The Future of Rare Earth Elements—
Will These High-Tech Industry Elements Continue in Short Supply?

By Keith R. Long

Open-File Report 2011–1189

U.S. Department of the Interior
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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Image of pure rare earth elements oxides from:

http://seeker401.wordpress.com/2010/11/18/experts-speak-about-a-rare-earth-bubble/.

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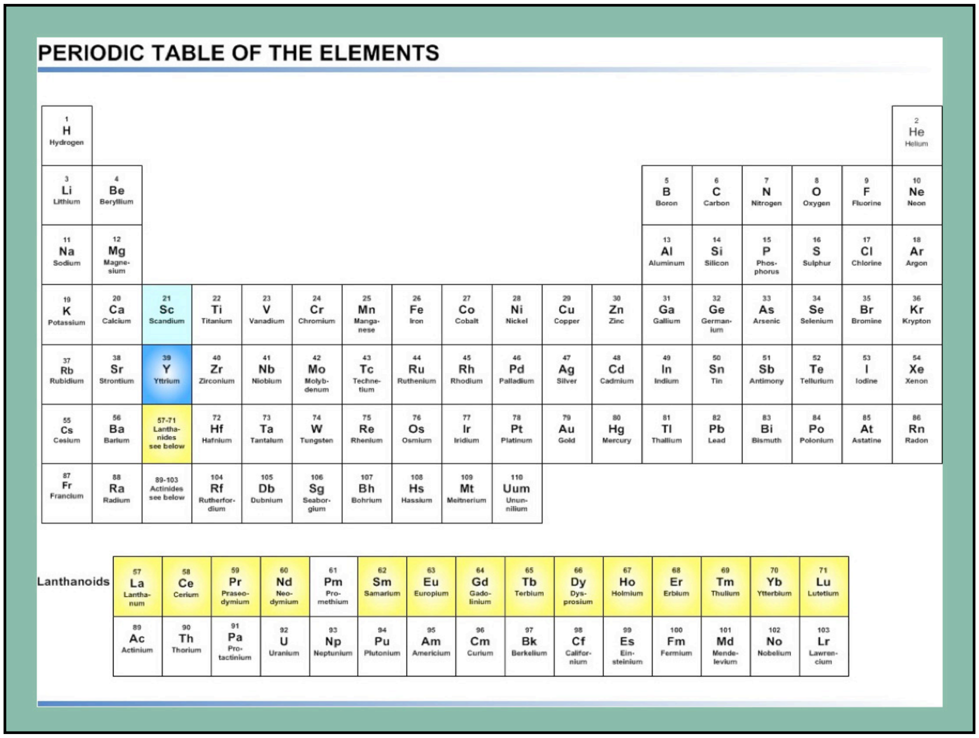
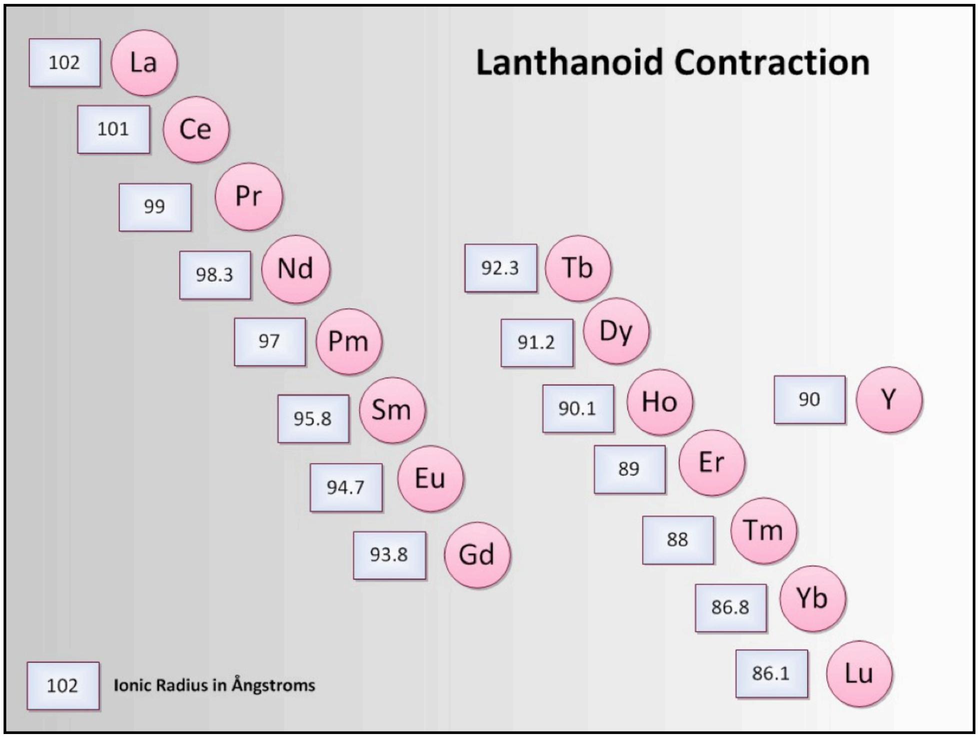


