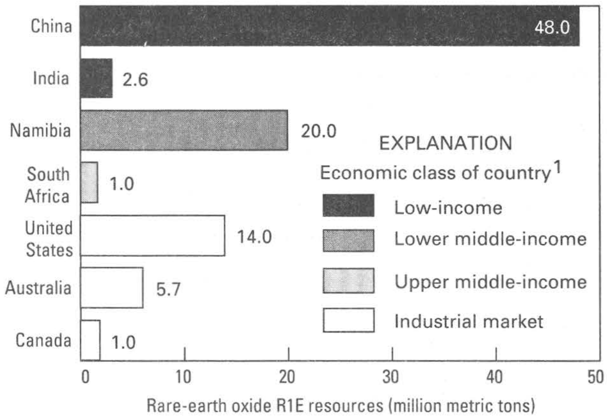
[N.r., not reported. Figures may not add to totals shown due to rounding]

Country	Deposit type (thousand metric tons)			Mineral (percent of R1E resource)	
	Placers	Hard rock	Total	Monazite	Bastnaesite and others
Africa					
Burundi	N.r.	2	2	N.r.	100
Egypt	122	N.r.	122	100	N.r.
Kenya	N.r.	13	13	100	N.r.
Malawi	N.r.	330	330	100	N.r.
Mauritania	N.r.	4	4	100	N.r.
Mozambique	6	N.r.	6	100	N.r.
Namibia	N.r.	20,000	20,000	N.r.	100
South Africa	630	405	1,035	87	13
Subtotal	758	20,755	21,513		
Percent of total				6	94
Asia					
China	N.r.	48,000	48,000	N.r.	100
India	2,560	N.r.	2,560	100	N.r.
Sri Lanka	1	N.r.	1	100	N.r.
Subtotal	2,561	48,000	50,561		
Percent of total				5	95
Australasia					
Australia	2,797	2,918	5,715	69	31
New Zealand	N.r.	N.r.	N.r.	100	N.r.
Subtotal	2,797	2,918	5,715		
Percent of total				69	31
North America					
Canada	N.r.	1,047	1,047	N.r.	100
Greenland	N.r.	270	270	N.r.	100
United States	393	13,598	13,990	73	27
Subtotal	393	14,915	15,307		
Percent of total				67	33
South America					
Argentina	3	N.r.	3	100	N.r.
Brazil	219	95	314	70	30
Subtotal	223	95	318		
Percent of total				70	30
Total	6,732	86,682	93,414		
Percent of world total				20	80

these figures are attributable to Namibia, which has a reported 20 million metric tons of REO.

Upper middle-income economy countries are fourth in amount of REO R1E resources, which are 1.4 million metric tons, of which about 63 percent is in placers and 83 percent is made up of monazite.

The distribution of the world's REO ore R1E resources among the World Bank economic classes, listed by mining method, is shown on table 11. In this specific case, the ore resource is used because it is more directly allied with the mining method than either the mineral or REO alternative. Mining methods are dredging, open pit, and underground. In many cases, the choice between using dredge or open-pit methods for a mineral sands deposit depends upon the availability of sufficient water to float a dredge. Some sands properties are mined by a modified open pit, whereby the sands are collected and sluiced to form a slurry for a wet mill. For



[1] Based principally on GNP per capita and, in some instances, other distinguishing economic characteristics (World Bank, 1986). Two additional economic classes, eastern European nonmarket economies and high-income oil exporters, are not listed because those countries have no reported major REO R1E resources.

FIGURE 5. Comparison of selected rare-earth oxide R1E resources, by economic class and country (World Bank, 1986; see also table 10, this paper).

those projects not yet working, the mining method was taken from associated studies, or assumed, based upon the disposition of the ore.

Approximately 15.1 billion metric tons (73 percent) of the REO ores are scheduled for mining by dredging, mostly along the coasts of Australia and South Africa. Open-pit methods account for 4.7 billion metric tons (23 percent), predominantly in China and the United States. About 0.7 billion metric tons (4 percent) are assigned to underground extraction, mainly in Australia and Canada.

The industrial-market economy countries contain the majority of the ore resources: 12.3 billion metric tons, or 60 percent of the world total. Mining methods are apportioned at 80 percent dredging, 14 percent open pit, and 6 percent underground. Of these, Australia has the largest resource at 8.6 billion metric tons, consisting of 90 percent dredging, 5 percent open pit, and 5 percent underground. The United States is second largest at 3.3 billion metric tons, consisting of 63 percent, 36 percent, and about 1 percent, respectively.

Second to the industrial-market economy countries are the upper middle-income economy countries, with 5.6 billion metric tons, or 27 percent of the total, consisting of 90 percent dredging and 10 percent open pit. South Africa has nearly all of the major tonnage, 5.2 billion metric tons, of which 97 percent is extractable using dredging methods.

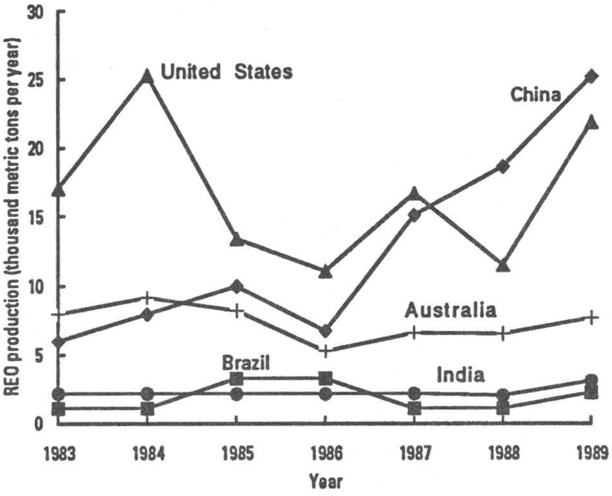


FIGURE 6. Rare-earth oxide production, 1983–89, for major producing countries (see table 12).

The low-income economy countries have 2.6 billion metric tons, which is equal to 13 percent of the global total and is mined 94 percent by open pit and 6 percent by dredging. Most of these resources are in open pits in China and India. Lower middle-income countries have 44.5 million metric tons or 2 percent of the global total, all of which will be mined by open-pit methods.

REO PRODUCTION

Worldwide REO production and potential production are shown in table 12, by country and by year from 1983 through 1989. During this period, global production has been variable (fig. 6), ranging from a low of 34,214 metric tons in 1986 to a high of 66,990 metric tons in 1989. Prior to 1985, the United States was the leading producer and Australia was second. However, China rose to second place by 1985 and was ahead of the United States by 1988. REO production in both countries is primarily from bastnaesite. The emergence of China as a leading producer of REO has drastically affected global prices and the potential for new projects.

Production of REO concentrates in Australia has been on a downtrend or at a lower level during the last few years, and some operations on the east coast have been closed due to environmental restrictions. However, improvement in sales prices has caused a rise in production more recently, and many new projects are starting or are under study. Brazilian production has shown little variation but is expected to rise as new projects begin to produce. Canada supplies a small amount of REO as a byproduct of uranium operations. REO output in India is steady and is consumed internally.

TABLE 10.—*Tonnages of rare-earth oxides in R1E resources, by World Bank economic class of country, deposit type, and mineral*

[N.r., not reported. Figures may not add to totals shown due to rounding]

Country	Deposit type (thousand metric tons)			Mineral (percent of R1E resource)	
	Placers	Hard rock	Total	Monazite	Bastnaesite and others
Low-income economies					
Burundi	N.r.	2	2	N.r.	100
China	N.r.	48,000	48,000	N.r.	100
India	2,560	N.r.	2,560	100	N.r.
Kenya	N.r.	13	13	100	N.r.
Malawi	N.r.	330	330	100	N.r.
Mozambique	6	N.r.	6	100	N.r.
Sri Lanka	1	N.r.	1	100	N.r.
Subtotal	2,567	48,345	50,912		
Percent of total				4	96
Lower middle-income economies					
Egypt	122	N.r.	122	100	N.r.
Mauritania	N.r.	4	4	100	N.r.
Namibia	N.r.	20,000	20,000	N.r.	100
Subtotal	122	20,004	20,126		
Percent of total				1	99
Upper middle-income economies					
Argentina	3	N.r.	3	100	N.r.
Brazil	219	95	314	70	30
South Africa	630	405	1,035	87	13
Subtotal	852	500	1,352		
Percent of total				83	17
Industrial market economies					
Australia	2,797	2,918	5,715	69	31
Canada	N.r.	1,047	1,047	N.r.	100
Greenland	N.r.	270	270	N.r.	100
New Zealand	N.r.	N.r.	N.r.	100	N.r.
United States	393	13,598	13,991	73	27
Subtotal	3,190	17,833	21,023		
Percent of total				67	33
Total	6,732	86,682	93,414		
Percent of world total				20	80

Actual 1989 production figures demonstrate a sharp rise in the output of REO for most countries. Compared to 1988, REO production climbed 47 percent from 45,683 metric tons to 66,990 metric tons. China continued to reign as premier producer; its 25,220 metric tons reflect a 35 percent increase. The United States remained second; the U.S. production of 21,875 metric tons was a 90 percent increase in 1 year. Australia was third; its 7,700 metric tons amounted to an 18 percent rise. Production in India increased by 51 percent.

Potential REO production for 1989 was 138,096 metric tons if the presently operating mines had all produced REO instead of discarding or stockpiling it. The chief, but not only, potential REO producers are those placer operations where the objective is to recover titanium minerals and to discard the other minerals. Hard-rock operations may also fail to recover rare-earth oxides. The Olympic Dam underground mine in Australia, for example, could potentially produce about 5,000 metric tons per year of REO as a byproduct of uranium recovery but has no plans to do so. In much the same manner, Canadian underground uranium mines have the potential for 610 metric tons per year of REO but actually produce about 150 metric tons per year (Vijayan

TABLE 11.—*Tonnages of rare-earth oxide ore-grade material in R1E resources, by World Bank economic class of country and by actual or proposed mining method*

[N.r., not reported. Figures may not add to totals shown due to rounding]

Country	Mining method, actual or proposed (million metric tons)			
	Dredge	Open pit	Underground	Total
	Low-income economies			
Burundi	N.r.	N.r.	0.1	0.1
China	N.r.	1,781.9	N.r.	1,781.9
India	N.r.	647.3	N.r.	647.3
Kenya	N.r.	.4	N.r.	.4
Malawi	N.r.	11.0	N.r.	11.0
Mozambique	166.8	N.r.	N.r.	166.8
Sri Lanka	1.6	N.r.	N.r.	1.6
Subtotal	168.4	2,440.6	0.1	2,609.0
	Lower middle-income economies			
Egypt	N.r.	44.4	N.r.	44.4
Mauritania	N.r.	.1	N.r.	.1
Subtotal	N.r.	44.5	N.r.	44.5
	Upper middle-income economies			
Argentina	N.r.	31.7	N.r.	31.7
Brazil	75.6	343.1	N.r.	418.7
South Africa	4,980.0	173.8	N.r.	5,153.8
Subtotal	5,055.6	548.6	N.r.	5,604.2
	Industrial market economies			
Australia	7,739.9	422.6	448.5	8,611.0
Canada	N.r.	52.6	223.8	276.3
Greenland	N.r.	30.0	N.r.	30.0
New Zealand	73.3	N.r.	N.r.	73.3
United States	2,091.3	1,187.2	53.4	3,331.9
Subtotal	9,904.5	1,692.4	725.7	12,322.5
Total	15,128.5	4,726.1	725.7	20,580.3

and others, 1989). South Africa has a fluorspar mine and adjacent copper-apatite mines (Phalaborwa) that together could make about 41,000 metric tons per year of REO. Finally, in the United States the operating open-pit phosphate mines would recover about 7,000 metric tons per year of REO, if the companies deemed it economical.

The country having the greatest potential for REO production is South Africa, which could produce 41,280 metric tons per year as compared to an actual production of about 700 metric tons per year; this would be an increase of approximately 59 times the present production. The United States has the capacity to produce about 32,764 metric tons per year, which is a 50 percent rise over the 1989 actual production of 21,875 metric tons per year. China could undoubtedly produce more REO than is reported, especially if Bayan Obo steel slag could be successfully treated. Australia could produce 11,462 metric tons per year, about half again the present rate, if Olympic Dam and some of the placer operations introduced REO mineral recovery plants. REO output in Brazil could be raised by a factor of five with little trouble.

The production figures in table 12 are shown by World Bank economic class of countries in table 13 and figure 7. From 1983 to 1989, the industrial-market economy countries began as the premier producers of REO. However, REO production from this class dropped from 69 percent of the world total in 1983, to just 44 percent in 1989, despite a big jump in output that year. On the contrary, the low-income economy countries, principally China, steadily increased their REO production until, by 1988, they temporarily surpassed the output of the industrial-market economy countries.

TABLE 12.—*Annual global rare-earth oxide production, by country, 1983–89*

[MEC's, market economy countries. CPE's, centrally planned economies. N.r., not reported. Figures may not add to totals shown due to rounding. See also figure 6. Source: U.S. Bureau of Mines, 1985–90]

Country	Annual production (metric tons of REO)							
	1983	1984	1985	1986	1987	1988	1989	1989 potential[1]
Australia	7,975	9,189	8,250	5,820	6,600	6,530	7,700	11,462
Brazil	1,100	1,100	3,300	3,300	1,100	1,100	2,280	11,028
Canada	N.r.	N.r.	N.r.	N.r.	50	100	[1]150	610
China	6,000	8,000	10,000	6,750	15,100	18,660	25,220	30,000
India	2,200	2,200	2,200	2,200	2,200	2,060	3,114	4,989
Malaysia[2]	187	2,563	3,300	3,300	3,300	3,300	3,300	3,300
South Africa	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	[1]688	41,280
Sri Lanka	N.r.	N.r.	N.r.	N.r.	N.r.	N.r.	[1]363	363
Thailand[2]	77	172	140	140	820	800	[1]800	800
United States	17,083	25,311	13,428	11,094	16,710	11,533	[1]21,875	32,764
Other MEC's	165	170	110	110	110	100	N.r.	N.r.
Other CPE's	1,500	1,500	1,500	1,500	1,500	1,500	[1]1,500	1,500
Total	36,287	50,205	42,228	34,214	47,490	45,683	[1]66,990	138,096

[1] Estimated.

[2] Not in the ISMI rare-earth oxide inventory.

TABLE 13.—*Rare-earth oxide production, by year and World Bank economic class of country*

[Figures may not add to totals shown due to rounding. See also figure 7. Source: U.S. Bureau of Mines, 1985–90; World Bank, 1986]

Economic class[1]	Annual production (metric tons of REO)							
	1983	1984	1985	1986	1987	1988	[2]1989	1989 potential
Low-income	8,200	10,200	12,200	8,950	17,300	20,720	28,697	35,352
Lower middle-income	77	172	140	140	820	800	800	800
Upper middle-income	1,452	3,833	6,710	6,710	4,510	4,500	6,268	55,608
Industrial market	25,058	34,500	21,678	16,914	23,360	18,163	29,725	44,836
Eastern European nonmarket	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Total	36,287	50,205	42,228	34,214	47,490	45,683	66,990	138,096

[1] Based principally on gross national product per capita and, in some instances, other distinguishing economic characteristics. An additional economic class, high-income oil exporters, is not listed because those countries have no reported REO production.

[2] Estimated.

The upper and lower middle-income economy classes are not heavy contributors to world REO production. Data from the eastern European countries are inconclusive, and the production shown is an estimate.

Potential production from operating mines is largest in the upper middle-income economy countries, from which 55,608 metric tons per year would be possible if the proper recovery plants were installed. Industrial-market economy countries would be second at 44,836 metric tons per year. The low-income economy countries are producing close to their potential of 35,352 metric tons per year. Lower middle-income economy countries are producing at their potential of 800 metric tons per year.

Table 14 shows 1989 REO production by type of deposit and by mining method, both actual and potential, for those countries where operating data are available. Figure 8 emphasizes the potential production capability of selected countries. Of the actual 1989 worldwide REO production, 41 percent comes from placer sands and 59 percent from hard-rock deposit types. If other operating mines that have potential REO production were included, these values would shift to 27 percent of production from placer sands and 73 percent from hard-rock deposits. Actual REO production from placer deposits could be raised by 42 percent, and production from hard-rock deposits could be increased by 168 percent.

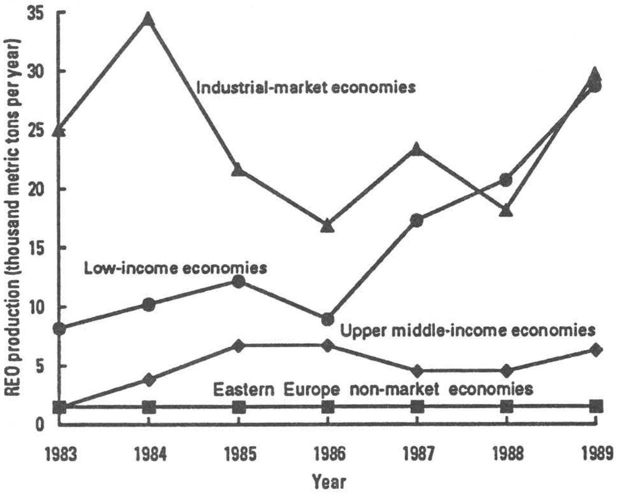


FIGURE 7. Rare-earth oxide production, 1983–89, for World Bank (1986) economic class of country (see table 13).

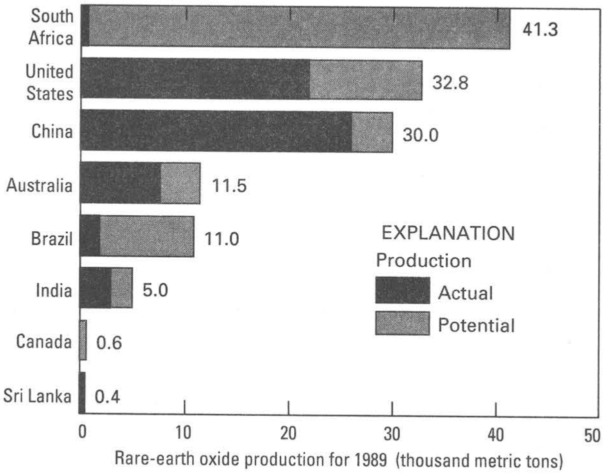


FIGURE 8. Actual and potential 1989 rare-earth oxide production, by country.

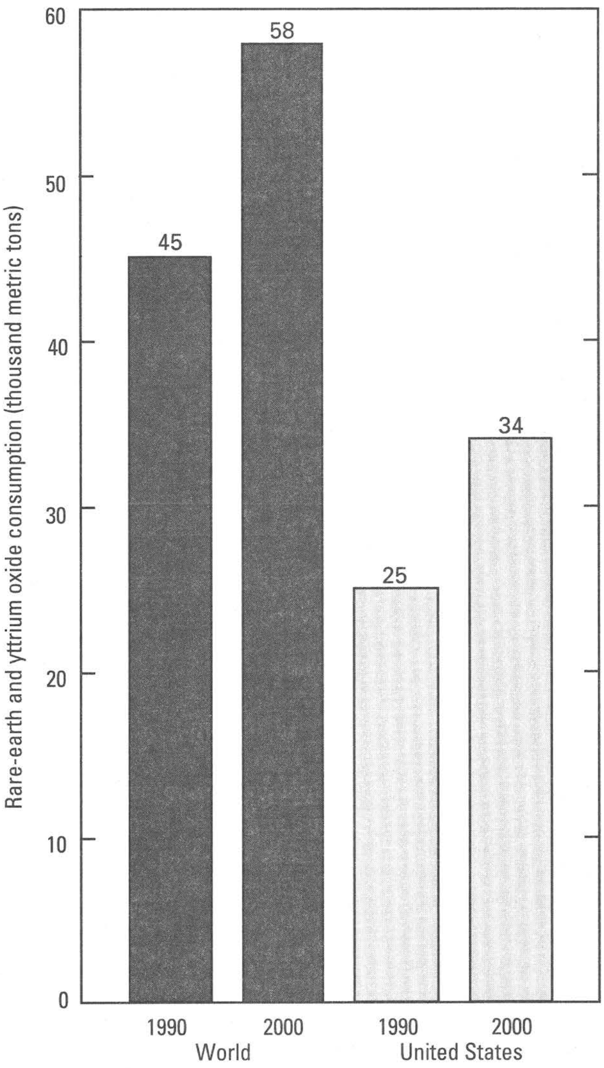


FIGURE 9. Forecast world and U.S. consumption of rare-earth and yttrium oxides for 1990 and 2000.

Mining methods for actual production are approximately 6 percent for dredging, 94 percent for open pit, and almost nil for underground. Inclusion of potential production estimates slightly changes mining method percentages. Potential production from open pits is 115 percent more than actual, and underground mines could supply about 36 times as much as they presently do.

Mining, either actual or potential, of placer sands is not always by dredging methods. In some low-wage placer-working countries, beach sands are recovered manually with baskets or sluices. In high-wage countries, placers are mined by open pits when dredging is impractical due to insufficient water or to shallow or thin ore layers.

Published forecasts for REO production range from glowing to pessimistic (Hedrick, 1988; Vijayan and others, 1989; Business Opportunity Report, 1989). In general, the market is expected to continue rising gradually, as demand grows. The U.S. Bureau of Mines predicts (fig. 9) that world consumption of REO and yttrium oxide will be 45,000 metric tons in 1990 and will rise by 2.6 percent per year to 58,000 metric tons in 2000. For the United States, consumption will be 25,000 metric tons in 1990 and 34,000 metric tons in 2000, which is equal to a growth rate of 3.1 percent per year.