Periodic table of the elements showing the elements generally included among the rare earth elements.

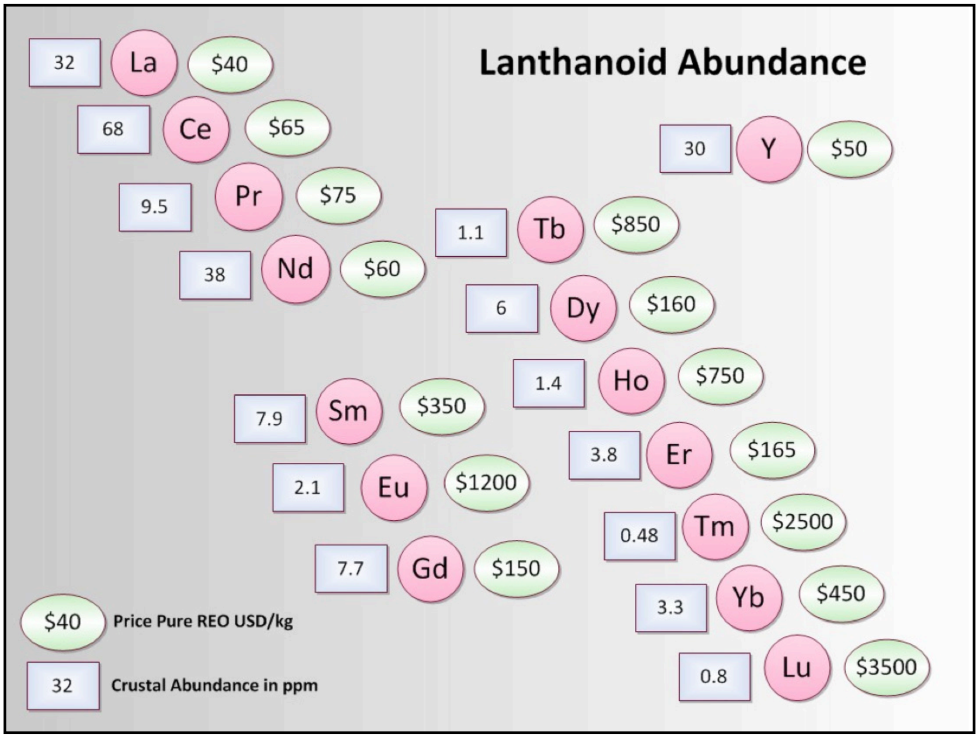
Yellow: The lanthanoid elements. Pm (promethium) is left blank because it does not occur in nature.

Dark Blue: Y (yttrium) is usually included with the lanthanoid elements as a rare earth element because it behaves chemically like a lanthanoid element.

Light blue: Sc (scandium) is sometimes included with yttrium and the lanthanoid elements as a rare earth element, but we do not do so here.



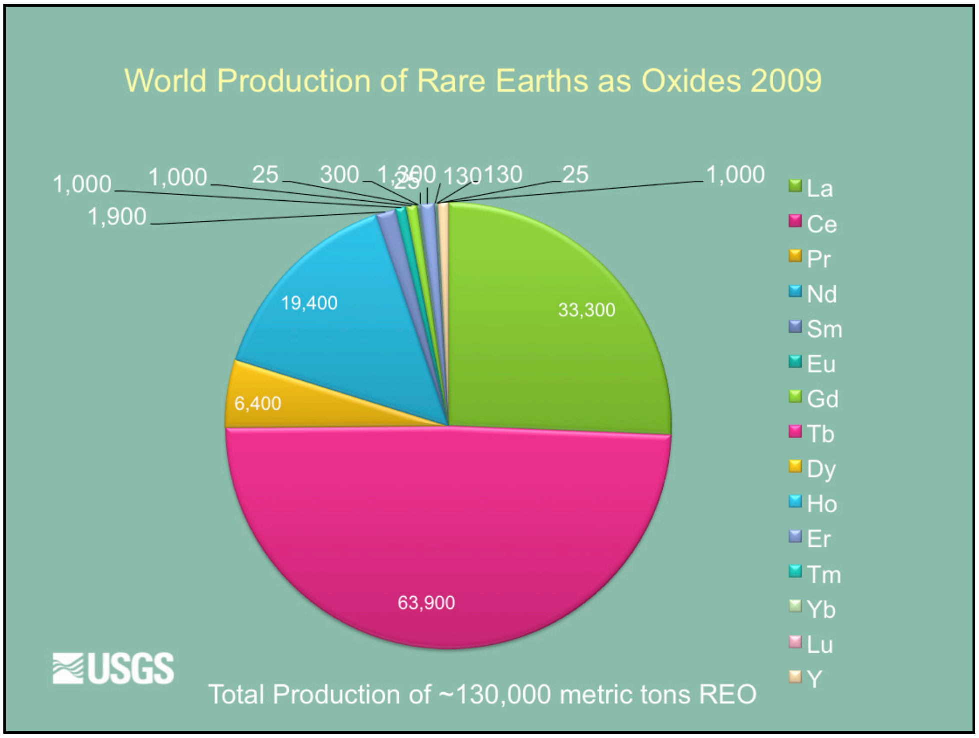
The lanthanoid contraction is a gradual decrease in the ionic radius of each element as atomic number increases. The decrease is approximately 1 Ångstrom per unit atomic number, except when going from Gd (gadolinium) to Tb (terbium) where the decrease is approximately 2 Ångstroms. La (lanthanum) to Gd (gadolinium) are often referred to as the light rare earth elements and Tb (terbium) to Lu (lutetium) as the heavy rare earth elements. Y (yttrium) is included with the heavy rare earth elements because its ionic radius is similar to that of Ho (holmium), one of the heavy rare earth elements. This gradual decrease in ionic radius results in sight differences in solubility between the rare earth elements. The difference is used to separate the individual rare earth elements during the production of rare earth elements chemicals.



Prices are for pure oxides from a leading rare earth elements chemical producer in 2009. Pm (prometheum) is not shown because it does not occur in nature and is not commercially available.

REO: rare earth oxide.

USD/kg: United States Dollars per kilogram.



Total estimated global production of the individual rare earth elements as oxides in metric tons for 2009.

Data from Lynas Corp.: www.lynascorp.com.

Principal Use Categories for Rare Earths

Use Category	Share by Volume %	Share by Value %	Growth Rate %
Catalysts	22	5	4 to 7
Magnets	22	37	10 to 16
Metal alloys	20	14	15 to 20
Polishing	9	4	6 to 8
Glass	9	2	negligible
Phosphors	5	31	7 to 10
Other	13	7	5 to 9

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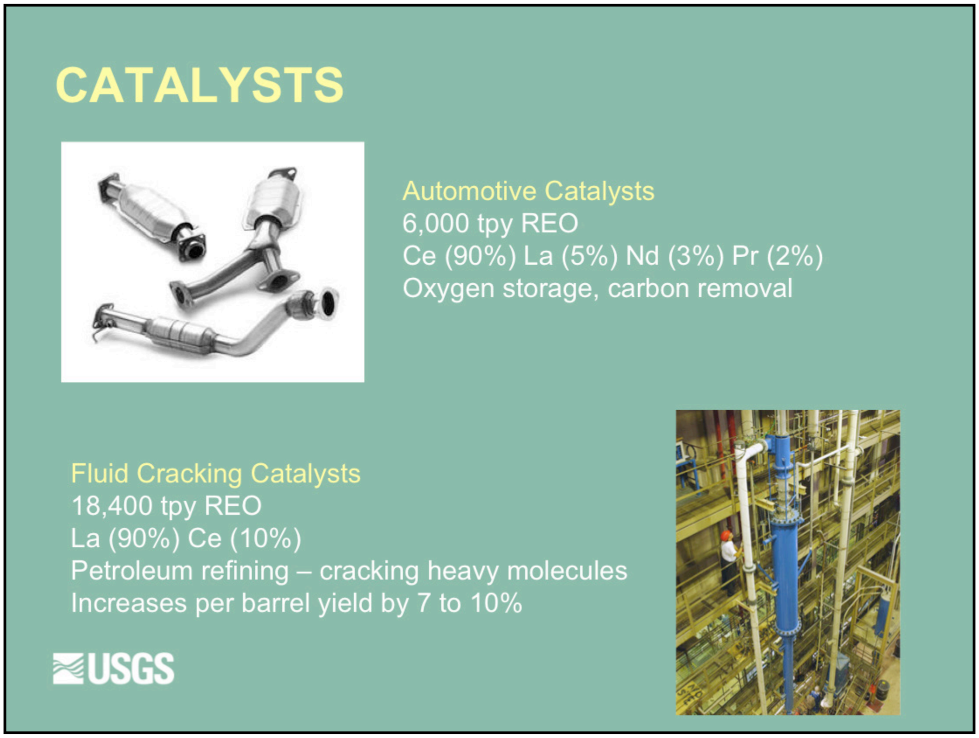
Data from IMCOA (Industrial Minerals Co. of Australia) and Lynas Corp.