There will be no difficulty in supplying REO at these predicted consumption rates. Some of the present working deposits have sufficient reserves for many

Table 14.—*Actual and potential rare-earth oxide production in 1989 for selected countries, by country, deposit type, and mining method*

[N.r., not reported. Figures may not add to totals shown due to rounding]

Country	Production, by deposit type (metric tons)					
	Actual			Potential		
	Placer	Hard rock	Total	Placer	Hard rock	Total
Australia[1]	7,700	N.r.	7,700	6,534	4,928	11,462
Brazil	2,280	N.r.	2,280	10,428	600	11,028
Canada	N.r.	150	150	N.r.	610	610
China	10,220	15,000	25,220	12,000	18,000	30,000
India	3,114	N.r.	3,114	4,989	N.r.	4,989
South Africa	688	N.r.	688	688	40,592	41,280
Sri Lanka	363	N.r.	363	363	N.r.	363
United States	1,088	20,787	21,875	1,088	31,676	32,764
Total	25,453	35,937	61,390	36,090	96,406	132,496
Percent	41	59	100	27	73	100

Country	Production, by mining method (metric tons)							
	Actual				Potential			
	Dredge	Open pit	Underground	Total	Dredge	Open pit	Underground	Total
Australia[1]	1,996	5,704	N.r.	7,700	1,694	4,840	4,928	11,462
Brazil	N.r.	2,280	N.r.	2,280	N.r.	11,028	N.r.	11,028
Canada	N.r.	N.r.	150	150	N.r.	N.r.	610	610
China	N.r.	25,220	N.r.	25,220	N.r.	30,000	N.r.	30,000
India	N.r.	3,114	N.r.	3,114	N.r.	4,989	N.r.	4,989
South Africa	688	N.r.	N.r.	688	688	40,592	N.r.	41,280
Sri Lanka	N.r.	363	N.r.	363	N.r.	363	N.r.	363
United States	1,088	20,787	N.r.	21,875	1,088	31,676	N.r.	32,764
Total	3,772	57,468	150	61,390	3,470	123,488	5,538	132,496
Percent	6	94	0	100	3	93	4	100

[1] The actual REO production numbers for Australia have been inflated by an unknown amount of monazite concentrates withdrawn from stockpiles established in earlier years; this inflation skews the placer and dredging and open-pit comparisons.

years, and adjacent unproved R2 resources will extend the operating periods. Those projects that could recover REO, but do not, could easily install REO circuits in their existing beneficiation plants. A few properties, especially in Australia, that were closed for environmental reasons could be restarted if approval was given by the local authorities. Some new projects are scheduled to start soon, and others under study could commence within a few years.

Australia.—Australia has many new placer and hard-rock projects pending. At WIM–150, a proposed inland dredging property, the operator is hoping to resolve a problem of fine-material recovery and could be producing 12,000 metric tons of monazite and 2,500 metric tons of xenotime per year when production of titanium minerals commences at a later date (R.J. Fantel, USBM, unpub. data, 1990). Cataby, a placer deposit, has the potential for 4,000 metric tons per year of monazite. Brockman, now undergoing feasibility studies, will be a hard-rock open pit that might produce 87 metric tons per year of REO. Mount Weld has a grade of 26 percent REO and yttrium; production could start in late 1994 if the company decides to proceed with development (Fantel, unpub. data, 1990). Yangibana, at a grade of 1.7 percent REO, and Alice Springs, at 0.8 percent REO, also are candidates for development. Plants for converting both monazite and bastnaesite concentrates to rare-earth products are under consideration.

Brazil.—There are a few new projects underway in Brazil. A dredging operation on the Sapucaí River is scheduled for start-up in the first half of 1991 and will be producing 1,600 metric tons per year of monazite, which is equal to 912 metric tons per year of REO (O'Driscoll, 1989). The phosphate mine at Tapira is undergoing modernization, including a REO recovery plant, so by late 1990 or early 1991 it can commence producing about 253 metric tons per year of REO.

Canada.—Canada is unlikely to increase rare-earth production; on the contrary, the operating mines are at the mercy of specific uranium contracts, which may or may not be renewed. A remote possibility exists that the Strange Lake deposit could be developed, primarily for its beryllium content, and would account for about 4,700 metric tons per year of REO as a byproduct.

China.—Output of REO from China is strictly a matter of how much the government wishes to participate in the world market, as with their alumina and tungsten operations. There are many placers and ion-absorption clays that could be worked. The independent REO operation at Bayan Obo could be expanded at any time, and extraction of REO from furnace slag awaits only research and development.

Mozambique.—The Congolone beach placer in Mozambique was scheduled to start in 1992 and would produce 1,000 metric tons per year of monazite. Extensive, abutting deposits of undrilled reserves could be used to augment this rate.

United States.—A rise in REO production by the United States will depend upon the status of the Pajarito project in New Mexico, which is currently undergoing more drilling and evaluation. The Mountain Pass mill was expanded recently, and another expansion is unlikely. The Maxville property in Florida may commence production in 1992, replacing some of the Green Cove Springs output. Figure 10 shows the operating and production status of the major global REO deposits and actual and potential annual tonnages.

SUPPLY AND CONSUMPTION

Available statistics for 1989 (Hedrick, 1990) indicate a global trend (compared to 1988) of higher bastnaesite consumption and lesser dependence on monazite. Processors also are showing an increasing preference for the higher purity rare-earth compounds over the more common mixed compounds. Two companies, Molycorp and Rhône-Poulenc, and their affiliates, and China, dominate world production capacity. Production is from raw ore, concentrates, or partially refined compounds, either imported or domestic, supplied by the United States, Australia, Canada, and South Africa. Major net exporters of rare earths in the form of monazite concentrates are Australia and South Africa; China exports bastnaesite-based products. Net importers are Japan and the former West Germany.

Several factors currently affect REO supply and consumption. REO production capacity, to date, exceeds consumption. Some of the placer-mining companies may stockpile, waste, or not recover the byproduct monazite. None of the phosphate-mining companies, for example, have monazite-recovery circuits. In addition, there are a number of prospects and developing rare-earth properties that may begin production within the next few years. Output of byproduct placer monazite is a function of primary ilmenite and rutile operations, and gyrations of the titanium industry strongly affect the availability of rare earths. While some individual rare-earth compounds find a ready market, other similar compounds, produced concurrently, have little or no market and are stockpiled until a market is developed.

Consumption of rare-earth products is not great in terms of weight; measurement is commonly reported in pounds, rather than in tons. Some markets, such as steel and petroleum, actually are shrinking in size. Growth in demand for specific products, like television sets and catalytic converters, depends upon market expansion; for example, other countries besides the United States might enact environmental legislation requiring automobiles to have catalytic converters. For those rare earths that have a limited or no market, research is directed toward new uses, or perhaps substitution, for the more saleable rare earths. Finally, reductions in processing costs would allow a more diverse market to develop since products would be cheaper and more available for testing.

World consumption of rare earths and their products in 1988 was 40 million pounds (Business Opportunity Report, 1989) (table 15 and fig. 11). For the major industries, consumption was 52.5 percent for chemicals (mostly catalysts), 42.5 percent for optics, and 5 percent for metallurgy and magnets. By 1995, world consumption is forecast to grow to 43 million pounds, distributed as 51.2 percent, 39.5 percent, and 7 percent in the respective industries above, and the remaining 2.3 percent spread between ceramics and electronics.

U.S. consumption in 1988 was 15 million pounds, 65 percent of which was used for chemicals, 27 percent for optics, 6.7 percent for metallurgy and magnets, 0.9 percent for ceramics, and 0.1 percent for electronics. Predictions for 1995 are for 16 million pounds to be consumed: 61 percent, 27 percent, 11 percent, 1.3 percent, and 0.14 percent, in those industries, respectively.

Besides weight, another measure of consumption is value (table 15 and fig. 12). World consumption of rare-earth products in 1988 was valued at $343 million

TABLE 15.—*Actual 1988 and forecast 1995 world and U.S. consumption of rare-earth products, by industry*

[Totals are rounded to compensate for other minor industries. Source: Business Opportunity Report, 1989, p. 185–189]

Industry	1988 Weight (million pounds)	1988 Value (million U.S. dollars)	1995 Weight (million pounds)	1995 Value (million U.S. dollars)
World				
Chemicals	21.0	$ 58.0	22.0	$ 57.0
Optics	17.0	230.0	17.0	290.0
Metallurgy and magnets	2.0	40.0	3.0	80.0
Ceramics	.25	12.0	.5	28.0
Electronics	.03	3.0	.5	4.0
Total	40.28	343.0	43.0	459.0
United States				
Chemicals	9.8	29.0	9.8	43.0
Optics	4.1	46.0	4.4	72.0
Metallurgy and magnets	1.0	21.0	1.7	29.0
Ceramics	.13	6.5	.21	11.0
Electronics	.015	1.5	.023	3.0
Total	15.045	104.0	16.133	158.0

(Business Opportunity Report, 1989). The optical market was the largest at 67.1 percent, followed in decreasing order by chemicals, metallurgy and magnets, ceramics, and electronics. Projections for 1995 world consumption total $459 million; optics will still have the largest share, but metallurgy and magnets will overtake chemicals for second place. The proportion of REO consumption value for ceramics will increase by 74 percent.

The value of U.S. REO consumption in 1988 was $104 million: 44.2 percent for optical and lesser amounts for the other industries. The estimate for 1995 U.S. consumption is $158 million of which the corresponding values will be roughly in the same proportions.

Growth rate, by weight, for the world will be 1.07 percent versus 0.95 percent per year for the United States. However, based on value, the growth rate per year will be 4.56 percent worldwide versus 7.42 percent for the United States (Business Opportunity Report, 1989).

Table 16 shows a comparison of the consumption by weight and by value for specific rare-earth compounds throughout the world and in the United States (Business Opportunity Report, 1989). On a world basis, the 80-percent lanthanum oxide was the consumption leader at 13 million pounds, followed by 60-percent cerium oxide, 96-percent cerium oxide, and 96-percent praseodymium oxide. However, on a value basis, the praseodymium oxide was first at $107 million, followed by 99.99-percent europium oxide, 99.99-percent yttrium oxide, and 96-percent cerium oxide.

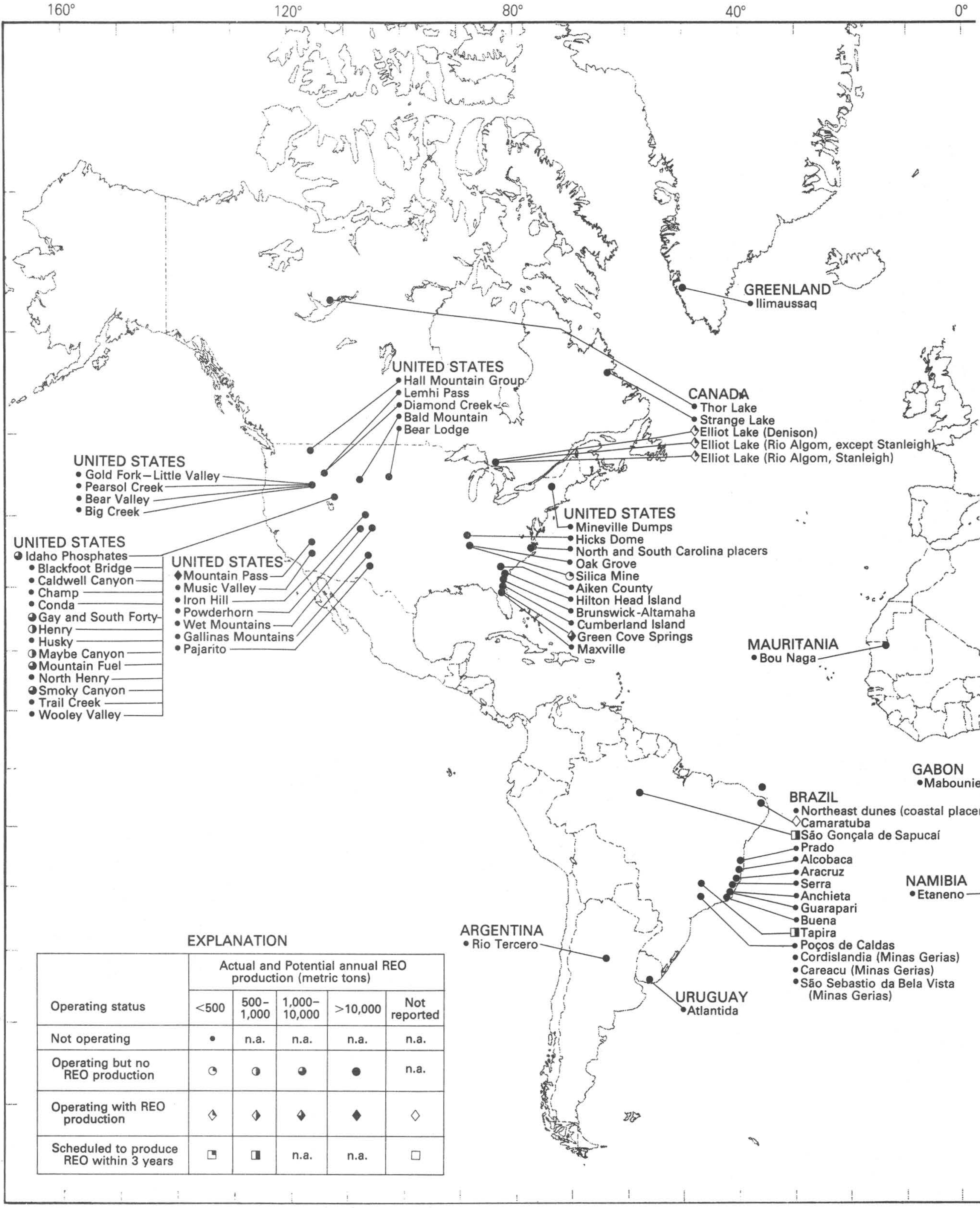
The consumption mix is different in the United States. The leader is again 80-percent lanthanum oxide at 5 million pounds, followed by 96-percent cerium oxide, 60-percent cerium oxide, and mischmetal. With respect to values, 96-percent cerium oxide and 99.99-percent europium oxide account for $22 million each, followed closely by 99.99-percent yttrium oxide and by 80-percent lanthanum oxide.

PRODUCTION AND CAPITAL COSTS

Production costs are those direct and indirect expenses incurred by the mining and beneficiation of ore. Direct costs include both operating and maintenance labor, salaried supervision, materials, payroll overhead, and utilities. Indirect costs are administration, site maintenance and supplies, research, and technical and clerical labor. Transportation and refining costs, which can be expensive, are not within the scope of this study.

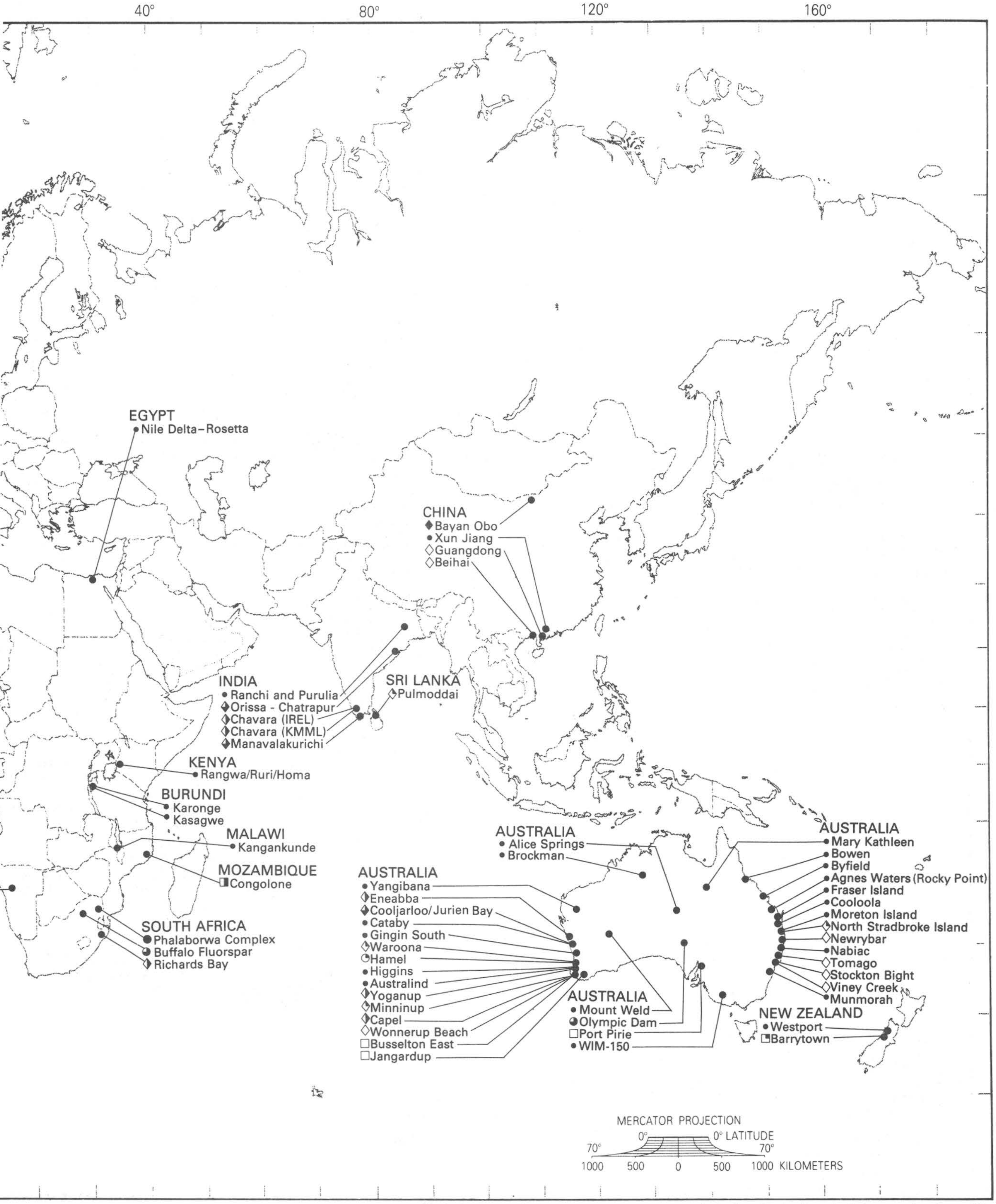
Anstett (1986) generated a substantive study on world rare-earth mine and mill operating costs. These costs, originally reported in January 1984 U.S. dollars per metric ton of ore, have been updated here to average 1989 U.S. dollars, as shown in table 17.

Average mine, mill, and total production costs per country show that Australia is the most economical of the producers at $1.26 per metric ton, followed by India



Operating status	Actual and Potential annual REO production (metric tons)				
	<500	500–1,000	1,000–10,000	>10,000	Not reported
Not operating	•	n.a.	n.a.	n.a.	n.a.
Operating but no REO production	◔	◑	◕	●	n.a.
Operating with REO production	⬘	⬖	⬗	◆	◇
Scheduled to produce REO within 3 years	◳	◧	n.a.	n.a.	□

FIGURE 10. Operating and production status of the world's major rare-earth



oxide deposits and districts and actual and potential annual production.

TABLE 16.—*Consumption of rare-earth compounds in 1988, by weight and value*

[N.r., not reported. Source: Business Opportunity Report, 1989, p. 237–246]

Compound (purity)	Consumption (million pounds)		Consumption (million U.S. dollars)	
	World	United States	World	United States
Lanthanum (N.r.)	0.15	0.095	$ 11.00	$ 6.60
Lanthanum oxide (99.995)	.045	.018	.41	.16
Lanthanum oxide (99.99)	.39	.15	3.50	1.40
Lanthanum oxide (80.00)	13.00	5.00	18.00	7.00
Cerium fluoride (N.r.)	.075	.03	.23	.09
Cerium oxide (96.00)	8.00	4.80	36.00	22.00
Cerium oxide (60.00)	9.50	3.80	15.00	5.70
Praseodymium oxide (96.00)	6.30	.06	107.00	1.00
Neodymium (N.r.)	.30	.20	9.00	6.00
Neodymium oxide (99.99)	.038	.015	1.50	.59
Samarium oxide (96.00)	.10	.067	8.00	5.40
Europium oxide (99.99)	.082	.028	66.00	22.00
Gadolinium (N.r.)	N.r.	N.r.	.012	.005
Gadolinium oxide (99.99)	.093	.037	5.80	2.30
Terbium (N.r.)	N.r.	N.r.	.072	.027
Terbium oxide (99.90)	.0023	.0009	.92	.37
Thulium oxide (99.90)	.0015	.0006	2.30	.91
Yttrium (N.r.)	.015	.006	2.80	1.10
Yttrium oxide (99.999)	.0007	.0003	.11	.03
Yttrium oxide (99.99)	1.00	.37	50.00	19.00
Mischmetal (N.r.)	1.10	.40	5.50	2.00

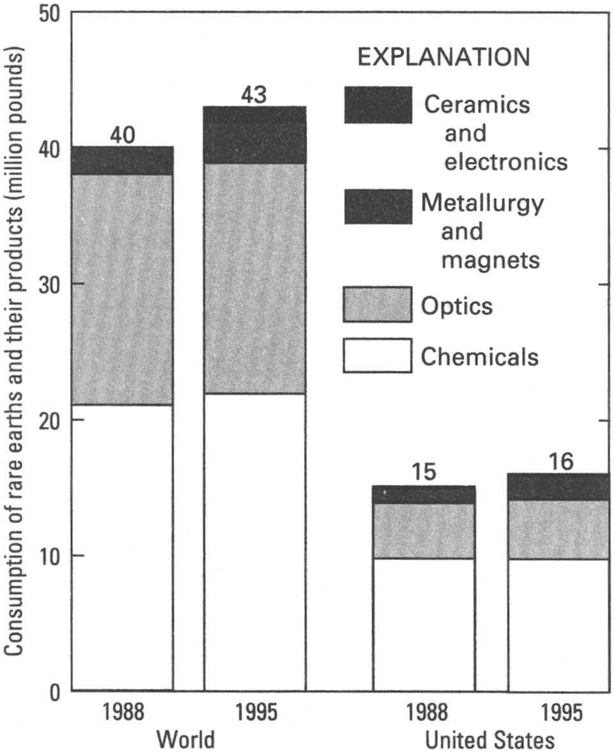


FIGURE 11. Amount of actual 1988 and forecast 1995 world and U.S. consumption of rare earths and their products (source: Business Opportunity Report, 1989, p. 185–189).

and Sri Lanka, the United States, and Brazil (table 17 and fig. 13). The lowest cost mining is in India and Sri Lanka, whereas the cheapest milling is in Australia.