For each application:

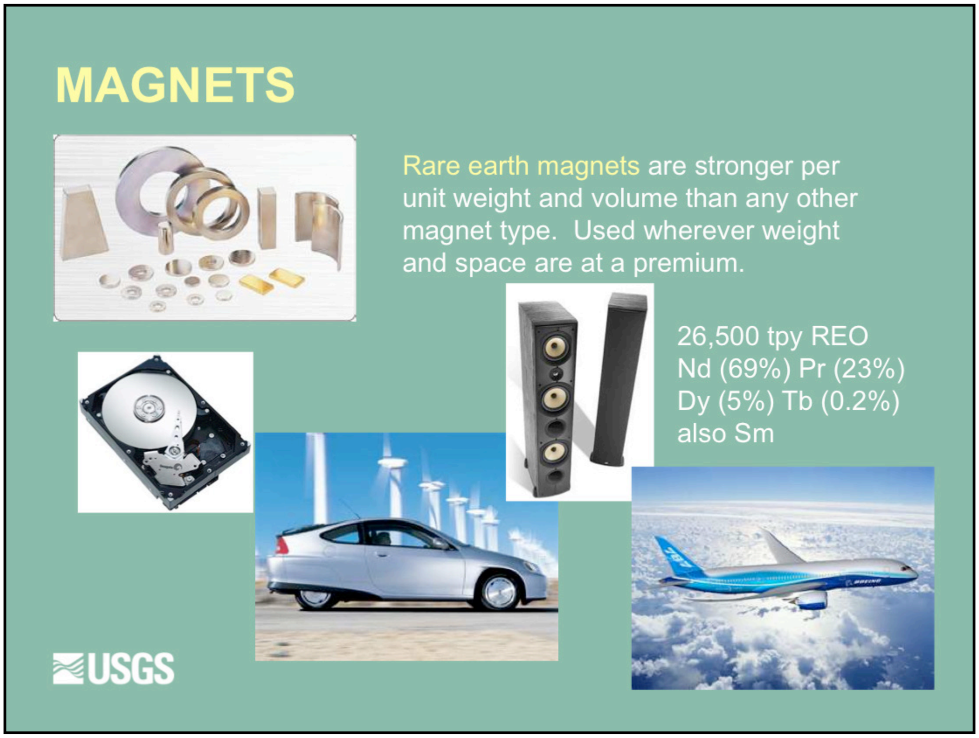
(1) Global consumption of rare earth oxides (REO) in metric tons per year (tpy) in that particular application;

(2) The different rare earth elements used in that application along with their percent (%) share of consumption;

(3) Principal uses in that application area.

Images were found by author on the World Wide Web.

Data from IMCOA (Industrial Minerals Co. of Australia) and Lynas Corp.



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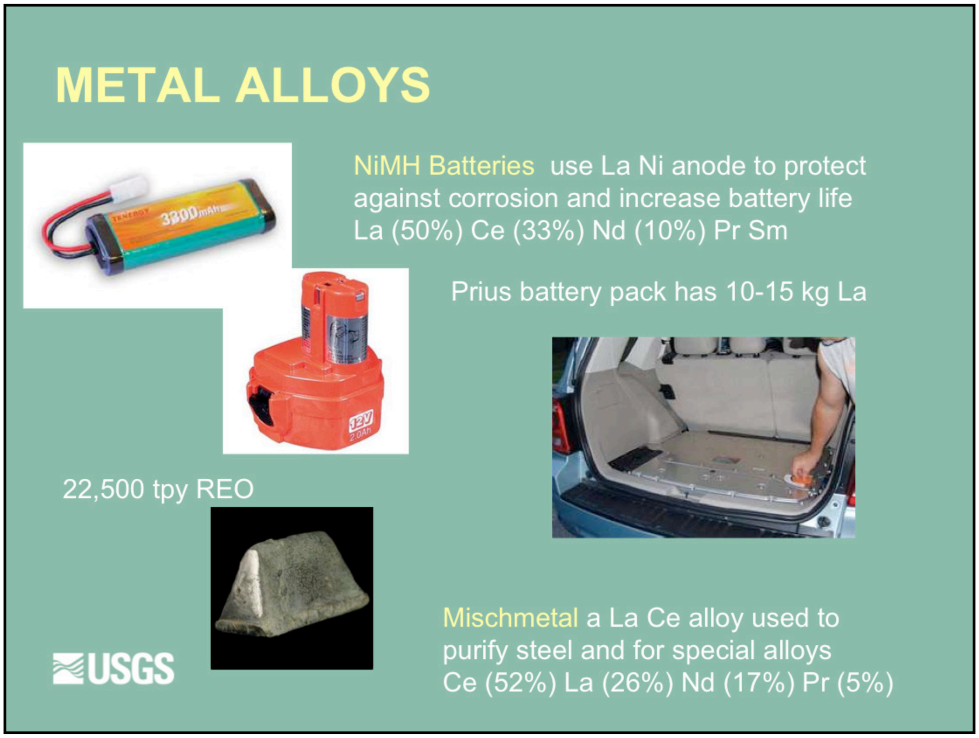

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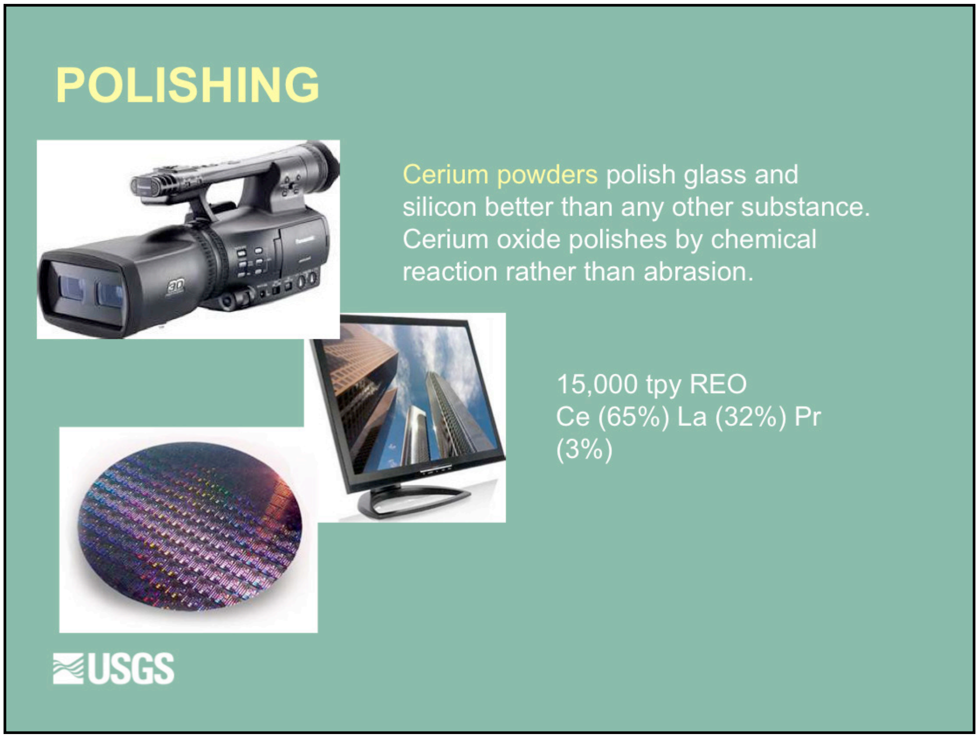