The highest mining costs are for underground methods; open pits and dredging are progressively cheaper, and manual extraction is the most economical in low-wage countries. The highest milling costs are in old plants that have antiquated machinery, whereas the lowest costs are in new plants that have a high degree of mechanization. Wage rates and production throughput also have a large effect on these costs.

Capital costs are a function of location, property payments, exploration, feasibility studies, construction, and development. As with production costs, producers are reluctant to share their capital costs with the public. However, some projects that will start up soon have published their capital costs.

Australia.—Most new projects are in Australia, and the majority of these will be mining and processing titaniferous sands. Beenup will spend A$110 million (exchange rate is US$1.00 = A$1.28) for a throughput of 500,000 metric tons per year of heavy-mineral concentrates (The Miner, 1990; Prospect, 1990). Cooljarloo will cost A$400 million for a complete project ranging from the mining of 12 million metric tons per year of sands to yield 500,000 metric tons per year of concen-

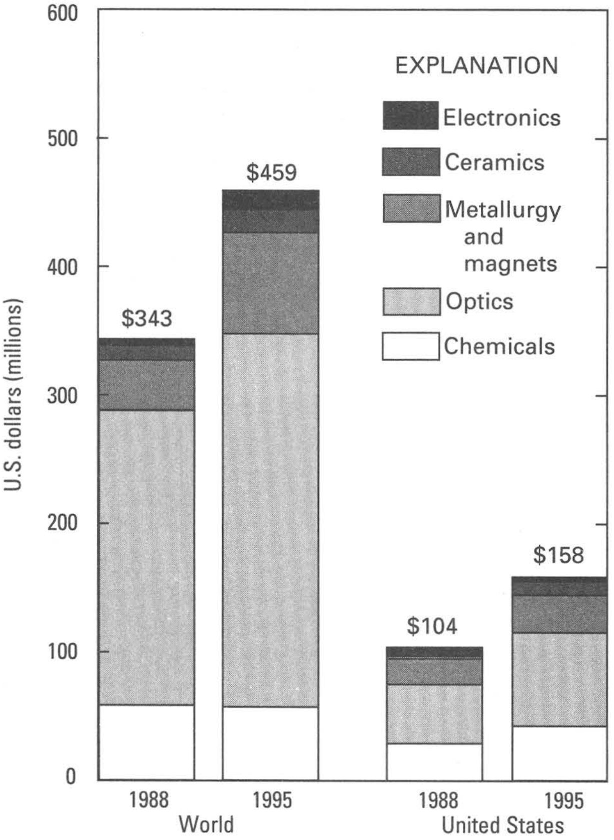


FIGURE 12. Value of actual 1988 and forecast 1995 world and U.S. consumption of rare earths and their products (source: Business Opportunity Report, 1989, p. 185–189).

TABLE 17.—*Average mine and mill production costs in 1989*

Category	Production costs[1] (1989 U.S. dollars per metric ton of ore)			
	Australia	Brazil	India and Sri Lanka	United States[2]
Mine	$0.83	$2.00	$0.52	$0.81
Mill	.43	2.04	1.25	1.30
Total........	1.26	4.04	1.77	2.11

[1] Costs applicable to placers cannot be extrapolated to final REO output since the primary minerals (for example, rutile, ilmenite, cassiterite, and collophane) incur most of the project expenses and earn most of the income. Derivation of the operating costs was based upon published material, company and other knowledgeable personnel, and proprietary unpublished studies. Costs were established for each producing and nonproducing property and averaged per country on the basis of actual or expected annual project tonnage.

[2] Costs for the producers in the United States are based upon current estimates of a hard-rock open-pit mine at Mountain Pass, Calif., and on the placer-sands dredging operation at Green Cove Springs, Fla. These costs were averaged on the basis of annual ore throughput.

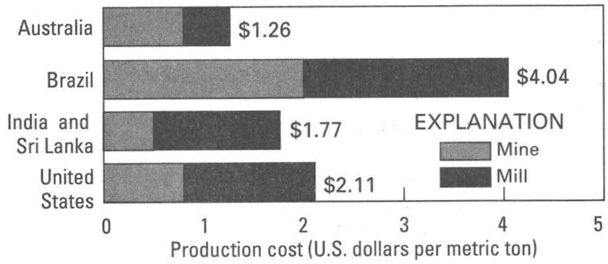


FIGURE 13. Average mine and mill production costs per metric ton of ore for selected countries.

trates; the titanium minerals will feed synthetic rutile and pigment plants (Prospect, 1990). Cost to Eneabba West is estimated to be A$115 million for a new mine and a plant expansion to handle 20 million metric tons per year of sand and 292,000 metric tons per year of concentrates, including 2,500 metric tons per year of monazite concentrates (Mining Magazine, 1989a). Jangardup expects to treat 3.7 million metric tons per year of sands and 270,000 metric tons per year of concentrates with a new mine and plant forecast at A$43 million (Prospect, 1989–90). Newrybar was planning for the conversion of 3.5 million metric tons per year of sands into 30,000 metric tons per year of concentrates for an investment of A$11 million (Mining Magazine, 1990).

Some capital costs are also available for three potential hard-rock mines in Australia. Brockman will cost A$115 million for a 200,000-metric-tons-per-year operation (Mining Journal, 1990b). Mount Weld expects the 20,000-metric-tons-per-year project to cost about A$20 million minimum; this cost could double if additional processing and refining lines are added (Prospect, 1989–90). Yangibana is currently expending A$5.3 million for a feasibility study (Mining Magazine, 1989b).

Two projects in Australia have been under consideration solely as processing and refinery plants for rare-earth products. The A$50-million project at Port Pirie (Hammond, 1990) will incorporate facilities to treat 200,000 metric tons of uranium tails on site, to separate yttrium from imported material, and to recover rare earths from 4,000 metric tons of Australian monazite concentrates. The second project, at Pinjarra, now abandoned, would have treated 15,000 metric tons per year of monazite concentrates for a capital cost of A$150 million (Prospect, 1989–90).

Brazil.—There are two developing projects in Brazil for which costs are available. The first is a dredging operation on the Sapucaí River that is expected to produce 52,000 metric tons per year of heavy-mineral concentrates; a partial investment of \$15 million was made in 1988 (O'Driscoll, 1989). Tapira, part of a phosphate project, has established a pilot plant, rated at 3,000 metric tons per year of REO-bearing material, for a cost of \$20 million (O'Driscoll, 1989).

Mozambique and the United States.—There are two other projects that merit mention. Congolone, in Mozambique, is spending \$100 million for a complete operation, including town and port, to handle 18.75 million metric tons per year of sands (Mining Journal, 1989). Molycorp is in the final stages of expending \$20 million for an expansion and upgrading of their rare-earth processing and refining facilities within the United States (O'Driscoll, 1990).

MINING AND BENEFICIATION

Hard-rock deposits.—Mining of hard-rock deposits is by open-pit and underground methods. At Mountain Pass, Calif., and at Bayan Obo, China, for example, open-pit operations are standard drill, blast, load, and haul to the mill. Underground room-and-pillar mining is conducted at the Canadian uranium properties.

The Mountain Pass beneficiation process is distinctive. The blasted bastnaesite rock is crushed, and the crushed product is built up in layers to average about 7 percent REO in blending piles and then reclaimed and fed to the mill fine-ore bin. Ore withdrawn from the bin is conveyed to a ball mill, where particle size is reduced to 100 percent passing 150 mesh. Oversized material is recovered by a cyclone and returned to the ball mill. Ground ore is fed to a conditioning tank, where reagents and steam are added to raise the slurry temperature to boiling, before cooling.

The conditioned slurry is pumped to the flotation circuits, where barium and strontium minerals are depressed and bastnaesite is floated. A fatty acid collector is added, and the pH is maintained at between 8 and 9 with soda ash. Concentrate is thickened, filtered, and dried in a rotary kiln.

The final dried concentrate at Mountain Pass contains 60 percent REO, equivalent to a 70 percent recovery. This basic concentrate can be upgraded to about 70 percent REO by leaching with hydrochloric acid to remove calcium and strontium carbonates. This latter concentrate can be enriched to 85 percent REO by calcination to remove the carbon dioxide. All three grades of concentrates are sold commercially and also used by Molycorp. A simplified flowsheet of the beneficiation process is shown on figure 14.

At Bayan Obo, beneficiation of bastnaesite ore is conducted differently. The concentrate is heated to above 500 °C in a rotary kiln to drive off carbon dioxide and hydrofluoric acid as gases. Water is used to leach the calcine, and sodium chloride is added to precipitate a rare-earth sodium phosphate. This compound is then converted to rare-earth chlorides.

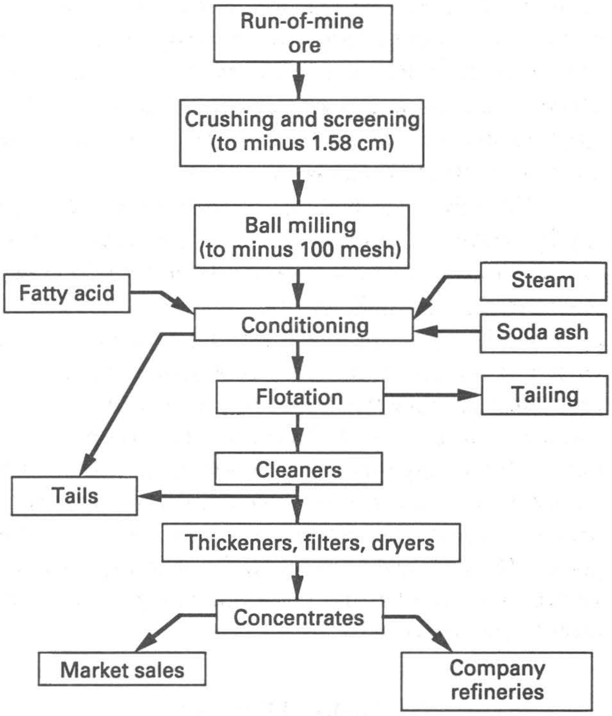


FIGURE 14. Bastnaesite beneficiation.

A third process for treating bastnaesite ore involves decomposition with sulfuric acid to produce a rare-earth compound plus effluent carbon dioxide and fluoride gases. This compound is calcined and cooled. Water is added to dissolve the calcine, and the material is filtered to produce a water-soluble rare-earth sulfate.

Placer deposits.—Placer sands that are under water or affected by a high water table are mined by dredges. Bucket-line and suction dredges are used for deeper material, whereas bucket-wheel units are operated on shallower sands. Where water is not available, variations of open-pit excavation methods, such as scrapers, front-end loaders, shovels, and draglines, are employed; drilling and blasting are not required, except for those small areas where the sand is cemented by ferruginous or calcareous precipitates. In countries where employment of large masses of people is critical, manual labor is used extensively to fill head-carried baskets or to work hand-operated sluices.

The placer sands, once mined, are directed to a wet mill for preliminary concentration of the heavy minerals.

In dredging operations, the wet mill is located on the dredge, on a special barge in the dredge pond, or on shore near the pond. At dry-land placers, the sands are usually fluidized with water then pumped a short distance to the wet mill; in some cases, the sands are transported dry by trucks or conveyors.

Wet mill concentration consists of a series of gravity separations to remove the waste sands and to produce a heavy-mineral concentrate as feed for a dry mill. At the dry mill, multiple stages of magnetic, electrostatic, and gravity separation methods are employed to produce ilmenite, rutile, leucoxene, zircon, and monazite concentrates. These concentrates are then washed, dewatered, and kiln dried. The prepared material is fed to high-tension roll separators. The final monazite product contains 55 to 60 percent REO. Raw xenotime concentrates produced mainly in China, Indonesia, Malaysia, and Thailand and containing about 24 percent Y_2O_3 can be enriched significantly before shipment to customers.

METALLURGY AND REFINING

Metallurgical processes are used to convert rare-earth concentrates to individual or combined rare-earth powders (fig. 15). These powders are then subjected to a refining stage to form rare-earth metals.

Bastnaesite processing.—Bastnaesite concentrate from Mountain Pass is calcined and leached with hydrochloric acid to produce a premium 90-percent cerium oxide powder and chloride solutions for the other rare earths. Solvent extraction treatment of these solutions precipitates high-purity lanthanum and praseodymium-neodymium carbonates. Europium, gadolinium, and samarium oxides, surpassing 96 percent purity after firing, are recovered from the remaining solution. A simplified flowsheet showing the separation stages for rare earths at Mountain Pass is shown on figure 15.

Monazite processing.—Recovery of rare earths from monazite is commonly accomplished by alkaline (caustic) or acidic methods (Vijayan and others, 1989). The caustic process is more popular because it produces rare-earth chlorides and a marketable trisodium phosphate byproduct from a relatively simple procedure that dissolves finely ground monazite in hot sodium hydroxide solution, followed by application of dilute hydrochloric acid. Rare-earth sulfates or oxalates are formed in the acid process by mixing the monazite with concentrated sulfuric acid, roasting, and treating with sodium sulfate or oxalic acid. A third process produces cerium as an oxide and the other rare earths as chlorides by sintering a mixture of monazite, sodium carbonate, and sodium fluoride and then applying a dilute hydrochloric acid.

The Elliot Lake uranium mines in Canada, upon demand, produce a 60- to 70-percent REO concentrate from uranium leachate. The process involves treatment with air and lime, filtration, addition of sulfuric acid, extraction by an organic agent in a solvent extraction circuit, stripping with nitric acid, and precipitation with lime and ammonia.

Apatite processing.—Rare earths can be recovered from apatite during production of phosphoric acid and fertilizer (Vijayan and others, 1989). The procedure consists of nitric acid leaching of the ore, addition of sodium nitrate, filtration, and partial neutralization with ammonia to precipitate rare-earth phosphates, followed by application of nitric acid and oxalic acid to form a rare-earth oxalate.

Pyrochlore processing.—Pyrochlore, an ore of niobium, may soon become a commercial source of REO. The ore is first digested with hot concentrated sulfuric acid. Niobium and rare earths are then selectively precipitated by gradual reduction of acid concentration and temperature (Vijayan and others, 1989).

Euxenite processing.—Euxenite is a potential future source for REO. The ore is digested in a hot sodium hydroxide solution. Production of rare-earth oxalates is achieved by ore digestion in hot sodium hydroxide, followed by consecutive additions of dilute hydrochloric acid, soda ash, dilute sulfuric acid, and oxalic acid (Vijayan and others, 1989).

Refining.—In general, the products derived from the metallurgical steps described above are rare-earth compounds composed of the elements lumped together as carbonates, chlorides, hydroxides, oxalates, oxides, and sulfates. Sometimes these compounds are useful end products and are employed as such. In most cases, though, these basic compounds are essential as a preliminary stage in the fabrication of high-purity single-element rare-earth compounds and metals.

Solvent extraction is the major process for separating the individual rare-earth elements. This method takes advantage of the relative affinities of the rare-earth elements for a liquid solvent and an aqueous feed solution. In practice, this solution, containing the rare-earth elements as soluble chloride hexahydrate, is mixed with the solvent; modifiers are added to enhance the extraction rate. Actual degree of separation for individual rare-earth elements is relatively small per contact; since multiple contacts are required to achieve acceptable extraction rates, numerous mixer-settler reaction cells are needed for the entire process. Once extracted,

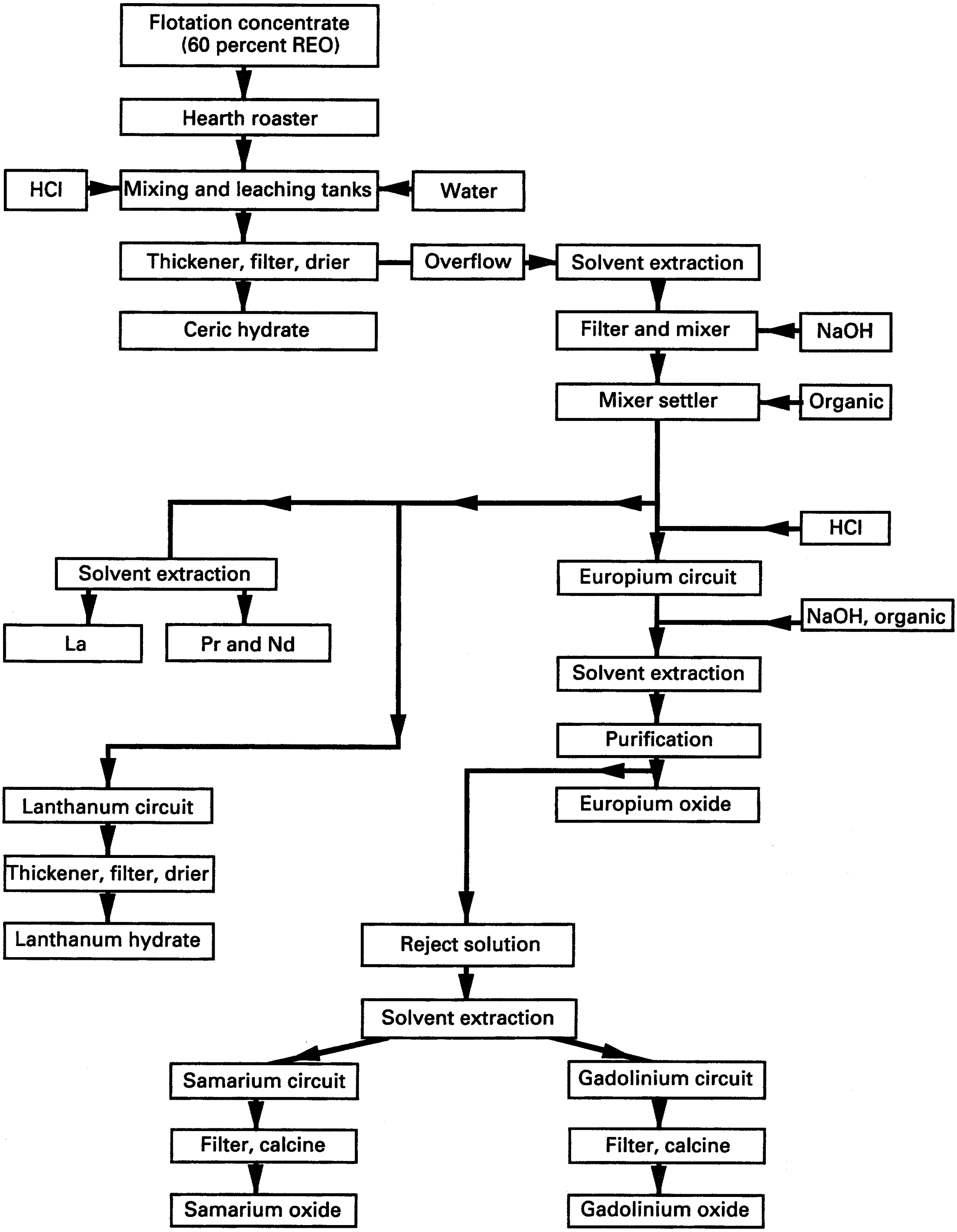


FIGURE 15. Separation process of individual rare earths.

the rare earths are converted to a carbonate, chloride, fluoride, halide, nitrate, oxalate, or oxide stipulated by the consumer. Some other separation methods are now outmoded or used only in laboratory research. Commercial processes are usually proprietary, and specific details are unknown.

Production of rare-earth metals is highly technical and costly. Reduction of the compounds to the metals is energy intensive, since most of the metals have high melting points. The reactions must be carried out in a vacuum or inert-gas atmosphere due to the reactivity of the metals in the molten state. Materials that are able to contain the hot metals in excess of 1,500 °C are limited and expensive.

Mischmetal is an alloy of the light rare earths. Ratios of rare earths in the alloy approximate the ratios in the source material. The usual starting material for the production of mischmetal is the rare-earth chloride hexahydrate, which is dehydrated and leaves a porous anhydrous material containing up to 10 percent water-insoluble basic chlorides. The next step is electrolysis in which the anhydrous material is fused with sodium, potassium, or calcium chloride, melted, and cast into ingots. The ingots are coated with plastic to prevent oxidation. Sometimes a small amount of magnesium is added to the mix to make the ingot more resistant to oxidation.

Production of the lighter rare-earth metals, such as lanthanum, cerium, praseodymium, neodymium, and gadolinium, is most commonly accomplished by the reduction of anhydrous chlorides or anhydrous fluorides with calcium metal. Higher yields of gadolinium are obtained with the fluoride process.

The chloride process is carried out in a refractory-lined steel autoclave; calcium metal is the reductant, and iodine is a temperature booster. The molten rare-earth and calcium alloy is withdrawn for further treatment. The calcium is later removed from the alloy by vacuum distillation.

The fluoride process commences with the hydrofluorination of rare-earth oxides with anhydrous hydrofluoric acid at an elevated temperature. The resultant anhydrous fluoride is mixed with calcium metal and heated to about 500 °C to initiate the reduction activity. The reaction raises the temperature to over 1,400 °C and results in molten metal and a calcium fluoride slag. The process can be conducted at lower temperatures if magnesium and calcium chloride are added to lower the respective melting points of the metal and the slag. Impurities are removed by vacuum remelting.

Recovery of samarium, europium, and ytterbium is accomplished by reducing their oxides with lanthanum metal or mischmetal. The oxide is mixed with metal shavings within a vacuum furnace, where the rare-earth metal begins to sublime on the cooler parts of the crucible and crucible cover. The sublimed crystalline product is removed and remelted in an argon atmosphere.

Samarium has also been produced commercially by the reduction of samarium oxide with barium metal. Several metal suppliers have been experimenting with the electrolysis of samarium fluoride and oxyfluoride to produce pure samarium metal.

Yttrium metal can be obtained by the reduction of yttrium fluoride, but high losses are incurred due to the volatility of the metal. A more acceptable method employs reduction of anhydrous yttrium fluoride with calcium metal; zinc fluoride or magnesium fluoride is used as an alloying agent. The yttrium alloy produced contains about 15 percent zinc or magnesium, which is removed by vacuum distillation at 1,100 °C.

The remaining heavy rare earths are obtained by the reduction of their purified oxide with lanthanum metal. Demand for the heavy elements in metallic form has been minor, and processes to produce these metals in quantity have not been developed. Rare-earth ferrosilicon alloys are made in electric arc furnaces, by direct smelting of bastnaesite concentrates.

There are about 66 rare-earth processing plants (refineries) around the world. The largest number is in China (24); Japan has 16, and the United States has 13. Figure 16 shows the location of these plants, and table 18 lists the plants and owners.

Although China has the most plants, many are small, and total production is not reported. Also, because most REO products are used within the country, China is not considered a major processor. The major rare-earth processors are Rhône-Poulenc S.A. (Rhône) of France, Molycorp, Inc., of the United States, and the country of Japan. A few other countries, such as Brazil, India, and Malaysia, have developed government-owned facilities. Australia, a major producer of monazite, has yet to establish a rare-earth processing industry.

Rhône.—Rhône has two plants: La Rochelle on the French Atlantic coast and Freeport in Texas. All the company's raw materials, consisting of 99 percent monazite and 1 percent xenotime, are purchased. There are two separate solvent extraction purification lines at La Rochelle—chloride and nitrate. Products from these lines are phosphors, magnets, and catalysts. The Freeport plant was constructed in 1981; its capacity of 4,000 metric tons per year has since been doubled. Freeport specializes in light rare-earth compounds derived from intermediate hydroxides. Although not currently a

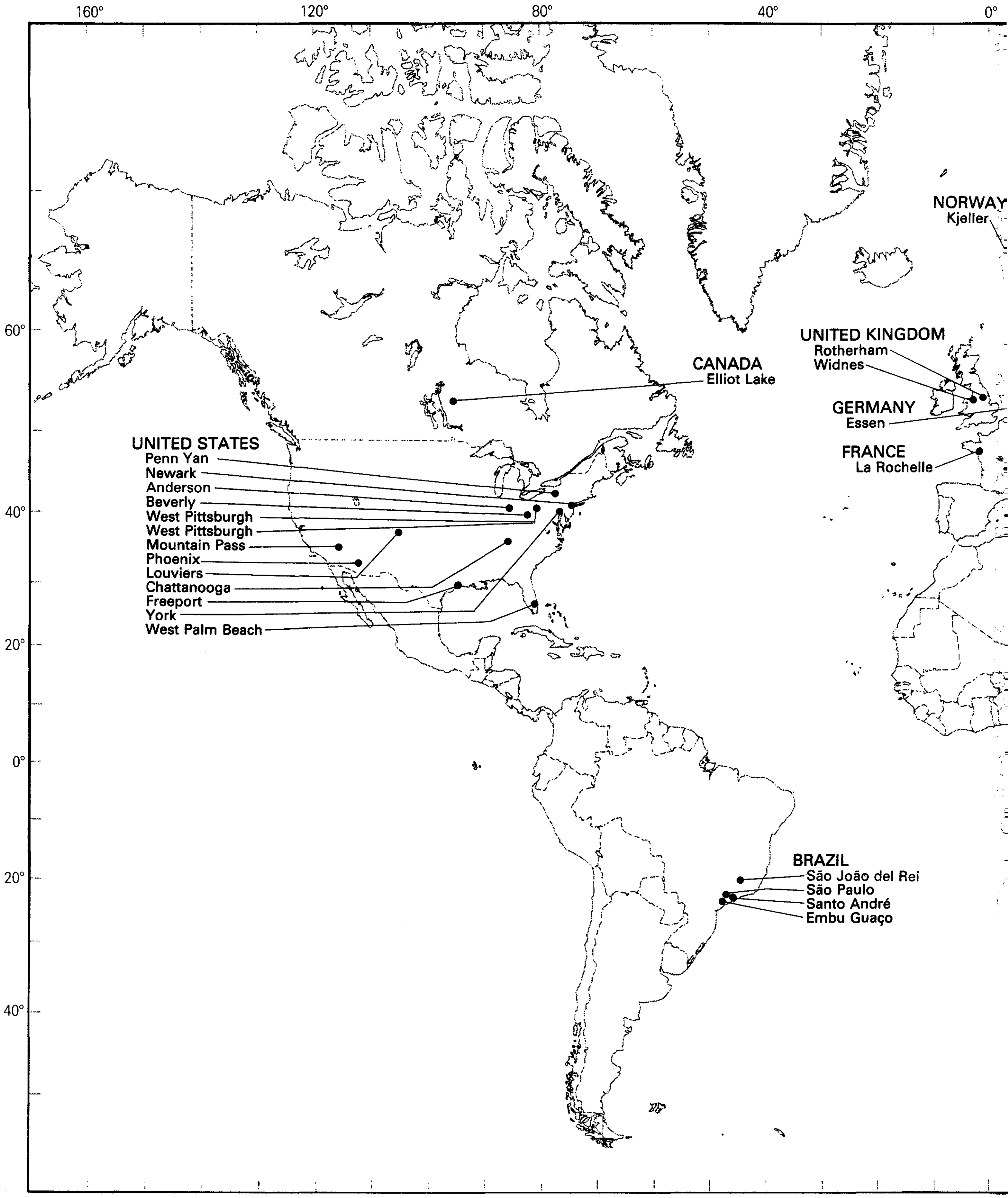
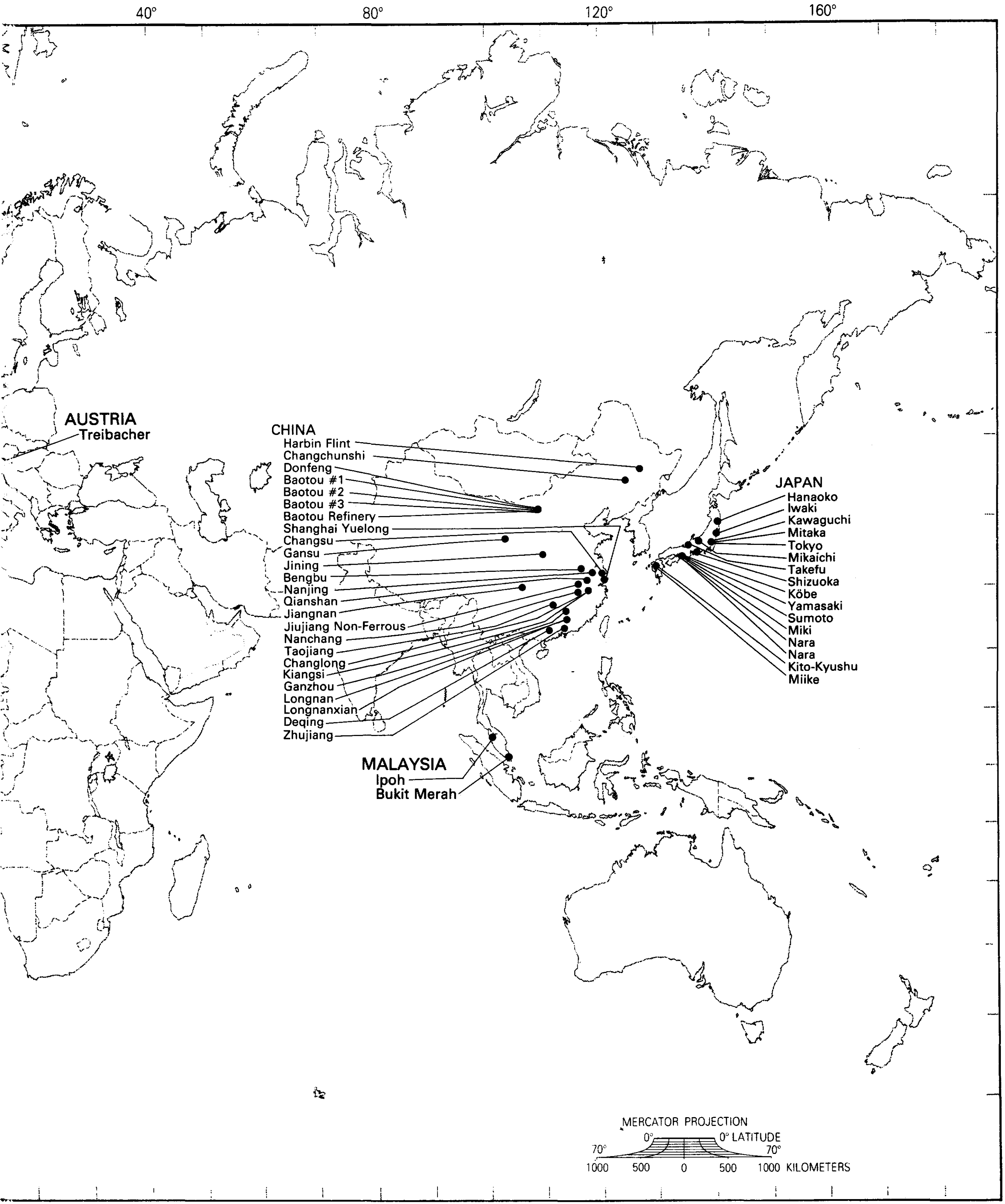


Figure 16. Location of the world's rare-earth processing plants.



Plant names and owners are shown in table 18.

TABLE 18.—*Location and ownership of the world's rare-earth processing plants*

[Names in parentheses under "Plant name" are geographic subsections of country. See also figure 16. Source: Hedrick and Templeton, 1991]

Country	Plant name	Owner
Austria	Treibacher	Treibacher Chemische Werke AG.
Brazil	Embu Guaço (São Paulo).	Metallurgica Corona Ltda.
	Santo André (São Paulo).	Do.
	São João del Rei (Minas Gerais).	Cia Industrial Fluminense.
	São Paulo (São Paulo).	Metallurgica Colibri Ltda.
Canada	Elliot Lake (Manitoba).	Unocal Canada Ltd.
China	Baotou #1	Government.
	Baotou #2	Do.
	Baotou #3	Do.
	Baotou Refinery	Do.
	Bengbu	Do.
	Changchunshi	Do.
	Changlong	Do.
	Changsu	Do.
	Deqing	Do.
	Donfeng	Do.
	Gansu	Do.
	Ganzhou	Do.
	Harbin Flint	Do.
	Jiangnan	Do.
	Jining	Do.
	Jiujiang Non-Ferrous	Do.
	Kiangsi	Do.
	Longnan	Do.
	Longnanxian	Do.
	Nanchang	Do.
	Nanjing	Do.
	Qianshan	Do.
	Shanghai Yuelong	Do.
	Taojiang	Do.
	Zhujiang	Do.
France	La Rochelle	Rhône-Poulenc SA.
Germany	Essen (Lower Saxony)	Th. Goldschmidt AG.
Japan	Hanaoka	Dowa Rare Earth Company.
	Iwaki (Fukashima)	Tokoku Metals and Chemicals.
	Kawaguchi (Tökyö)	Nissan Rare Earth Chemicals.
	Kito-Kyushu	Mitsubishi Chemical.
	Köbe (Hyogo)	Santoku Metal Industry.
Japan—Cont.	Miike	Mitsui Mining & Smelting.
	Mikaichi	Nippon Mining.
	Miki	Do.
	Mitaka (Tökyö)	Nippon Yttrium.
	Nara (Nara)	Do.
	Nara (Nara)	Seimi Chemicals.
	Shizuoka (Shizuoka)	Shin Nippon Kinzoku Kogyo.
	Sumoto (Tokushima)	Nippon Rare Earths KK.
	Takefu (Fukui)	Shin-Etsu Chemical Company.
	Tokyo (Tökyö)	Shin Nippon Kinzoku Kagaku.
	Yamasaki	Sumitomo Special Metals.
Malaysia	Bukit Merah	Asian Rare Earths Ltd.
	Ipoh	Malaysian Rare Earth Corp.
Norway	Kjeller	A/S Megon.
United Kingdom.	Rotherham (England)	London & Scandinavian Metallurgical Co. Ltd.
	Widnes (England)	Rare Earths Products Ltd.
United States.	Anderson (Indiana)	Delco Remy (General Motors).
	Beverly (Ohio)	Globe (Interlake).
	Chattanooga (Tennessee).	Davison Chemical Division (W.R. Grace & Co.).
	Freeport (Texas)	Rhône-Poulenc Inc.
	Louviers (Colorado)	Molycorp, Inc.
	Mountain Pass (California).	Do.
	Newark (New Jersey)	Ronson Metals Corp.
	Penn Yan (New York)	Transelco (Ferro).
	Phoenix (Arizona)	Research Chemicals Inc.
	West Palm Beach (Florida).	Cercoa Inc.
	West Pittsburgh (Pennsylvania).	Neomet.
	West Pittsburgh (Pennsylvania).	Reactive Metals & Alloys Corp.
	York (Pennsylvania)	Molycorp, Inc.

minerals producer, Rhône now owns the Mineville, N.Y., xenotime-bearing apatite property, which has potential for europium and yttrium production. In 1986, Rhône formed a joint venture, called Nippon Rare Earths KK, in Japan with Sumitomo Metal Mining Company to operate a small processing plant. Rhône also has been trying to establish a rare-earth and gallium plant at Pinjarra, Western Australia, to treat 15,000 metric tons per year of monazite. However, the government has not approved the company's plans for disposal of ammonium nitrate, thorium, and radium waste products (Industrial Minerals, 1990a).

Molycorp.—Molycorp is a fully integrated producer of rare earths; it has a bastnaesite mine at Mountain Pass in California and plants at Louviers in Colorado and Washington and at York in Pennsylvania. Some feed material, such as yttrium concentrate from the uranium operation at Elliot Lake, Ontario, is imported. Emphasis is on the production of lighter rare-earth oxides, specialty neodymium alloys, and yttrium metal. A major expansion program, started in 1987 and due for completion in 1991, is designed to improve their position in downstream refined materials. Molycorp is currently (1991) evaluating the Pajarito (Mescalero) eudialyte project in New Mexico as a domestic source of yttrium.

Other U.S. refiners.—Of the other U.S. refiners, Ronson Metals Corp., transforms imported mischmetal ingots into marketable end products. Reactive Metals & Alloys Corp., makes two grades of mischmetal, and silicides, for nodular-iron graphite control. Research Chemicals Inc., is a custom fabricator of rare-earth-bearing alloys and magnets, and Davison Chemical Division, a subsidiary of W.R. Grace & Co., converts monazite into chemicals, catalysts, ceramics, and polishing powders.

Japan.—Despite the drawback of having to import all of its raw material, mostly from China, Japan is actively engaged in becoming a premier producer of rare-earth products. To guarantee supplies, Japanese companies have formed joint ventures in Australia, Canada, China, Malaysia, and the United States. In 1987, Shin-Etsu Chemical Company opened a new plant at Takefu; using both the solvent extraction and the ion-exchange processes, Shin-Etsu produces a variety of rare-earth compounds and neodymium magnets. In the same year, Dowa Rare Earth Company built a new separation plant at Hanaoka; output rate began at 200 metric tons per year and was scheduled for 300 metric tons per year in 1989.

China.—In China, the rare-earth industry is advanced, technically competent, and growing. Based on bastnaesite concentrates from the Bayan Obo mine, the large processing complex (four plants) at Baotou is undergoing an expansion program that is expected to be completed in 1990. Capacities will be increased by 450 percent for rare-earth concentrates, by 230 percent for chlorides, and by 730 percent for monoxides. Neodymium oxide output has grown from 0.5 metric tons to 20 metric tons per year. The Kiangsi plant, run by Jiangxi Rare Earths Corp., is designed to produce 170 metric tons per year of REO concentrate, 40 metric tons per year of yttrium oxide, and 80 metric tons per year of fluorescent-grade yttrium oxide; a second plant was under construction in 1987. The Ganzhou plant in the Gannan district of Jiangxi Province receives a feed grading 92 percent REO from five mines. In 1988, capacity was 10 metric tons per year, mostly of phosphor-grade yttrium oxide.

Brazil.—Brazilian mineral sands are mined primarily for their monazite, and zircon and ilmenite are byproducts. By government edict, all monazite is processed within the country to remove thorium. Almost all of the REO produced is converted to mischmetal by three companies and exported; output is about 1,000 metric tons per year.

Canada.—Denison Mines Ltd., is in a joint venture with Unocal Canada Ltd., to produce REO from primary uranium leach solutions at Elliot Lake; past byproduct processing has been sporadic due to fluctuating market conditions. A possibility exists for development of the Thor Lake beryllium project, which could yield REO as a profitable byproduct.

Malaysia.—The Malaysian Rare Earth Corp., a joint venture between Beh Minerals and Mitsubishi Chemical, recovers monazite and xenotime from tin-mine tailings. Plant capacity is 135 metric tons per year of 60 percent yttrium oxide concentrate, which goes to Japan. Plans were underway in 1979 to add a rare-earth chloride line.

Norway.—A/S Megon produces 30 metric tons per year of high-purity yttrium oxide from a plant at Kjeller, near Oslo. Capacity was scheduled to be doubled in 1989. There is also small laboratory-scale production of lutetium oxide.

United Kingdom.—The United Kingdom has two rare-earth processors. London & Scandinavian Metallurgical Co. Ltd., imports bastnaesite and produces cerium-based polishing powders at its Rotherham plant. Rare Earth Products Ltd., manufactures rare-earth metals, alloys, and compounds.

Germany and Austria.—Th. Goldschmidt AG specializes in the production of alloy powders and neodymium compounds. In Austria, Treibacher Chemische AG has a capacity of 1,000 metric tons per year of mischmetal, 90 percent of which is exported for steel, casting, and zinc markets.

WORLD TRADE IN REO

REO products range from mineral concentrates of bastnaesite, monazite, and xenotime through assorted compounds to pure metals. REO minerals concentrates are traded much more extensively than high-purity compounds and metals. Countries vary from total exporters to total importers. Unlike the case for major metals such as copper and gold, REO production and trade figures are proprietary for most companies involved, which makes the tracking of export numbers difficult.

Concentrates.—Australia, Canada, and Sri Lanka export all of their concentrates. Australia and Sri Lanka ship monazite concentrates to the world market, whereas Canada exports about 150 metric tons per year of yttrium in concentrate (Vijayan and others, 1989) to Japan and the United States.

Some countries that produce monazite concentrates do not permit exportation because the governments involved wish to extract contained thorium for domestic use or for stockpiling for use in future nuclear materials. Brazil and India, for example, convert the material left after the thorium is removed into basic compounds, such as chlorides and mischmetal. Some of these products are used internally, but most are exported. In 1989, India produced 4,023 metric tons of rare-earth compounds, of which 3,705 metric tons were exported to Japan and Germany.

China sells some monazite concentrates. However, the remaining monazite concentrates and all of the bastnaesite concentrates produced are transformed into rare-earth compounds, some of which are used internally by industries based on particular compounds. Most of China's rare-earth products are exported (8,300 metric tons in 1988), mainly to Japan. Problems with quality control and tardy deliveries have led to some customer dissatisfaction.

The United States is self-sufficient in bastnaesite as a source for the light rare earths but must import about 5,000 metric tons per year of monazite concentrates and products to satisfy a deficiency in the heavier elements (Industrial Minerals, 1990a). As a result, the United States is a net importer of concentrates. Molycorp sells and uses four types of bastnaesite concentrate, plus the downstream derivatives of compounds and metals; it also converts imported monazite concentrates to heavy rare-earth compounds. Green Cove Springs produces about 1,000 metric tons per year of monazite concentrates (Industrial Minerals, 1990a), all of which is used by the owner. Several other private concerns produce compounds and metals based on materials supplied by Molycorp or by imported concentrates.