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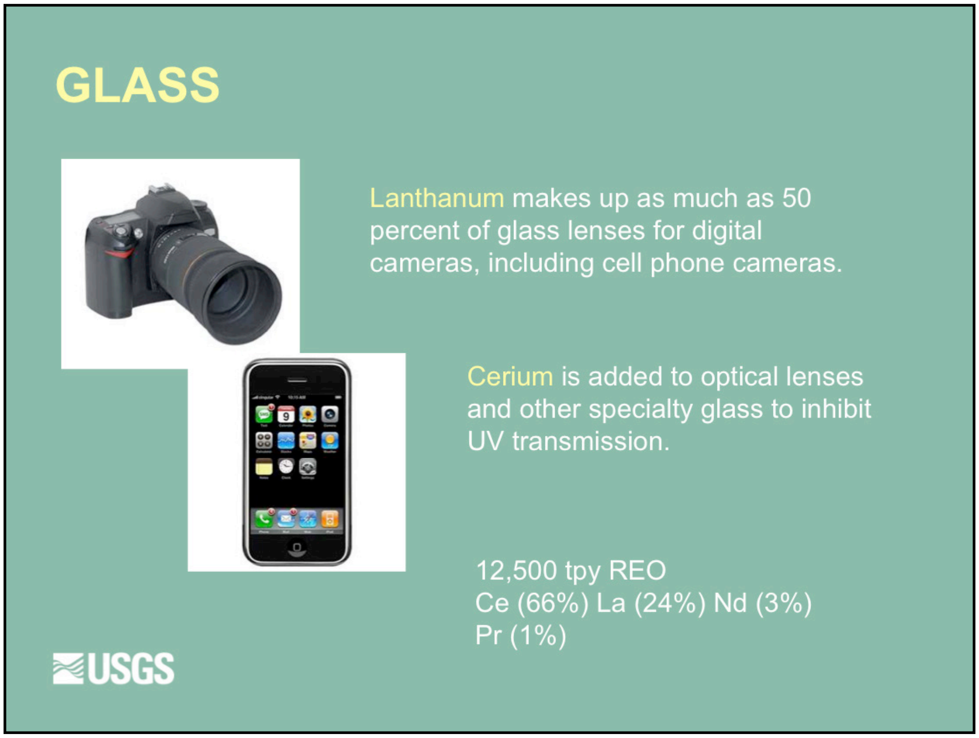

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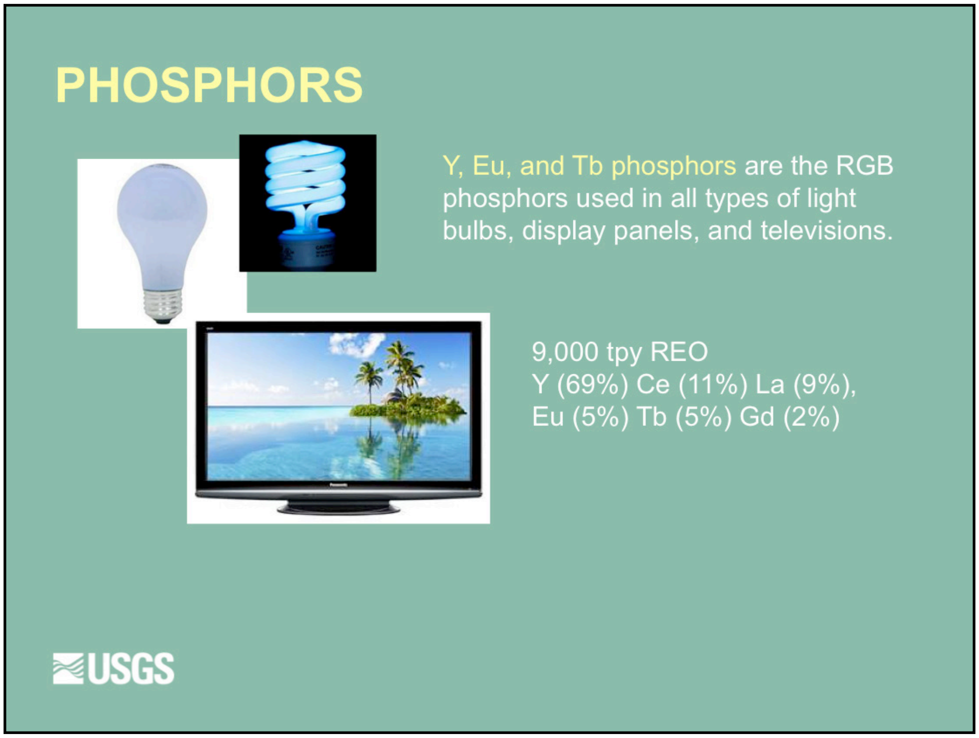