Several countries have large REO industries based solely upon imports. Japan relies heavily on China and Australia and is developing partnerships within these countries to assure supplies at minimum prices. France, West Germany, the United Kingdom, and other European countries purchase REO materials on the world market.

In the near future, Mozambique and New Zealand are expected to supply monazite concentrates for export. Australia could be starting some hard-rock mines to furnish even more REO in concentrates, and some of this production may be upgraded on site.

Compounds and metals.—The United States engages in a detailed and vigorous international trade of rare-earth products. In 1989, it exported 1,900 metric tons of this material to more than 35 countries and imported 10,100 metric tons from about 27 countries (Hedrick and Templeton, 1991). Apparent trade consumption was 8,200 metric tons.

Almost 50 percent of the rare-earth-product exports from the United States goes to Japan and South Korea, where rare-earth processing industries are rapidly expanding. Unusually high 1989 U.S. exports to Dominica give this small Caribbean island an atypical third place ranking. West Germany and the United Kingdom are fourth and fifth, respectively (table 19). Figure 17 graphically emphasizes the dominance of Japan and Korea with respect to receipts from the United States.

Approximately 72 percent of rare-earth products imported by the United States were from France (table 20). Brazil was second, followed by India, Japan, West Germany, and China. Figure 18 demonstrates how overwhelming France is compared to the other countries in the supply of rare-earth products to the United States.

CONCLUSIONS

The unique properties of rare earths and their use in critical military and civilian industries, coupled with relative scarcity in industrialized countries and sales mainly as byproducts, qualify the rare-earth oxides as strategic mineral commodities. Only China is self-sufficient in all of the rare earths, although Australia and the United States could be with development of new projects. REO supplies, as byproducts of the titanium, tin, and uranium markets, would be unreliable if these major markets should fail.

Present and potential industrial applications of rare earths are numerous and varied. In metallurgy, rare-earth alloys improve metal ductility and high-temperature corrosion resistance. Magnets containing samarium or

TABLE 19.—*U.S. exports of rare-earth products in 1989, by country, in order of export rank*

[See also figure 17. Source: Hedrick and Templeton, 1991, p. 51]

Rank	Country	Rare-earth products	
		Metric tons	Percent
1	Japan	621.505	33.5
2	South Korea	282.737	15.2
3	Dominica[1]	170.697	9.2
4	West Germany	117.059	6.3
5	United Kingdom	102.956	5.5
6	Dominican Republic	92.896	5.0
7	Brazil	67.103	3.6
8	Canada	63.282	3.4
9	Hong Kong	53.681	2.9
10	Taiwan	53.160	2.9
11	France	48.424	2.6
12	Thailand	47.140	2.5
13	Australia	36.376	2.0
14	Spain	14.609	.8
15	Italy	13.717	.7
16	Mexico	13.563	.7
17	Norway	11.442	.6
18	Venezuela	10.433	.6
19	Trinidad and Tobago	8.628	.5
20	Singapore	5.828	.3
21	Panama	3.938	.2
22	Colombia	2.124	.1
23	Greece	1.926	.1
	Others	14.285	.8
	Total	1,857.509	100.0

[1] Exports to Dominica in 1989 were unusually high.

TABLE 20.—*U.S. imports of rare-earth products in 1989, by country, in order of import rank*

[Figures may not add to totals shown due to rounding. See also figure 18. Source: Hedrick and Templeton, 1991, p. 49–50]

Rank	Country	Rare-earth products	
		Metric tons	Percent
1	France	7,259.776	72.0
2	Brazil	1,029.734	10.2
3	India	592.800	5.9
4	Japan	397.638	3.9
5	West Germany	264.062	2.6
6	China	240.468	2.4
7	Canada	108.309	1.1
8	United Kingdom	91.993	.9
9	Soviet Union	29.033	.3
10	South Korea	18.890	.2
11	Norway	14.841	.1
12	Switzerland	13.576	.1
13	Austria	8.705	.1
	Others	14.523	.1
	Total	10,084.348	100.0

neodymium are exceptionally strong for their size. Rare earths increase the density and heat resistance of ceramics, leading to high thermal-insulation and superconductivity properties. Cerium improves the effectiveness of catalysts in the petroleum and automotive industries. Rare earths are used in optics to add color, to absorb ultraviolet light, and to expedite the melting and polishing of glass. Phosphors of rare earths contribute to the vivid colors of television and computer screens. Because of their ability to absorb neutrons, rare earths are utilized in nuclear power plant control rods. Lanthanides are used in the fabrication of hydrogen-based rechargeable batteries.

Major ore minerals containing rare earths are bastnaesite, monazite, and xenotime. Each mineral has a specific suite of the 15 rare-earth elements, and no one mineral can meet all market requirements. In general, bastnaesite occurs in carbonatites, whereas monazite and xenotime are found in coastal or fluvial black-sand placers.

Globally, economically recoverable REO ore resources, based on 106 properties, amount to 20.6 billion metric tons, of which 85 percent is in placers and 15 percent is in hard-rock deposits. REO in the ore at 103 deposits amounts to 93.4 million metric tons, of which 7 percent are located in placers and 93 percent are in hard-rock deposits and are composed of 20 percent monazite and 80 percent bastnaesite plus other minerals. China holds the majority of the REO resources, followed by Namibia, the United States, Australia, and India.

Worldwide REO production is about 67,000 metric tons per year; the leading producer is China, followed by the United States and Australia. Mining methods are 94 percent open-pit mining and 6 percent dredging. Potential production, which includes those operations that currently do not recover REO in ore, could have doubled the actual 1989 production level. This potential for additional tonnage, plus the prospect of scheduled and studied projects, assures the market that supplies of rare-earth concentrates are expected to exceed demand for the foreseeable future. Additional supplies, if required, could be obtained by installing REO recovery plants in existing placer sand, phosphate, and uranium operations.

World consumption of rare earths and their products in 1988 was 40 million pounds (18,000 metric tons) valued at $343 million, of which the U.S. portion was 15 million pounds (6,800 metric tons) worth $104 million. The major consumer by weight was in chemicals, whereas the major user by value was the optical industry.

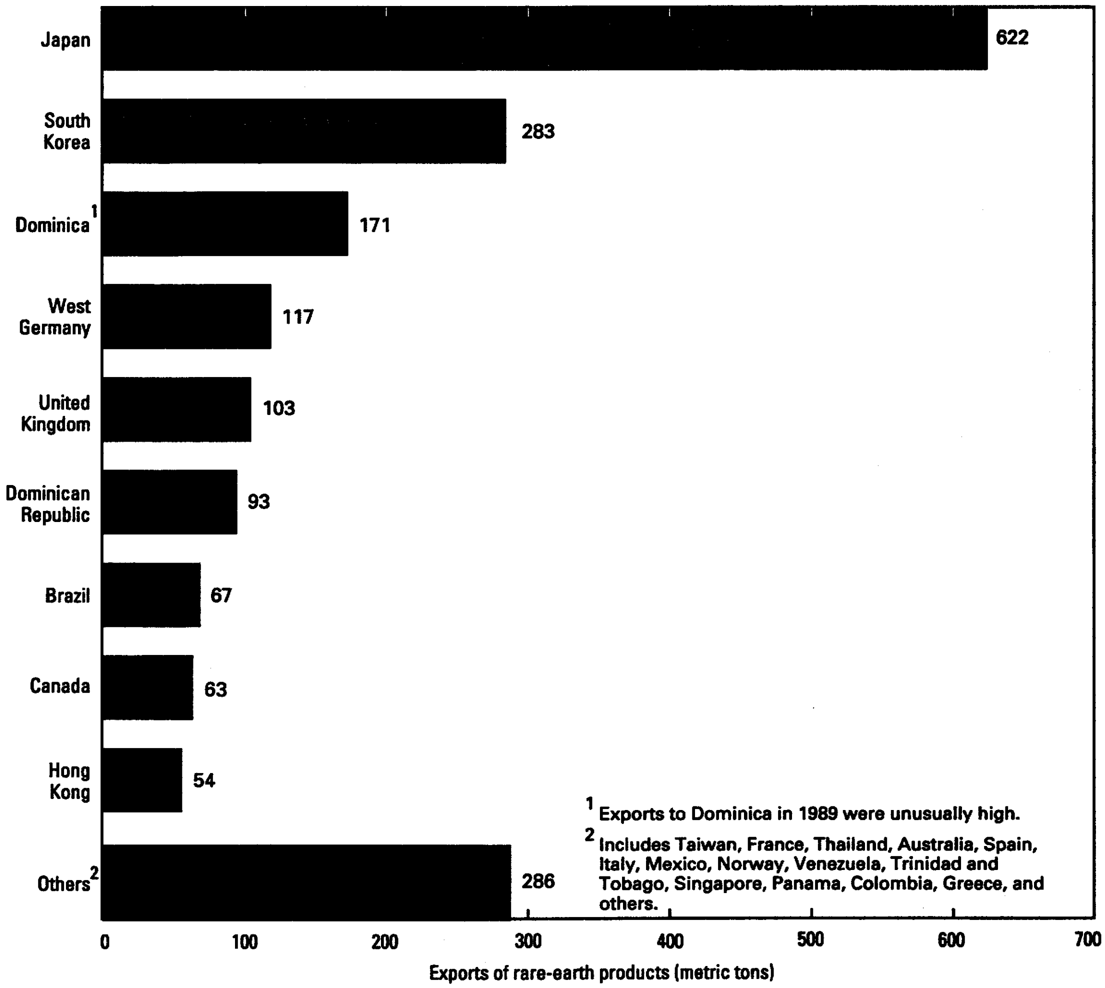


FIGURE 17. U.S. exports of rare-earth products in 1989, by country (see table 19).

Average nationwide production costs for rare-earth mine and mill projects range from $1.26 per metric ton of ore in Australia to $4.04 per metric ton in Brazil. Most of the new and proposed projects are in Australia, where investments vary from $8.6 million to as much as $312.5 million. Congolone, in Mozambique, will cost $100 million, which includes a complete infrastructure of town and port.

Monazite sands are mined mostly by dredging or open-pit methods and are beneficiated by gravity separation in a wet mill, followed by magnetic, electrostatic, and gravity procedures in a dry mill. Bastnaesite ore is recovered in open pits and processed by flotation circuits as in the United States or by leach-precipitation methods as in China. Monazite concentrates usually contain 55 to 60 percent REO. Bastnaesite concentrates in the United States are available in three grades: 60 percent, 70 percent, and 85 percent REO.

Recovery of the individual rare-earth compounds and metals is a long, involved, and costly series of procedures. Both bastnaesite and monazite concentrates are treated to form a chloride solution, which undergoes solvent extraction routines to precipitate a mix of rare-earth compounds. These compounds are redissolved and fed to a more detailed solvent extraction circuit to precipitate individual rare-earth compounds. Reduction of these compounds to rare-earth metals is energy intensive and must be carried out in an oxygen-free atmosphere.

International trade in rare-earth concentrates, compounds, and metals is complicated and vigorous. Countries like Australia and Sri Lanka export their monazite concentrates without treatment. Other nations, such as Brazil and India, convert their monazite concentrates to specific compounds. Japan, South Korea, France, West Germany, and the United Kingdom import concentrates

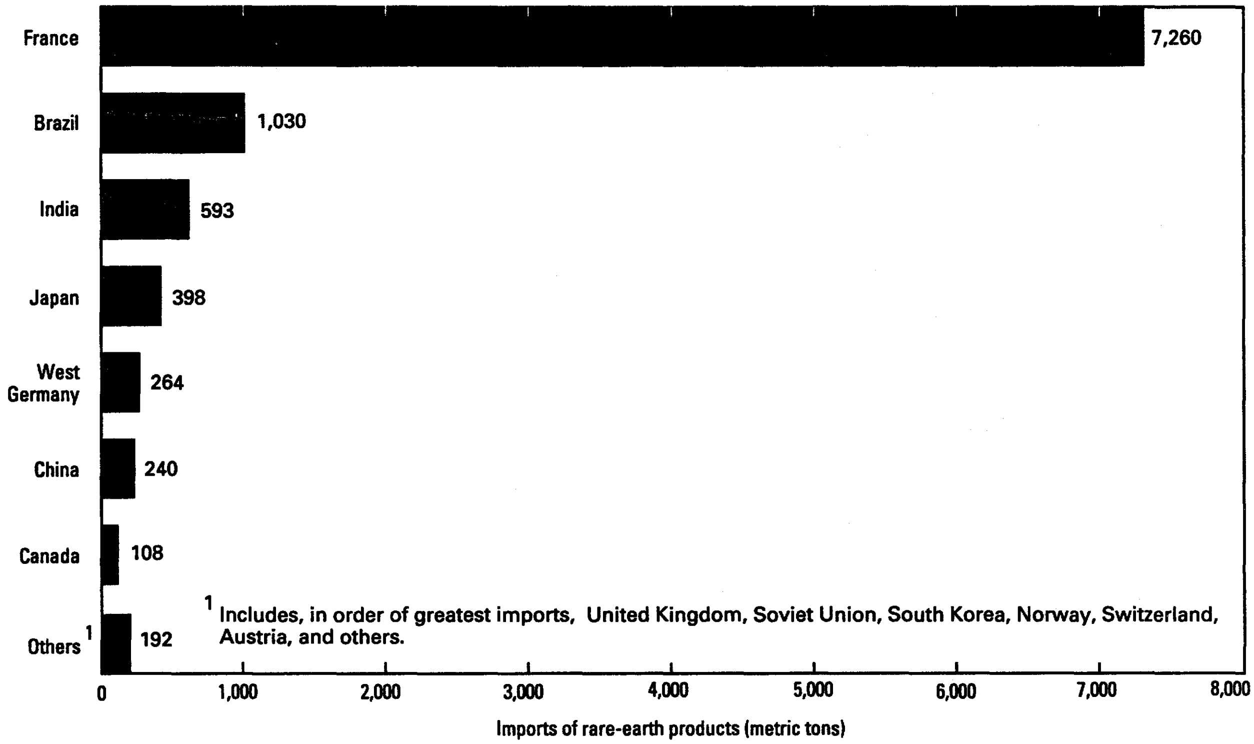


FIGURE 18. U.S. imports of rare-earth products in 1989, by country (see table 20).

and compounds for their electronic and ceramic industries. The United States imports about 5,000 metric tons of monazite concentrates and 10,100 metric tons per year of rare-earth compounds and metals (mainly from France) and exports about 2,000 metric tons per year of rare-earth products (mostly to Japan).

PART II—SELECTED INVENTORY INFORMATION FOR REO DEPOSITS AND DISTRICTS

Tables 21 and 22 contain information from the International Strategic Minerals Inventory record forms for REO deposits and districts. Only selected items of information about the geology and location (table 21) and mineral production and resources (table 22) of the deposits are listed here.

Summary descriptions and data are presented in the tables essentially as they were reported in the inventory record or other sources. For instance, significant digits for tonnages have been maintained as reported, and all tonnages are shown as metric tons. Some of the data in the table are more aggregated than in the inventory records, such as cumulative production totals instead of annual totals. Some of the abbreviations used in the inventory record forms have been used in the tables; they are explained in the headnotes.

TABLE 21.—*Selected geologic and location information from*

Abbreviations used throughout this table include

—, not reported on the ISMI record form.

Ma, million years. Fm, formation.

Host rock includes all or some of the following items (separated by semicolons); main host rock type; formation name; and host rock age.

Age abbreviations and prefixes:

Cenozoic	CEN	Cretaceous	CRET	Late	L
Quaternary	QUAT	Permian	PERM	Middle	M
Holocene	HOLO	Ordovician	ORD	Early	E
Pleistocene	PLEIS	Cambrian	CAMB		
Tertiary	TERT	Precambrian	PREC		
Pliocene	PLIO	Proterozoic	PROT		

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization	Tectonic setting
ARGENTINA						
Rio Tercero (Cordoba)	32° 02′ S.	64° 12′ W.	Placer, fluvial	Sand; QUAT	QUAT	Basin
AUSTRALIA						
Agnes Waters (Rocky Point) (Queensland)	24° 14′ S.	151° 56′ E.	Placer, marine	Sand; TERT	TERT	Basin
Alice Springs (Northern Territory)	23° 04′ S.	134° 33′ E.	Magmatic	Pegmatite	—	Shield
Australind (Western Australia)	33° 14′ S.	115° 45′ E.	Placer, marine	Sand; QUAT	QUAT	Basin
Bowen (Abbot Point) (Queensland)	19° 53′ S.	148° 05′ E.	...do.....	Sand	—	...do.....
Brockman (Western Australia)	18° 19′ S.	127° 47′ E.	Magmatic	Tuff; PROT	PROT	Mobile belt.
Busselton East (Western Australia)	33° 40′ S.	115° 23′ E.	Placer, marine	Sand; HOLO	HOLO	Basin
Byfield (Queensland)	22° 48′ S.	150° 46′ E.	...do.....	Sand; LTERT	LTERT	...do.....
Capel South (Western Australia)	33° 37′ S.	115° 27′ E.	...do.....	Sand; QUAT	QUAT	...do.....
Cataby (Western Australia)	30° 43′ S.	115° 31′ E.	...do.....	Sand; PLEIS	PLEIS	...do.....
Cooljarloo/Jurien Bay (Western Australia)	30° 40′ S.	115° 20′ E.	...do.....	...do.....	...do.....	...do.....
Cooloola (Queensland)	26° 05′ S.	153° 07′ E.	...do.....	...do.....	...do.....	...do.....
Eneabba (Western Australia)	29° 55′ S.	115° 15′ E.	...do.....	Sand; LTERT	LTERT	...do.....
Fraser Island (Queensland)	25° 22′ S.	153° 07′ E.	...do.....	...do.....	...do.....	...do.....
Gingin South (Western Australia)	31° 24′ S.	115° 56′ E.	...do.....	Sand; QUAT	QUAT	...do.....
Hamel (Waroona) (Western Australia)	32° 53′ S.	115° 54′ E.	...do.....	Sand; HOLO	HOLO	...do.....
Higgins (Western Australia)	33° 35′ S.	115° 36′ E.	...do.....	...do.....	...do.....	...do.....
Jangardup (Western Australia)	34° 22′ S.	115° 37′ E.	...do.....	...do.....	...do.....	...do.....
Mary Kathleen (Queensland)	20° 44′ S.	140° 01′ E.	Magmatic	—	—	Shield
Minninup, beach, dunes (Western Australia)	33° 28′ S.	115° 34′ E.	Placer, marine	Sand; QUAT	QUAT	Basin
Moreton Island (Queensland)	27° 11′ S.	153° 24′ E.	...do.....	...do.....	...do.....	...do.....

ISMI records for rare-earth oxide deposits and districts

Abbreviations for mineral names (after Longe and others, 1978, p. 63–66, with some additions):

Allanite	ALNT	Columbite	CLMB	Kyanite	KYNT	Rare-earth oxides	REO
Amphibole	AMPB	Davidite	DVDT	Leucoxene	LCXN	Rutile	RUTL
Anatase	ANTS	Eudialyte	EDLT	Limonite	LMON	Sillimanite	SLMN
Apatite	APTT	Feldspar	FLDP	Magnetite	MGNT	Scheelite	SCLT
Barite	BRIT	Fluocerite	FLCR	Martite	MRTT	Sphalerite	SPLR
Bastnaesite	BSNS	Fluorite	FLRT	Monazite	MNZT	Staurolite	STRL
Biotite	BOTT	Gadolinite	GDLN	Perovskite	PRVK	Sulfides	SLPD
Bornite	BRNT	Garnet	GRNT	Plagioclase	PLGC	Thorite	THRT
Brannerite	BRNR	Goethite	GTHT	Pyrite	PYRT	Tourmaline	TRML
Cassiterite	CSTR	Gold	GOLD	Pyrochlore	PCLR	Uraninite	URNN
Chalcocite	CLCC	Heavy minerals	HM	Pyroxene	PRXN	Vanadinite	VNDN
Chalcopyrite	CLCP	Hematite	HMTT	Quartz	QRTZ	Xenotime	XNTM
Clay	CLAY	Hornblende	HBLD	Rare-earth elements	REE	Zircon	ZRCN
Collophane	CLPN	Ilmenite	ILMN				

Local environment	Principal mineral assemblages	Average grades and comments	References
		ARGENTINA—Continued	
Flood plain	MNZT	0.0173 percent monazite containing 60 percent REO and 3.8 percent ThO_2.	USBM, unpub. data (1983).
		AUSTRALIA—Continued	
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	1.36 percent ilmenite, 0.18 percent rutile	Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
—	ALNT	4.0 percent allanite containing 20 percent REO.	O'Driscoll (1988).
Dune	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ, GRNT.	15 percent HM, 0.03 percent monazite	USBM, unpub. data (1982); Fantel, R.J., unpub. data (1990).
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	—	Fantel, R.J., unpub. data (1990).
Sheared zone	CLMB, PCLR, BSNS, XNTM, CSTR, SPLR.	0.09 percent REO, 0.124 percent Y_2O_3	Australian BMR, unpub. data (1990); O'Driscoll (1988).
Coastal plain	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ.	Elevated strandline	Fantel, R.J., unpub. data (1990).
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	1.14 percent HM, 0.05 percent monazite	Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
...do.....	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ.	0.06 percent monazite	Do.
Beach	ILMN, RUTL, ZRCN, MNZT, QRTZ	7.7 percent HM, 0.1 percent monazite	USBM, unpub. data (1982); Fantel, R.J., unpub. data (1990).
Dune, beach	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ.	3.2 percent HM, 0.2 percent monazite	Fantel, R.J., unpub. data (1990).
...do.....	ILMN, RUTL, ZRCN, MNZT; QRTZ	0.00846 percent monazite	Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
...do.....	ILMN, RUTL, ZRCN, KYNT, MNZT; QRTZ.	0.05 percent monazite	Do.
...do.....	ILMN, RUTL, ZRCN, MNZT, QRTZ	1.75 percent HM, 0.005 percent monazite	Do.
...do.....	ILMN, RUTL, ZRCN, KYNT, LCXN; QRTZ.	10.02 percent HM	USBM, unpub. data (1982); Fantel, R.J., unpub. data (1990).
Coastal plain	ILMN, LCXN, ZRCN, KYNT, STRL, MNZT; QRTZ.	Now owned by Japanese interests	Fantel, R.J., unpub. data (1990).
...do.....	ILMN, ZRCN	...do.....	Do.
...do.....	ILMN, RUTL, ZRCN, LCXN, KYNT, MNZT, XNTM, QRTZ, GRNT.	6.8 percent HM, 0.0476 percent monazite, 0.0204 percent xenotime.	Do.
—	—	Former uranium mine	Australian BMR, unpub. data (1990).
Dune, beach	ILMN, LCXN, ZRCN, MNZT, XNTM; QRTZ.	8.0 percent HM. Now owned by Japanese interests.	Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
...do.....	ILMN, LCXN, ZRCN; QRTZ	Shut down by the government	W. Germany BGR, unpub. data (1990); Fantel, R.J., unpub. data (1990).

TABLE 21.—*Selected geologic and location information from ISMI*

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization	Tectonic setting
AUSTRALIA—Continued						
Mount Weld (Western Australia)	28° 52′ S.	122° 32′ E.	Magmatic	Carbonatite; PROT	PROT	Shield
Munmorah (New South Wales)	33° 12′ S.	151° 35′ E.	Placer, marine	Sand; LTERT	LTERT	Basin
Nabiac, Southeast (New South Wales)	32° 00′ S.	152° 30′ E.	...do.....	Sand; PLEIS	PLEIS	...do.....
Newrybar (New South Wales)	28° 46′ S.	153° 34′ E.	...do.....	Sand; QUAT	QUAT	...do.....
North Capel (Western Australia)	33° 31′ S.	115° 35′ E.	...do.....	...do.....	...do.....	...do.....
North Stradbroke Island (Queensland)	27° 35′ S.	153° 27′ E.	...do.....	Sand; LTERT	LTERT	...do.....
Olympic Dam (South Australia)	30° 27′ S.	136° 53′ E.	Magmatic	Granite; MPROT	MPROT	Shield
Port Pirie (South Australia)	33° 12′ S.	138° 00′ E.	...do.....	Uranium tails	—	...do.....
Stockton Bight (New South Wales)	32° 46′ S.	152° 08′ E.	Placer, marine	Sand; HOLO	HOLO	Basin
Tomago (New South Wales)	32° 48′ S.	151° 47′ E.	...do.....	Sand; PLEIS	PLEIS	...do.....
Viney Creek (New South Wales)	32° 37′ S.	152° 07′ E.	...do.....	Sand; QUAT	QUAT	...do.....
Waroona, North and South (Western Australia).	32° 50′ S.	115° 55′ E.	...do.....	Sand; LTERT	LTERT	...do.....
WIM–150 (Victoria)	36° 48′ S.	142° 22′ E.	Placer, fluvial	Sand; EPLIO	EPLIO	...do.....
Wonnerup Beach (Western Australia)	33° 37′ S.	115° 25′ E.	Placer, marine	Sand; HOLO	HOLO	...do.....
Yangibana (Western Australia)	23° 50′ S.	116° 10′ E.	Magmatic	Carbonatite; LPROT	LPROT	Shield
Yoganup Extended (Western Australia)	33° 36′ S.	115° 40′ E.	Placer, marine	Sand; LTERT	LTERT	Basin
BRAZIL						
Alcobaca (Southern Bahia)	17° 30′ S.	39° 20′ W.	Placer, marine	Sand; LTERT	LTERT	Basin
Anchieta (Espirito Santo)	20° 48′ S.	40° 33′ W.	...do.....	...do.....	...do.....	...do.....
Aracruz (Espirito Santo)	19° 59′ S.	40° 02′ W.	...do.....	...do.....	...do.....	...do.....
Buena (Rio de Janeiro)	21° 31′ S.	41° 05′ W.	...do.....	...do.....	...do.....	...do.....
Camaratuba (Rio Grande do Norte)	06° 54′ S.	35° 00′ W.	...do.....	Sand	—	...do.....
Careacu (Minas Gerais)	—	—	—	—	—	—
Cordislandia (Minas Gerais)	—	—	—	—	—	—
Guarapari (Espirito Santo)	20° 48′ S.	40° 33′ W.	—	—	—	—
Northeast dunes	—	—	Placer, marine	Sand	—	Basin
Poços de Caldas (Minas Gerais)	21° 48′ S.	46° 33′ W.	Magmatic	Carbonatite	—	Shield
Prado (Bahia)	17° 24′ S.	39° 12′ W.	—	—	—	—
São Gançalo do Sapucaí (Minas Gerais).	03° 13′ S.	56° 35′ W.	Placer, fluvial	Sand	—	Basin
São Sebastio da Bela Vista (Minas Gerais).	—	—	—	—	—	—
Serra (Espirito Santo)	20° 10′ S.	39° 20′ W.	Placer, marine	Sand; LTERT	LTERT	Basin
Tapira (Minas Gerais)	19° 52′ S.	46° 50′ W.	Magmatic	Carbonatite; CRET	CRET	Shield

records for rare-earth oxide deposits and districts—Continued

Local environment	Principal mineral assemblages	Average grades and comments	References
		AUSTRALIA—Continued	
Supergene enrichment.	APTT, PCLR, MGNT, ILMN, MNZT; QRTZ.	17 percent REO and yttrium	Australian BMR, unpub. data (1990); Engineering and Mining Journal (1990).
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	0.81 percent HM, 0.006 percent monazite.	USBM, unpub. data (1982); Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
Beach	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ, GRNT.	0.0091 percent monazite	Fantel, R.J., unpub. data (1990).
Dune, beach	ILMN, RUTL, ZRCN, MNZT, TRML; QRTZ, GRNT.	1.1 percent HM, 0.0418 percent monazite.	Do.
...do.....	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ.	0.080 percent monazite	W. Germany BGR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
...do.....	ILMN, RUTL, ZRCN, MNZT; QRTZ	1.5 percent HM, 0.0015 percent monazite.	Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
Granite breccia.	CLCC, BRNT, CLCP, URNN, BRNR, HMTT, BSNS, FLCR.	0.3285 percent REO associated with U_3O_8 in a major Cu/Au/Ag/U mine.	W. Germany BGR, unpub. data (1990).
U_2O_3 tails	URNN, DVDT	Tails from Radium Hill	Mining Journal (1989); Hammond (1988).
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	Feeds Hawks Nest plant	W. Germany BGR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
...do.....	ILMN, RUTL, ZRCN, MNZT; QRTZ, GRNT.	Dune and beach deposits	Fantel, R.J., unpub. data (1990).
Beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	Feeds Hawks Nest plant	Do.
Dune, beach	ILMN, LCXN, ZRCN, MNZT; QRTZ	15 percent HM	Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
Strandplain	ILMN, LCXN, ZRCN, ANTS, MNZT, XNTM; QRTZ.	5.221 percent HM, 0.076 percent REO	Do.
Dune, beach	ILMN, ZRCN, MNZT; QRTZ, GRNT	Now owned by Japanese interests	Fantel, R.J., unpub. data (1990).
Carbonatite dikes.	MNZT	3.09 percent monazite, 1.7 percent REO	Mining Magazine (1989b).
Dune, beach	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ.	13.5 percent HM, 0.056 percent monazite.	Australian BMR, unpub. data (1990); Fantel, R.J., unpub. data (1990).
		BRAZIL—Continued	
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	0.47 percent monazite	USBM, unpub. data (1983); Anuário Mineral Brasileiro (1988).
...do.....	ILMN, RUTL, ZRCN, MNZT; QRTZ	0.71 percent monazite	Do.
...do.....	ILMN, RUTL, ZRCN, MNZT; QRTZ	1.05 percent monazite	Do.
...do.....	ILMN, RUTL, ZRCN, MNZT; QRTZ	0.83 percent monazite	Do.
Dune	ILMN, RUTL, ZRCN, TRML, MNZT, XNTM; QRTZ, GRNT.	Elevated dunes at the base of an ancient sea cliff.	USBM, unpub. data (1981).
—	—	—	Anuário Mineral Brasileiro (1988).
—	—	—	Do.
—	—	—	Do.
Dune	ILMN, RUTL, ZRCN, MNZT; QRTZ	0.033 percent monazite	Mining Journal (1990a).
—	—	3.33 percent REO in bastnaesite	USBM, unpub. data (1990).
—	—	—	Anuário Mineral Brasileiro (1988).
River	ILMN, ZRCN, GOLD, MNZT; GRNT	0.066 percent monazite	Mining Journal (1990b).
—	—	—	Anuário Mineral Brasileiro (1988).
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	0.80 percent monazite	USBM, unpub. data (1983).
Rolling hills	ANTS, APTT, PRVK; LMON, MGNT, GRNT.	0.03 percent REO in anatase overburden at a phosphate mine.	USBM, unpub. data (1988).

TABLE 21.—*Selected geologic and location information from ISMI*

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization	Tectonic setting
BURUNDI						
Karonge	03° 25′ S.	29° 25′ E.	Magmatic	Stockwork; PREC	PREC	Shield
Kasagwe	03° 25′ S.	29° 25′ E.	...do.....	—	—	—
CANADA						
Elliot Lake (Denison) (Ontario)	46° 29′ N.	82° 32′ W.	Magmatic	Conglomerate; EPROT.	EPROT	Shield
Elliot Lake (Rio Algom, except Stanleigh) (Ontario).	46° 30′ N.	82° 38′ W.	...do.....	...do.....	...do.....	...do.....
Elliot Lake (Rio Algom, Stanleigh) (Ontario).	46° 24′ N.	82° 38′ W.	...do.....	...do.....	...do.....	...do.....
Strange Lake (Newfoundland/Quebec)	56° 19′ N.	64° 07′ W.	...do.....	Granite; MPROT	MPROT	Intracratonic.
Thor Lake (Northwest Territories)	62° 06′ N.	112° 35′ W.	...do.....	Syenite; EPROT	EPROT	...do.....
CHINA						
Bayan Obo (Inner Mongolia)	41° 45′ N.	109° 58′ E.	Magmatic	Dolomite; MPROT	MPROT	Rifting
Beihai (Guangxi)	21° 29′ N.	109° 06′ E.	Placer, fluvial	Sand; CEN	CEN	Basin
Guangdong (Guangdong)	21° 30′ N.	111° 01′ E.	...do.....	Sand	—	...do.....
Xun Jiang (Guangxi)	23° 30′ N.	110° 50′ E.	...do.....	Sand; CEN	CEN	...do.....
EGYPT						
Nile Delta-Rosetta	31° 00′ N.	31° 00′ E.	Placer, marine	Sand; LPLIO	LPLIO	Basin
GABON						
Mabounie	00° 42′ S.	11° 42′ E.	Magmatic	Carbonatite	—	Shield
GREENLAND						
Ilimaussaq	63° 00′ N.	51° 12′ W.	Magmatic	Carbonatite	—	Shield
INDIA						
Chavara (IREL) (Kerala)	08° 57′ N.	76° 30′ E.	Placer, marine	Sand; QUAT	QUAT	Basin
Chavara (KMML) (Kerala)	09° 00′ N.	76° 30′ E.	...do.....	...do.....	...do.....	...do.....
Manavalakurichi (Tamil Nadu)	08° 20′ N.	77° 00′ E.	...do.....	...do.....	...do.....	...do.....
Orissa-Chatrapur (Orissa)	19° 18′ N.	84° 57′ E.	...do.....	...do.....	...do.....	...do.....
Ranchi and Purulia (Bihar)	23° 25′ N.	86° 00′ E.	Placer, fluvial	Sand	—	...do.....
KENYA						
Rangwa/Ruri/Homa	00° 30′ S.	34° 15′ E.	Magmatic	Carbonatite; TERT	TERT	Shield
MALAWI						
Kangankunde	15° 08′ S.	34° 55′ E.	Magmatic	Carbonatite; LCRET	LCRET	Volcanic dome.
MAURITANIA						
Bou Naga	20° 48′ N.	13° 42′ W.	Magmatic	—	—	Shield
MOZAMBIQUE						
Congolone	16° 00′ S.	40° 00′ W.	Placer, marine	Sand	—	Basin

records for rare-earth oxide deposits and districts—Continued

Local environment	Principal mineral assemblages	Average grades and comments	References
BURUNDI—Continued			
Mountainous	FLCR, CSTR, MNZT; BRIT, GTHT, QRTZ.	3.0 percent bastnaesite, 1.59 percent REO	USBM, unpub. data (1983).
—	—	...do.....	USBM, unpub. data (1990).
CANADA—Continued			
Rolling hills	URNN, BRNR, MNZT, ZRCN; PYRT, QRTZ.	0.0072 percent REO and yttrium in a uranium mine.	Pincock, Allen and Holt (1988); USBM, unpub. data (1983).
...do.....	URNN, BRNR, MNZT, ZRCN; PYRT, QRTZ.	0.0064 percent REO and yttrium in a uranium mine.	Do.
...do.....	URNN, BRNR, MNZT, ZRCN; PYRT, QRTZ.	0.0071 percent REO and yttrium in a uranium mine.	Do.
Low plains	ZRCN, MNZT, ALNT, GDLN; PCLR, FLRT.	1.3 percent REE and 0.66 percent Y_2O_3 in a primary beryllium property.	Mineral Policy Sector, unpub. data (1988).
—	XNTM, GDLN, ALNT, CLMB; AMPB, FLRT.	REE and yttrium occur in a primary beryllium property.	Pincock, Allen and Holt (1988); USBM, unpub. data (1983).
CHINA—Continued			
Hills, ridges	HMTT, MGNT, MNZT, RUTL, MRTT	6 percent REO at a major hematite mine	Drew, L.J., USGS, unpub. data (1990); Argall (1980).
Coastal plain	ILMN, RUTL, ZRCN, MNZT; QRTZ	1.5 percent HM	USBM, unpub. data (1982).
...do.....	ILMN, RUTL, ZRCN, MNZT; QRTZ	2.3 percent HM	Do.
River plain	ILMN, RUTL, ZRCN, MNZT; QRTZ	6.0 percent HM	Do.
EGYPT—Continued			
Delta	ILMN, RUTL, ZRCN, MNZT; MGNT, GRNT.	0.5 percent monazite	Hedrick (1988).
GABON—Continued			
—	—	A carbonatite with florencite; 2.52 percent REO in the ore.	USBM, unpub. data (1990).
GREENLAND—Continued			
—	PCLR, EDLT	0.9 percent Y_2O_3 in a carbonatite	Engineering and Mining Journal (1990).
INDIA—Continued			
Beach	ILMN, RUTL, ZRCN, LCXN, SLMN, MNZT; QRTZ, GRNT.	18 percent HM, 0.135 percent monazite	USBM, unpub. data (1982).
...do.....	ILMN, RUTL, ZRCN, LCXN, SLMN, MNZT, QRTZ, GRNT.	...do.....	Do.
...do.....	ILMN, RUTL, ZRCN, SLMN, MNZT, GRNT, QRTZ.	2.5 percent monazite	Do.
Dune	ILMN, RUTL, ZRCN, SLMN, MNZT; GRNT, QRTZ.	0.585 percent monazite	USBM, unpub. data (1982).
Valley alluvium.	ILMN, RUTL, ZRCN, MNZT, APTT, CLMB; MGNT, QRTZ.	1.64 percent HM, 0.31 percent monazite, 0.03 percent apatite.	Do.
KENYA—Continued			
Volcanoes	MNZT, BRIT, FLRT	5.6 percent monazite	USBM, unpub. data (1983).
MALAWI—Continued			
Volcanic plug	STRL, MNZT	5.0 percent monazite	USBM, unpub. data (1983).
MAURITANIA—Continued			
Quarry	MNZT	4.4 percent REO in massive monazite	USBM, unpub. data (1990).
MOZAMBIQUE—Continued			
Dune, beach	ILMN, RUTL, ZRCN, MNZT; QRTZ	2.8 percent HM, 0.007 percent monazite	Engineering and Mining Journal (1990); Mining Journal (1989).

TABLE 21.—*Selected geologic and location information from ISMI*

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization	Tectonic setting
NAMIBIA						
Etaneno	20° 42′ S.	16° 12′ E.	Magmatic	Carbonatite	—	Shield
NEW ZEALAND						
Barrytown (South Island)	42° 14′ S.	171° 19′ E.	Placer, marine	Sand	—	Basin
Westport (South Island)	41° 06′ S.	171° 24′ E.	...do.....	...do.....	—	...do.....
SOUTH AFRICA						
Buffalo Fluorspar (Transvaal)	24° 30′ S.	28° 30′ E.	Magmatic	Granite	MPROT	Shield
Phalaborwa (Transvaal)	23° 59′ S.	31° 07′ E.	...do.....	Carbonatite	...do.....	...do.....
Richards Bay (Natal)	28° 41′ S.	32° 11′ E.	Placer, marine	Sand; PLEIS	PLEIS	Basin
SRI LANKA						
Pulmoddai	08° 55′ N.	81° 00′ E.	Placer, marine	Sand	—	Basin
UNITED STATES						
Aiken County (South Carolina)	33° 26′ N.	81° 51′ W.	Placer, fluvial	Sand; CEN	CEN	Basin
Bald Mountain (Wyoming)	44° 48′ N.	107° 48′ W.	Magmatic	Conglomerate; Deadwood Fm.	—	...do.....
Bear Lodge (Wyoming)	44° 24′ N.	104° 24′ W.	...do.....	Trachyte; MTERT	MTERT	Shield
Bear Valley (Idaho)	44° 21′ N.	115° 24′ W.	Placer, fluvial	Sand	—	Basin
Big Creek (Idaho)	44° 28′ N.	115° 59′ W.	...do.....	...do.....	—	...do.....
Blackfoot Bridge (Idaho)	42° 07′ N.	111° 31′ W.	Magmatic	Mudstone; PERM	PERM	...do.....
Brunswick-Altamaha (Georgia)	31° 14′ N.	81° 30′ W.	Placer, marine	Sand; PLEIS	PLEIS	...do.....
Caldwell Canyon (Idaho)	42° 44′ N.	111° 22′ W.	Magmatic	Mudstone; PERM	PERM	...do.....
Champ (Idaho)	42° 40′ N.	111° 16′ W.	...do.....	...do.....	...do.....	...do.....
Conda (Idaho)	42° 44′ N.	111° 32′ W.	...do.....	...do.....	...do.....	...do.....
Cumberland Island (Georgia)	30° 54′ N.	81° 27′ W.	Placer, marine	Sand; PLEIS	PLEIS	...do.....
Diamond Creek (Idaho)	45° 15′ N.	113° 54′ W.	Magmatic	Quartzite; PREC	PREC	...do.....
Gallinas Mountains (New Mexico)	34° 12′ N.	105° 44′ W.	...do.....	Sandstone; PERM	PERM	...do.....
Gay and South Forty (Idaho)	43° 03′ N.	112° 07′ W.	...do.....	Mudstone; PERM	...do.....	...do.....
Gold Fork-Little Valley (Idaho)	44° 41′ N.	115° 58′ W.	Placer, fluvial	Sand; PLEIS	PLEIS	...do.....
Green Cove Springs (Florida)	29° 52′ N.	81° 43′ W.	Placer, marine	...do.....	...do.....	...do.....
Hall Mountain Group (Idaho)	48° 59′ N.	116° 26′ W.	Magmatic	Quartzite	—	...do.....
Henry (Idaho)	42° 53′ N.	111° 28′ W.	...do.....	Mudstone; PERM	PERM	...do.....
Hicks Dome (Illinois)	37° 36′ N.	88° 24′ W.	...do.....	Limestone; ORD	ORD	...do.....
Hilton Head Island (South Carolina)	32° 12′ N.	80° 44′ W.	Placer, marine	Sand	—	...do.....

records for rare-earth oxide deposits and districts—Continued

Local environment	Principal mineral assemblages	Average grades and comments	References
NAMIBIA—Continued			
—	—	Requires an effective separation process	Murray (1989).
NEW ZEALAND—Continued			
Coastal plain	ILMN, RUTL, ZRCN, MGNT, CSTR, GOLD, MNZT, SCLT.	0.001 percent monazite	USBM, unpub. data (1982); USBM, unpub. data (1990).
...do.....	ILMN, RUTL, ZRCN, MGNT, CSTR, GOLD, MNZT, SCLT.	Undergoing feasibility study	USBM, unpub. data (1982).
SOUTH AFRICA—Continued			
Rugged hills	FLRT, MNZT, APTT	1.0 percent monazite	USBM, unpub. data (1989); USBM, unpub. data (1983).
Hill above a plain.	BRNT, CLCP, APTT; PRXN, HBLD, PLGC.	Major copper producer	USBM, unpub. data (1980).
Dune, beach	ILMN, RUTL, ZRCN, MGNT, LCXN, MNZT; QRTZ, GRNT.	6.5 percent HM, 0.023 percent monazite	USBM, unpub. data (1988); USBM, unpub. data (1982).
SRI LANKA—Continued			
Beach	ILMN, RUTL, ZRCN, SLMN, MNZT; GRNT, QRTZ.	70 percent HM, 0.15 percent monazite	Industrial Minerals (1990a); USBM, unpub. data (1982).
UNITED STATES—Continued			
Flood plain	ILMN, RUTL, ZRCN, MNZT; QRTZ, CLAY.	0.031 percent monazite	USBM, unpub. data (1983).
Rounded mountains.	ILMN, ZRCN, MNZT; MGNT, HMTT, QRTZ.	0.2 percent monazite, 0.011 percent ThO_2	Do.
Mountainous	MNZT, XNTM; HMTT, FLDP, QRTZ	1.306 percent REO, 0.034 percent ThO_2	Staatz and others (1979).
Meadowland	ILMN, MGNT, MNZT; GRNT, QRTZ	0.0052 percent monazite	USBM, unpub. data (1982).
Mountain and basin.	ILMN, MGNT, ZRCN, MNZT, GRNT	0.04 percent monazite	Do.
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	USBM, unpub. data (1984).
Terrace	ILMN, MGNT, ZRCN, MNZT; QRTZ	0.0285 percent monazite	USBM, unpub. data (1982).
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	USBM, unpub. data (1984).
Steep canyons	CLPN, VNDN, URNN, REE; PYRT, CLAY.	...do.....	Do.
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	...do.....	Do.
Barrier Island	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ.	Production unlikely	USBM, unpub. data (1982).
Mountainous	MNZT, XNTM; FLRT, HMTT, FLDP, QRTZ.	1.22 percent REO, 0.21 percent ThO_2	Staatz and others (1979).
...do.....	FLRT, REE; PYRT, QRTZ, CLAY	2.95 percent REO	USBM, unpub. data (1983).
Broad valleys	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	USBM, unpub. data (1984).
Mountain and basin.	ILMN, MGNT, ZRCN, GOLD, MNZT; QRTZ.	0.009 percent monazite	USBM, unpub. data (1981).
Forest and wetlands.	ILMN, MGNT, ZRCN, STRL, MNZT	0.0077 percent monazite	USBM, unpub. data (1988).
Mountainous	GOLD, ZRCN, APTT, MNZT; HMTT, QRTZ.	0.026 percent Y_2O_3, 0.668 percent ThO_2	USBM, unpub. data (1983).
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.12 percent rare earths at phosphate property.	USBM, unpub. data (1985).
Explosion breccia.	THRT, XNTM, REE, FLRT, BRIT, APTT; SLPD, HMTT.	0.42 percent REO, 0.15 percent ThO_2	Staatz and others (1979).
Dune, beach	ILMN, RUTL, ZRCN, STRL, MGNT, MNZT; QRTZ, CLAY GRNT.	0.018 percent monazite in high grade	USBM, unpub. data (1983).