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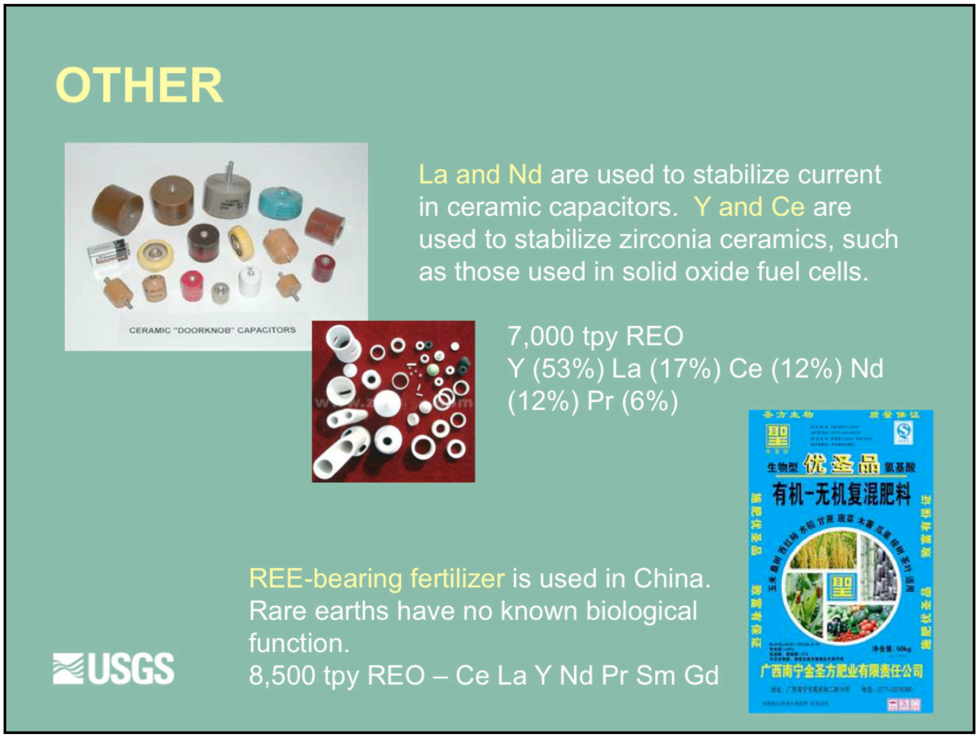