TABLE 21.—*Selected geologic and location information from ISMI*

Site name	Latitude	Longitude	Deposit type	Host rock	Age of mineralization	Tectonic setting
UNITED STATES—Continued						
Husky (Idaho)	42° 42′ N.	111° 15′ W.	Magmatic	Mudstone; PERM	PERM	Basin
Iron Hill (Colorado)	38° 16′ N.	107° 03′ W.	...do.....	Carbonatite; PREC	PREC	Shield
Lemhi Pass (Idaho)	44° 57′ N.	113° 37′ W.	...do.....	Quartzite; PREC	...do.....	Basin
Maxville (Florida)	29° 55′ N.	81° 45′ W.	Placer, marine	Sand	—	...do.....
Maybe Canyon (Idaho)	42° 45′ N.	111° 18′ W.	Magmatic	Mudstone; PERM	PERM	...do.....
Mineville dumps (New York)	44° 04′ N.	73° 29′ W.	...do.....	Gneiss; PREC	PREC	Shield
Mountain Fuel (Idaho)	42° 39′ N.	111° 17′ W.	...do.....	Mudstone; PERM	PERM	Basin
Mountain Pass (California)	35° 29′ N.	115° 32′ W.	...do.....	Carbonatite; PREC	PREC	Shield
Music Valley (California)	34° 01′ N.	115° 57′ W.	...do.....	Gneiss; PREC	...do.....	...do.....
North Henry (Idaho)	42° 54′ N.	111° 30′ W.	...do.....	Mudstone; PERM	PERM	Basin
North and South Carolina placers (North and South Carolina).	34° N.	79° W.	Placer, fluvial	Sand	—	...do.....
Oak Grove (Tennessee)	36° 23′ N.	88° 08′ W.	...do.....	Sand; CRET	CRET	...do.....
Pajarito (New Mexico)	33° 14′ N.	105° 26′ W.	Magmatic	Syenite; PREC	PREC	Shield
Pearsol Creek (Idaho)	44° 31′ N.	116° 05′ W.	Placer, fluvial	Sand	—	Basin
Powderhorn (Colorado)	38° 16′ N.	107° 01′ W.	Magmatic	Carbonatite	—	Shield
Silica mine (Tennessee)	36° 02′ N.	88° 11′ W.	Placer, fluvial	Sand; CRET	CRET	Basin
Smoky Canyon (Idaho)	42° 43′ N.	111° 08′ W.	Magmatic	Mudstone; PERM	PERM	...do.....
Trail Creek (Idaho)	42° 44′ N.	111° 25′ W.	...do.....	...do.....	...do.....	...do.....
Wet Mountains (Colorado)	38° 12′ N.	105° 24′ W.	...do.....	Carbonatite; CAMB	CAMB	Shield
Wooley Valley (Idaho)	42° 50′ N.	111° 24′ W.	...do.....	Mudstone; PERM	PERM	Basin
URUGUAY						
Atlantida	35° 12′ S.	55° 48′ W.	Placer, fluvial	Sand	—	Basin

records for rare-earth oxide deposits and districts—Continued

Local environment	Principal mineral assemblages	Average grades and comments	References
		UNITED STATES—Continued	
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	USBM, unpub. data (1984).
Hill and plain	ILMN, RUTL, ZRCN, PCLR, APTT, MNZT, FLRT; PYRT.	Mining goal would be Nb_2O_5	USBM, unpub. data (1982).
Mountainous	MNZT, THRT, RUTL; QRTZ, HMTT, PYRT.	Mining goal would be ThO_2	USBM, unpub. data (1983).
Wetland	ILMN, ZRCN, STRL, MNZT; QRTZ	Extension of Green Cove Springs being developed.	Industrial Minerals (1990b).
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	USBM, unpub. data (1985).
Glaciated highland.	MGNT, MRTT, APTT; QRTZ, FLDP	1.04 percent REO, 0.0136 percent ThO_2 in iron-mine dumps.	USBM, unpub. data (1983).
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	USBM, unpub. data (1984).
Rolling upland	ALNT, MNZT, BRIT; QRTZ	12 percent bastnaesite, 7.68 percent REO in major rare-earth producer.	USBM, unpub. data (1990).
High-desert basin.	XNTM, MNZT, GOLD; BOTT, QRTZ	REO value ranges from 3 to 14 percent	USBM, unpub. data (1983).
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	USBM, unpub. data (1985).
Flood plain	ILMN, RUTL, ZRCN, SLMN, STRL, MNZT; GRNT, KYNT.	Series of separate placers	Staatz and others (1979).
Alluvial terrace	ILMN, RUTL, ZRCN, LCXN, STRL, MNZT; QRTZ, KYNT, TRML.	0.09 percent REO	USBM, unpub. data (1982).
Indian reservation.	EDLT, ZRCN	0.18 percent Y_2O_3 in major potential source of yttrium in United States.	Mining Engineering (1989); USBM, unpub. data (1986).
Mountain and basin.	ILMN, MGNT, ZRCN, MNZT, GRNT. QRTZ.	0.0185 percent monazite	USBM, unpub. data (1982).
Hills	PRVK, PCLR, APTT; BOTT, FLDP	0.36 percent REO in 12 percent TiO_2 material.	Do.
Dissected upland.	ILMN, RUTL, ZRCN, LCXN, MNZT; QRTZ.	0.0105 percent monazite in sand, 0.07 percent monazite in HM dump.	Do.
Steep canyons	CLPN, VNDN, URNN, REE; PYRT, CLAY.	Phosphate mine	USBM, unpub. data (1984).
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.1 percent rare earths at phosphate property.	Do.
Plateau	THRT, XNTM, BRIT; HMTT, QRTZ	ThO_2:REO ratio of 2.2:1.0	Staatz and others (1979).
Parallel ridges	CLPN, VNDN, URNN, REE; PYRT, CLAY.	0.11 percent rare earths at phosphate property.	USBM, unpub. data (1984).
		URUGUAY—Continued	
Beach	MNZT	3.2 percent monazite	USBM, unpub. data (1990).

TABLE 22.—*Selected production and mineral-resource information from*

Abbreviations used throughout this table include

—, no information available.
t, metric tons.
conc, concentrate.

Abbreviations for *mining method* are S, surface; P, open pit; D, dredge; U, underground; N, not producing.

Annual production includes some or all of the following items (separated by semicolons): annual production in thousand metric tons; year of production (or range of years used to estimate average annual production); and degree of accuracy (accurate (Acc) or estimate (Est)).

Cumulative production includes some or all of the following items (separated by semicolons): cumulative production in thousand metric tons; years of reported cumulative production; and degree of accuracy (accurate (Acc) or estimate (Est)).

Resources includes some or all of the following items (separated by semicolons): resource in thousand metric tons of R1E resources (see fig. 1) unless otherwise stated; and year of estimate.

Site name	Year of discovery	Mining method	Year of first production	Commodities	Annual production (in 1,000 t)
				ARGENTINA	
Rio Tercero (Cordoba)	1957	N	None	MNZT	None
				AUSTRALIA	
Agnes Waters (Rocky Point) (Queensland)	1956	N	None	ILMN, RUTL, ZRCN	None
Alice Springs (Northern Territory).	1987	N	None	ALNT	None
Australind (Western Australia).	Unknown	N	None	ILMN, RUTL, ZRCN, LCXN, MNZT.	None
Bowen (Abbot Point) (Queensland).	Unknown	N	None	ILMN, RUTL, ZRCN, MNZT	None
Brockman (Western Australia).	1973	N	None	CLMB, PCLR, CERN, BSNS, XNTM, CSTR.	None
Busselton East (Western Australia).	Unknown	N	None	ILMN, RUTL, ZRCN, LCXN, MNZT.	Proprietary
Byfield (Queensland)	1956	N	None	ILMN, RUTL, ZRCN, MNZT	None
Capel South (Western Australia).	1954	D	1956	ILMN, LCXN, ZRCN, MNZT, XNTM.	MNZT conc: 0.5;1984; Acc.
Cataby (Western Australia)	1976	N	None	ILMN, RUTL, ZRCN, MNZT	None
Cooljarloo/Jurien Bay (Western Australia).	1971	D	1975	ILMN, RUTL, ZRCN, LCXN, MNZT.	Ore: 12,000; MNZT conc: 2.5; 1988; Acc.
Cooloola (Queensland)	1948	N	1956	ILMN, RUTL, ZRCN, MNZT	Ore: 23,760; ILMN: 170; RUTL: 42; ZRCN: 32; MNZT: 0.7; 1975; Acc.
Eneabba (Western Australia)	1968	D, P	1974	ILMN, RUTL, ZRCN, MNZT	MNZT conc: 8.9; 1987; Est.
Fraser Island (Queensland)	1948	D	1971	ILMN, RUTL, ZRCN, MNZT	Ore: 14,400; ILMN: 223; RUTL: 35; ZRCN: 40; MNZT: 1; 1976; Est.
Gingin South (Western Australia).	Unknown	N	None	ILMN, RUTL, ZRCN, LCXN, MNZT.	None
Hamel (Waroona) (Western Australia).	Unknown	P	1989	ILMN, RUTL, ZRCN	Proprietary
Higgins (Western Australia).	Unknown	N	None	ILMN, RUTL, ZRCN	Proprietary
Jangardup (Western Australia).	1986	N	None	ILMN, RUTL, ZRCN, LCXN, MNZT, XNTM.	HM conc: 271; 1990; Acc.
Mary Kathleen (Queensland)	Unknown	U	Unknown	URNN, REO	None
Minninup, beach, dunes (Western Australia).	1973	N	1986	ILMN, LCXN, ZRCN, MNZT, XNTM.	Included in Waroona figures

ISMI records for rare-earth oxide deposits and districts

Abbreviations for mineral names (after Longe and others, 1978, p. 63–66, with some additions):

Allanite	ALNT	Collophane	CLPN	Heavy minerals	HM	Rare-earth oxides	REO
Anatase	ANTS	Columbite	CLMB	Hematite	HMTT	Rutile	RUTL
Apatite	APTT	Davidite	DVDT	Ilmenite	ILMN	Sillimanite	SLMN
Barite	BRIT	Eudialyte	EDLT	Leucoxene	LCXN	Staurolite	STRL
Bastnaesite	BSNS	Fluocerite	FLDR	Magnetite	MGNT	Sulfides	SLPD
Bornite	BRNT	Fluorite	FLRT	Malachite	MLCT	Thorite	THRT
Brannerite	BRNR	Gadolinite	GDLN	Martite	MRTT	Uraninite	URNN
Cassiterite	CSTR	Galena	GLEN	Monazite	MNZT	Vermiculite	VMCL
Cerianite	CERN	Garnet	GRNT	Perovskite	PRVK	Xenotime	XNTM
Chalcocite	CLCC	Gold	GOLD	Pyrochlore	PCLR	Zircon	ZRCN
Chalcopyrite	CLCP						

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	ARGENTINA—Continued	
None	Ore: 31,700; MNZT: 5.48; 1983	No current production plans.
	AUSTRALIA—Continued	
None	Ore: 217,800; 1982	Estimate of resources is proprietary.
None	Ore: 1,000; ALNT: 40; 1988	Remote location may preclude development.
None	Ore: 6,000; HM: 901; ILMN: 662; RUTL: 3.6; ZRCN: 61; LCXN: 50; MNZT: 1.8; 1982.	Mining to be by surface sluice.
None	Proprietary	This is a prospect.
None	Ore: 9,290; REO: 20; 1990	Undergoing feasibility study.
None	Proprietary	Scheduled to start in 1990.
None	Ore: 2,400,000; HM: 27,360; MNZT: 14; 1990	Awaiting feasibility study.
MNZT conc; 16.5; 1956–74; Acc.	Ore: 25,333; MNZT: 15.2; 1989	1990 production and resources estimates are confidential.
None	Ore: 8,974; HM: 700; ILMN: 490; RUTL: 49; ZRCN: 84; MNZT: 10.5; 1982	Mining would be by open pit.
Unknown	Ore: 589,980; MNZT: 55.3; 1990	Cooljarloo is operating; Jurien Bay is on standby.
Unknown	Proprietary	Mining ceased in 1975; area is now a national park.
MNZT conc: 35.4; 1984–87; Est.	Proprietary	—
Unknown	Proprietary	Mining ceased in 1976; area is now a national park.
None	Ore: 29,210; HM: 2,931; ILMN: 1,434; RUTL: 156; ZRCN: 147; LCXN: 210; 1982.	Monazite content is not reported.
Unknown	Proprietary	Monazite content is low and is not recovered.
None	Proprietary	Future open pit will replace Hamel.
None	Ore: 30,000; HM: 2,040; ILMN: 1,679; RUTL: 51; ZRCN: 171; LCXN: 61; MNZT: 14; 1990.	Scheduled to start in 1992.
Unknown	Ore: 6,800; REO: 272; 1990	Underground uranium mine closed in 1963; rare earths could be recovered from tails.
Unknown	Proprietary	Production and plant will shift to Busselton East.

TABLE 22.—*Selected production and mineral-resource information from*

Site name	Year of discovery	Mining method	Year of first production	Commodities	Annual production (in 1,000 t)
			AUSTRALIA—Continued		
Moreton Island (Queensland)	1950's	N	1957	ILMN, LCXN, ZRCN	None
Mount Weld (Western Australia).	1948	N	None	APTT, PCLR	None
Munmorah (New South Wales).	1950	N	1969	ILMN, RUTL, ZRCN, MNZT	None
Nabiac, Southeast (New South Wales).	Unknown	N	None	ILMN, RUTL, ZRCN, MNZT	None
Newrybar (New South Wales).	1935	D	1990	ILMN, RUTL, ZRCN	Ore: 3,500; RUTL: 12; ZRCN: 10; 1990; Acc.
North Capel (Western Australia).	Unknown	N	Unknown	ILMN, LCXN, ZRCN, MNZT, XNTM.	None
North Stradbroke Island (Queensland).	1947	D	1949	ILMN, RUTL, ZRCN, MNZT	Ore: 46,093; 1989; Est. MNZT conc: 400; 1988; Est.
Olympic Dam (South Australia).	1975	U	1988	CLCC, BRNT, CLCP, URNN, BSNS, FLRT.	Ore: 1,500; Cu: 45; U_3O_8: 1.5; 1988; Acc.
Port Pirie (South Australia)	Not applicable.	N	None	DVDT	None
Stockton Bight (New South Wales).	Unknown	D	1985	ILMN, RUTL, ZRCN, MNZT	Proprietary
Tomago (New South Wales)	1965	D	1972	ILMN, RUTL, ZRCN, MNZT	Proprietary
Viney Creek (New South Wales).	Unknown	D	1986	ILMN, RUTL, ZRCN	Proprietary
Waroona, North and South (Western Australia).	1970	P	1984	ILMN, LCXN, ZRCN, MNZT, XNTM.	Ore: 590; MNZT: 0.235; 1988; Acc.
WIM–150 (Victoria)	1987	N	None	ILMN, LCXN, ZRCN, MNZT, XNTM.	None
Wonnerup Beach (Western Australia).	Unknown	P	1959	ILMN, ZRCN, MNZT	Proprietary
Yangibana (Western Australia).	Unknown	N	None	MNZT	None
Yoganup (Extended) (Western Australia)	1954	N	1972	ILMN, LCXN, ZRCN, MNZT	MNZT: 1.7; 1986; 1.75; 1987; 1.8; 1988; Acc.
			BRAZIL		
Alcobaca (Southern Bahia)	1970's	N	None	ILMN, RUTL, ZRCN, MNZT	None
Anchieta (Espirito Santo)	1900's	N	Unknown	ILMN, RUTL, ZRCN, MNZT	None
Aracruz (Espirito Santo)	1972	N	None	ILMN, RUTL, ZRCN, MNZT	None
Buena (Rio de Janeiro)	1960's	P	Unknown	ILMN, RUTL, ZRCN, MNZT	MNZT: 3.8; 1987; Acc.
Camaratuba (Rio Grande do Norte).	1970's	P	Unknown	ILMN, RUTL, ZRCN, MNZT	Ore: 3,160; 1981; Est.
Careacu (Minas Gerais)	Unknown	N	None	MNZT	None
Cordislandia (Minas Gerais)	Unknown	N	None	MNZT	None
Guarapari (Espirito Santo)	Unknown	N	None	MNZT	None
Northeast Dunes	Unknown	N	None	ILMN, RUTL, ZRCN, MNZT	None
Poços de Caldas (Minas Gerais).	Unknown	N	None	BSNS	None

ISMI records for rare-earth oxide deposits and districts—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	AUSTRALIA—Continued	
Unknown	Proprietary	Closed by the government.
None	Ore: 6,300; REO: 1,085; 1990	Could commence at 20,000–50,000 t/yr of ore.
None	Ore: 71,250; MNZT: 4.3; R2E; 1990	Closed by the government in 1977.
None	Ore: 2,000; HM: 27; RUTL: 8; ZRCN: 13; MNZT: 0.1; 1990.	—
None	Ore: 22,000; HM: 242; 1990	—
None	Proprietary	Property closed in 1987, resumed operation in 1990.
Ore: 195,750; 1966–81. MNZT conc: 2.3; 1975–87.	Proprietary	Consolidated Rutile, Ltd., purchased Associated Minerals Consolidated leases in 1985.
Unknown	Ore: 450,000; Cu: 11,250; U_3O_8: 360; REO: 1,478; 1988	REO in the uranium is not recovered.
None	Ore: 200; 1989	Plan to reprocess uranium tails.
Unknown	Proprietary	HM concentrate goes to Hawk's Nest plant.
Unknown	Proprietary	—
Unknown	Proprietary	HM concentrate goes to Hawk's Nest plant.
Unknown	Proprietary	South operation replaced north one in 1988.
None	Ore: 2,474,707; HM: 129,204; MNZT: 3,407; 1990	Studies and tests are underway but scaled down in 1992.
Unknown	Proprietary	Beach resources depleted; mining dunes.
None	Ore: 3,500; MNZT: 108; 1989	Feasibility study concluding.
Unknown, proprietary	—	HM concentrate goes to North Capel plant
	BRAZIL—Continued	
None	MNZT: 3.44; 1987	Data from Brazil is incomplete.
Ore: 271; MNZT: 2.3; 1982–87; Est.	Ore: 57; MNZT: 0.407; 1987	Probably mined out by 1991.
None	Ore: 282; MNZT: 2.964; 1987	No production planned yet.
Unknown	MNZT: 0.3; 1987	Probably mined out by 1991.
Unknown	Ore: 44,724; MNZT: 246; 1989 Ore: 490,000; R2E; 1981	—
None	MNZT: 2.5; 1987	—
None	MNZT: 8.2; 1987	—
None	MNZT: 0.95; 1987	—
None	Ore: 145,000; ILMN: 1,700; RUTL: 59; ZRCN: 398; MNZT: 48; 1990	—
None	BSNS: 1,500; REO: 50; 1990	Average REO content of 3.33 percent in BSNS.

TABLE 22.—*Selected production and mineral-resource information from*

Site name	Year of discovery	Mining method	Year of first production	Commodities	Annual production (in 1,000 t)
			BRAZIL—Continued		
Prado (Bahia)	Unknown	N	None	MNZT	None
São Gançalo do Sapucaí (Minas Gerais).	Unknown	N	None	ILMN, ZRCN, GRNT, GOLD, MNZT.	None
São Sebastio da Bela Vista (Minas Gerais).	Unknown	N	None	MNZT	None
Serra (Espirito Santo)	1960	N	None	ILMN, RUTL, ZRCN, MNZT	None
Tapira (Minas Gerais)	1966	P	1983	ANTS, APTT, PRVK, CLMB	Ore: 2,000; ANTS conc: 200; REO: 1.0; 1988; Est.
			BURUNDI		
Karonge	1940's	N	1948	BSNS	None
Kasagwe	Unknown	N	None	BSNS	None
			CANADA		
Elliot Lake (Denison) (Ontario).	1953	U	1957	URNN, BRNR, MNZT	Ore: 4,766; 1983; Est.
Elliot Lake (Rio Algom, except Stanleigh) (Ontario).	1953	U	1956	URNN, BRNR, MNZT	Ore: 3,273; 1983; Acc.
Elliot Lake (Rio Algom, Stanleigh) (Ontario).	Unknown	U	Unknown	URNN, BRNR, MNZT	Ore: 1,559; 1983; Est.
Strange Lake (Newfoundland/ Quebec).	1980	N	None	PCLR, ZRCN, FLRT, GDLN, ALNT, MNZT.	None
Thor Lake (Northwest Territories).	1979	N	None	CLMB, ZRCN, ALNT, GDLN, XNTM, MNZT.	None
			CHINA		
Bayan Obo (Inner Mongolia)	1951	P	1957	HMTT, MGNT, MRTT, BSNS, MNZT.	Fe_2O_3 Ore: 7,000; REO: 15; 1990; Acc.
Beihai (Guangxi)	Unknown	P	1966	ILMN, RUTL, ZRCN, MNZT	Ore: 3,385: HM: 33; ILMN: 30; ZRCN: 0.4; MNZT: 0.07; 1982; Acc.
Guangdong (Guangdong)	1950's	P	1960's	ILMN, RUTL, ZRCN, MNZT	Ore: 6,085; ILMN: 15; ZRCN: 0.6; MNZT: 0.075; 1982; Acc.
Xun Jiang (Guangxi)	1975	N	None	ILMN, RUTL, ZRCN, MNZT	None
			EGYPT		
Nile Delta-Rosetta	1920's	P	1965	ILMN, RUTL, ZRCN, MGNT, MNZT.	None
			GABON		
Mabounie	Unknown	N	None	FLCR	None
			GREENLAND		
Ilimaussaq	Unknown	N	None	PCLR, EDLT	None
			INDIA		
Chavara (IREL) (Kerala)	1920's	P	1932	ILMN, RUTL, ZRCN, SLMN, MNZT.	Ore: 219; ILMN: 135; RUTL: 6; ZRCN: 3; SLMN: 5; MNZT: 0.8; 1982; Acc.
Chavara (KMML) (Kerala)	1920's	P	1932	ILMN, RUTL, ZRCN, SLMN, LCXN, MNZT.	Ore: 1,152; ILMN: 100; RUTL: 10; ZRCN: 6; LCXN: 1.4; MNZT: 0.5; 1989; Est.
Manavalakurichi (Tamil Nadu).	1900's	P	1911	ILMN, RUTL, ZRCN, SLMN, GRNT, MNZT.	Ore: 285; MNZT conc: 3.8; 1982; Est.

ISMI records for rare-earth oxide deposits and districts—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	BRAZIL—Continued	
None	MNZT: 4.6; 1987	—
None	Ore: 75,600; ILMN: 630; ZRCN: 115; GRNT: 33; GOLD: 1.4; MNZT: 50; 1990.	Scheduled to begin in early 1991.
None	MNZT: 4.1; 1987	—
None	Ore: 436; MNZT: 3.5; 1982	Potential open pit.
Unknown	Ore: 150,000; TiO_2: 33,000; REO: 45; 1988	REO occurs in overburden of operating phosphate mine.
	BURUNDI—Continued	
Ore: 141; BSNS conc: 2.8; 1967–87; Acc.	Ore: 2.2; BSNS: 1.9; REO: 1.2; 1983 Ore: 3.2; R2E; 1983	Minable ore is 60,000 t at 3 percent BSNS.
None	Ore: 67; BSNS: 2; REO: 1; 1990	—
	CANADA—Continued	
Ore: 37,212; U_3O_8: 44; 1957–81; REO: 101; 1974–76; Acc.	Ore: 105,681; REO: 10.8; 1989 Ore: 223,800; R2E; 1983	Scheduled to close March 1992. REO was produced sporadically.
Ore: 24,793; 1967–81; Acc.	Ore: 68,197; REO: 5; 1989 Ore: 149,200; R2E; 1983	Closed in 1990.
Unknown	Ore: 49,877; REO: 4.3; 1989 Ore: 59,700; R2E; 1983	Potential for 152 t/yr REO.
None	Ore: 52,000; R1S; 1981; Est.	Could be started as a beryllium project.
None	Ore: 510; REO: 2.3; R1M; 1987; Est.	Essentially a Nb_2O_5-Ta_2O_5 project.
	CHINA—Continued	
Unknown	Fe_2O_3 Ore: 1,500,000; REO ore: 800,000; REO: 48,000; Nb: 1,000; 1990	The largest known REO deposit.
Unknown	Ore: 529,920; 1989	HM recovered from sands manually.
Unknown	Ore: 385,320; 1989	Covers five separate mines and plants.
None	Ore: 66,700; 1982	No local market yet.
	EGYPT—Continued	
ILMN: 29; MGNT: 10; ZRCN: 2; 1965–68; Acc.	Ore: 44,393; MNZT: 222; 1989	Also worked in 1929.
	GABON—Continued	
None	Unknown	2.52 percent REO in ore.
	GREENLAND—Continued	
None	Ore: 30,000; Zr_2O_3: 330; Y_2O_3: 270; 1990	One of three reported properties.
	INDIA—Continued	
Ore: 1,245; ILMN: 813; RUTL: 31; 1968–80; Acc.	Ore: 118,029; MNZT: 189; REO: 101; 1989	Sands mined manually.
Ore: 567; ILMN: 232; RUTL: 22; ZRCN: 6; 1966–80; Acc.	Ore: 114,752; MNZT: 184; REO: 101; 1989	Do.
Ore: 1,933; 1966–81; Acc.	Ore: 103,656; MNZT: 2,591; REO: 1,425; 1989	Do.

TABLE 22.—*Selected production and mineral-resource information from*

Site name	Year of discovery	Mining method	Year of first production	Commodities	Annual production (in 1,000 t)
				INDIA—Continued	
Orissa-Chatrapur (Orissa)	1958	P	1983	ILMN, RUTL, ZRCN, SLMN, MNZT.	Ore: 2,880; 1989; Est.
Ranchi and Purulia (Bihar)	1956	N	None	ILMN, RUTL, ZRCN, SLMN, MGNT, MNZT.	None
				KENYA	
Rangwa/Ruri/Homa	1940's	N	None	BSNS, MNZT, BRIT, FLRT	None
				MALAWI	
Kangankunde	1907	N	None	MNZT, STRL	None
				MAURITANIA	
Bou Naga	Unknown	P	1968	MNZT	None
				MOZAMBIQUE	
Congolone	Unknown	P	1992	ILMN, RUTL, ZRCN, MNZT	Ore: 17,558; ILMN: 422; RUTL: 8; ZRCN: 38; MNZT: 1; 1990; Est.
				NAMIBIA	
Etaneno	Unknown	N	None	MNZT	None
				NEW ZEALAND	
Barrytown (South Island)	1960's	N	None	ILMN, RUTL, ZRCN, CSTR, MGNT, GOLD, MNZT.	None
Westport (South Island)	Unknown	N	None	ILMN, RUTL, ZRCN, GOLD, MNZT.	None
				SOUTH AFRICA	
Buffalo Fluorspar (Transvaal)	1943	P	1948	FLRT, APTT, MNZT	Ore: 1,800; FLRT: 177; 1989; Acc.
Phalaborwa (Transvaal)	1912	P	1932	BRNT, CLCP, MGNT, VMCL, APTT, ZRCN, URNN.	Ore: 29,231; Cu conc: 294; U_3O_8; 87; ZRCN: 13; 1988; Acc.
Richards Bay (Natal)	1967	D	1977	ILMN, RUTL, ZRCN, LCXN, MGNT, MNZT.	Ore: 20,000; ILMN: 1,750; ZRCN: 200; MNZT: >1; 1988; Est.
				SRI LANKA	
Pulmoddai	1920's	P	1961	ILMN, RUTL, ZRCN, MNZT	Ore: 220; ILMN: 150; RUTL: 13; ZRCN: 13; MNZT: 0.7; 1990; Est.
				UNITED STATES	
Aiken County (South Carolina).	1950's	P	1955	ILMN, RUTL, ZRCN, MNZT	None
Bald Mountain (Wyoming)	1951	N	None	ILMN, MGNT, ZRCN, MNZT	None
Bear Lodge (Wyoming)	Unknown	N	None	MNZT, XNTM, THRT	None
Bear Valley (Idaho)	1950	D	1955	ILMN, MGNT, GRNT, MNZT, XNTM.	None
Big Creek (Idaho)	1940's	D	1950	ILMN, MGNT, ZRCN, GRNT, MNZT.	None
Blackfoot Bridge (Idaho)	Unknown	N	None	CLPN, MNZT	None
Brunswick-Altamaha (Georgia).	1959	N	None	ILMN, RUTL, ZRCN, MNZT	None

ISMI records for rare-earth oxide deposits and districts—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	INDIA—Continued	
Unknown	Ore: 224,397: MNZT: 1,418; REO: 780; 1989 Ore: 350,000; R2E; 1982	—
None	Ore: 86,480; ILMN: 330; RUTL: 64; ZRCN: 146; SLMN: 379; MGNT: 147; MNZT: 272; 1989	Inland alluvium.
	KENYA—Continued	
None	Ore: 375; MNZT: 24; REO: 13; 1989 Ore: 3,750; R2E; 1989	Potential open pit.
	MALAWI—Continued	
None	Ore: 11,000; MNZT: 550; STRL: 1,430; 1983 Ore: 22,000; R2E; 1983	MNZT is low-thorium.
	MAURITANIA—Continued	
Ore: 1.4; 1968–70; Acc.	Ore: 100; MNZT: 8; REO: 4.4; 1970	Operations limited to 6 months per year.
	MOZAMBIQUE—Continued	
None	Ore: 166,800; ILMN: 4,190; RUTL: 90; ZRCN: 373; MNZT: 11; 1990	Scheduled for early 1992 start.
	NAMIBIA—Continued	
None	REO: 20,000; 1989	Much crucial data missing.
	NEW ZEALAND—Continued	
None	Ore: 73,300; MNZT: 0.7; REO: 0.4; 1989	Pilot-plant study stage.
None	Ore: 850,200; R2E; 1989; Est.	Undergoing feasibility study.
	SOUTH AFRICA—Continued	
Ore: 12,120; 1972–80; Acc.	Ore: 50,000; CaF_2: 6,500; MNZT: 500; 1989	MNZT is not reclaimed.
Ore: 528,382; 1964–88; Acc.	Ore: 123,840; APTT: 1,858; REO: 130; 1989	REO is not reclaimed.
Unknown	Ore: 4,980,000; MNZT: 1,145; REO: 630; 1989	Mines having three dredges and wet plants.
	SRI LANKA—Continued	
Ore: 1,963; ILMN: 1,141; RUTL: 87; ZRCN: 24; MNZT: 0.7; 1966–82; Acc.	Ore: 1,593; MNZT: 2.4; REO: 1.3; 1989 Ore R2E: 55,967; HM: 7,141; 1982	HM replenished by annual monsoons.
	UNITED STATES—Continued	
None	Ore: 19,000; MNZT: 7.8; REO: 4.9; 1983	Closed in 1958.
None	Ore: 18,144; MNZT: 23; REO: 14; 1983	Potential open pit.
None	Ore: 726,000; REO: 9,480; 1978	Potential open pit; high thorium.
None	Ore: 109,900; MNZT: 17; REO: 11; 1982 Ore R2E: 1,232,150; MNZT: 64; REO: 40; 1982	Mining ceased in 1959.
None	Ore: 116,100; ILMN: 341; MGNT: 5; ZRCN: 16; GRNT: 39; MNZT: 47; 1982.	Date of shutdown unknown.
None	Ore: 5,900; P_2O_5: 1,534; MNZT: 9.4; 1984	Mining to start in 2023 at close of Caldwell Canyon.
None	Ore: 65,850; ILMN: 1,087; RUTL: 75; ZRCN: 213; MNZT: 19; 1982.	Mining would be by dredge.

TABLE 22.—*Selected production and mineral-resource information from*

Site name	Year of discovery	Mining method	Year of first production	Commodities	Annual production (in 1,000 t)
			UNITED STATES—Continued		
Caldwell Canyon (Idaho)	Unknown	N	None	CLPN, MNZT	None
Champ (Idaho)	Unknown	P	1982	CLPN, MNZT	None
Conda (Idaho)	1906	P	1920	CLPN, MNZT	None
Cumberland Island (Georgia)	1940's	N	None	ILMN, RUTL, ZRCN, LCXN, MNZT.	None
Diamond Creek (Idaho)	Unknown	N	None	MNZT, XNTM, THRT	None
Gallinas Mountains (New Mexico).	About 1885	P, U	1943	FLRT, GLEN, MLCT, BSNS	None
Gay and South Forty (Idaho)	Unknown	P	1946	CLPN, MNZT	Ore: 1,800; 1984; Est.
Gold Fork-Little Valley (Idaho).	1880's	D	1880's	ILMN, MGNT, ZRCN, GRNT, GOLD, MNZT.	None
Green Cove Springs (Florida)	1950's	D	1972	ILMN, RUTL, ZRCN, LCXN, MNZT.	Ore: 9,405; ILMN: 135; RUTL: ;48; ZRCN: 57; LCXN: 8; MNZT: 1; 1989; Est.
Hall Mountain Group (Idaho)	1930's	P, U	1930's	THRT, MGNT, GOLD, ZRCN, APTT, ALNT, MNZT.	None
Henry (Idaho)	Unknown	P	1969	CLPN, MNZT	None
Hicks Dome (Illinois)	1954	N	None	THRT, FLRT, SLPD, APTT, XNTM, BSNS.	None
Hilton Head Island (South Carolina).	1954	N	None	ILMN, RUTL, ZRCN, MNZT	None
Husky (Idaho)	Unknown	P	1993	CLPN, MNZT	None
Iron Hill (Colorado)	1880's	N	None	PCLR, RUTL, ZRCN, FLRT, APTT, MNZT.	None
Lemhi Pass (Idaho)	1949	N	None	THRT, RUTL, MNZT	None
Maxville (Florida)	Unknown	D	1992	ILMN, ZRCN, STRL	None
Maybe Canyon (Idaho)	Unknown	P	1966	CLPN, MNZT	Ore: 910; 1985; Est.
Mineville dumps (New York)	1700's	P	1824	MGNT, MRTT, APTT	None
Mountain Fuel (Idaho)	Unknown	P	1986	CLPN, MNZT	Ore: 1,358; 1989; Est.
Mountain Pass (California)	1949	P	1965	BRIT, BSNS, MNZT, ALNT	Ore: 308; REO: 24.7; 1989; Acc.
Music Valley (California)	1949	N	None	XNTM, MNZT, GOLD	None
North Henry (Idaho)	Unknown	P	1991	CLPN, MNZT	None
North and South Carolina placers (North and South Carolina).	1880's	N	1887	ILMN, RUTL, ZRCN, MNZT	None
Oak Grove (Tennessee)	1960's	N	None	ILMN, RUTL, ZRCN, MNZT	None
Pajarito (New Mexico)	1984	N	None	EDLT	None

ISMI records for rare-earth oxide deposits and districts—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
	UNITED STATES—Continued	
None	Ore: 11,000; P_2O_5: 2,574; MNZT: 17; 1984	Mining to start in 2035 at close of Trail Creek.
Ore: 2,716; 1982–86; Est.	Unknown	Mining ceased in 1986.
Ore: 17,583; 1922–82; Acc.	Unknown	Mining ceased in 1984.
None	Ore: 241,000; MNZT: 43; REO: 27; 1982	Partially in a national park.
None	Ore: 235; MNZT: 4.6; REO: 2.9; 1978	Would be an underground mine.
BSNS conc: 0.06; 1954–55; Est.	Ore: 46; CaF_2: 28; REO: 1.4; 1983 Ore: 18; R2E; 1983	Fluorite mine closed in 1956.
Ore: 39,959; 1946–82; Acc.	Ore: 18,000; P_2O_5: 4,590; MNZT: 18; 1989	Mining will continue to 1995.
None	Ore: 296,317; MNZT: 46; REO: 29; 1981	Originally a gold placer.
Ore: 19,842; 1986–88; Est.	Ore: 110,079; MNZT: 8; REO: 5; 1989	The only placer REO producer in the United States.
None	Ore: 71; 1983 Ore: 68; R2E; 1983	Mining ceased in the 1940's.
Ore: 13,322; 1969–85; Acc.	Ore: 847; P_2O_5: 231; MNZT: 1.6; 1989	Mining halts in 1990.
None	Ore: 14,700; REO: 62; 1978 Ore: 658,000; R2E; 1978	No production plans.
None	Ore: 759,300; ILMN: 2,020; RUTL: 911; ZRCN: 524; MNZT: 61; 1983	Mining unlikely; active resort community.
None	Ore: 23,000; P_2O_5: 5,750; MNZT: 37; 1989	Starts in 1993 at 1,358,000 t/yr.
None	Ore: 655,622; REO: 2,603; 1989	Mainly a Nb_2O_5 property.
None	Ore: 39,009; MNZT: 316; REO: 199; 1989 Ore: 491; R2E; 1989	Would be mined underground for ThO_2.
None	Unknown	Extension of Green Cove Springs.
Ore: 21,148; 1966–84; Acc.	Ore: 6,350; P_2O_5: 1,562; MNZT: 10; 1989	Scheduled through 1996.
Unknown	Ore: 15,672; REO: 163; 1983	Dumps from former iron-ore mine.
Ore: 4,074; 1986–89; Est.	Ore: 5,432; P_2O_5: 1,358; MNZT: 9; 1989	Scheduled through 1993.
REO: 293; 1972–89; Acc.	Ore: 28,123; BSNS: 3,375; REO: 2,503; 1989 Ore: 156,877; R2E; 1989	The major REO producer in the United States.
None	Ore: 50; REO: 4.3; 1983	Ore is highly radioactive.
None	Ore: 3,200; P_2O_5: 867; REO: 3.8; 1985	Will operate through 1994.
None	MNZT: 90; REO: 57; 1978	No plans for production.
None	Ore: 174,600; MNZT: 271; REO: 157; 1982	Do.
None	Ore: 2,400; ZRCN: 29; REO: 4; 1989	Good potential for Y_2O_3 production.

TABLE 22.—*Selected production and mineral-resource information from*

Site name	Year of discovery	Mining method	Year of first production	Commodities	Annual production (in 1,000 t)
			UNITED STATES—Continued		
Pearsol Creek (Idaho)	1940's	D	1950	ILMN, MGNT, ZRCN, GRNT, MNZT.	None
Powderhorn (Colorado)	1980's	N	None	PRVK, PCLR, APTT	None
Silica mine (Tennessee)	1930's	S	1942	ILMN, RUTL, ZRCN, LCXN, MNZT.	Ore: 1,000; 1982; Est.
Smoky Canyon (Idaho)	Unknown	P	1984	CLPN, MNZT	Ore: 1,861; 1984; Est.
Trail Creek (Idaho)	Unknown	N	None	CLPN, MNZT	None
Wet Mountains (Colorado)	1960's	N	None	BRIT, THRT, XNTM	None
Wooley Valley (Idaho)	Unknown	P	1955	CLPN, MNZT	None
				URUGUAY	
Atlantida	Unknown	N	None	MNZT	None

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ISMI records for rare-earth oxide deposits and districts—Continued

Cumulative production (in 1,000 t)	Resources (in 1,000 t)	Comments
UNITED STATES—Continued		
None	Ore: 172,471; ILMN: 376; MNZT: 32; 1982	Unknown shutdown date.
None	Ore: 246,000; REO: 886; 1982 Ore: 223,000; R2E; 1982	Potential open pit.
Ore: 3,923; 1972–82; Acc.	Ore: 26,700; MNZT: 3.6; REO: 2.1; 1989	Only sand produced; HM stockpiled.
Ore: 9,895; 1984–89; Est.	Ore: 35,455; P_2O_5: 9,573; MNZT: 56; 1989	Production will continue through 2007.
None	Ore: 27,000; P_2O_5; 6,750; MNZT: 43; 1984	Production will start in 2005.
None	Ore: 13,957; REO: 141; 1989	No plans for production.
Ore: 11,453; 1955–87; Est.	Unknown	Mining ceased in 1987.
URUGUAY—Continued		
None	Ore: contains 3.2 percent MNZT	Meager data.

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