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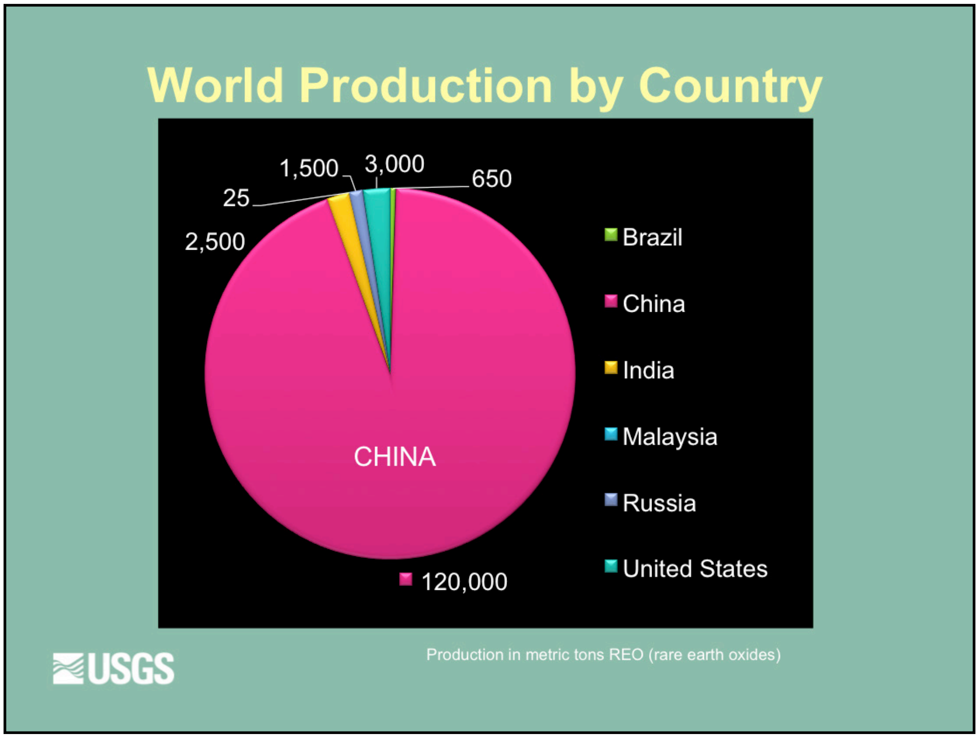
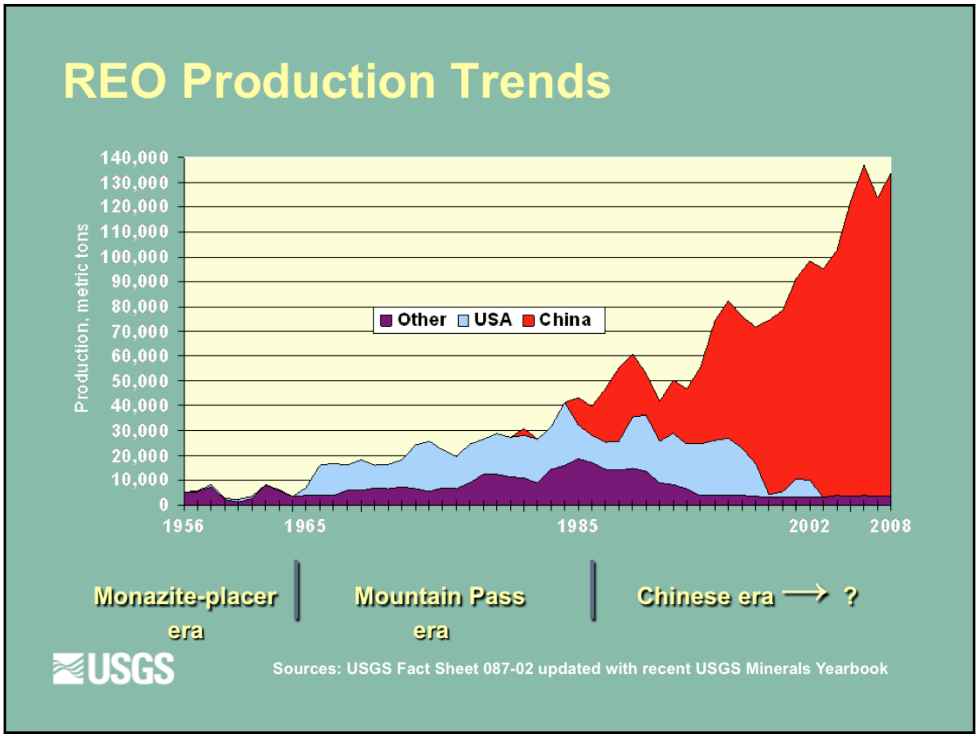
Data from IMCOA (Industrial Minerals Co. of Australia) and Lynas Corp.

Fertilizer image was found at:

http://www.gxjsf.com/en/products.asp?id=2&menu=ShowDetail&P_Id=1041.



Global production of rare earth elements expressed as total rare earth oxides in metric tons for 2009. Source of data: USGS Mineral Commodity Summaries 2010.



Graph courtesy of Daniel Cordier, USGS Mineral Commodity Specialist for rare earth elements.

Types of Rare Earth Deposits

Carbonatite and Peralkaline Intrusive-Related (71,000 tpy REO)
There are very rare intrusive rocks found in rift zones. REE-minerals may be rock-forming minerals or may be deposited by hydrothermal activity in veins.

Heavy Mineral Placers (4,000 tpy REO)
Monazite, a common REE-bearing accessory mineral in igneous, metamorphic, and sedimentary rocks, may be concentrated with other heavy minerals in placer deposits.

Residual (45,000 tpy REO)
Intense weathering of carbonatite and peralkaline intrusives may form concentrated residual deposits or REE minerals. REE-laterite in south China result from weathering of tin granites.

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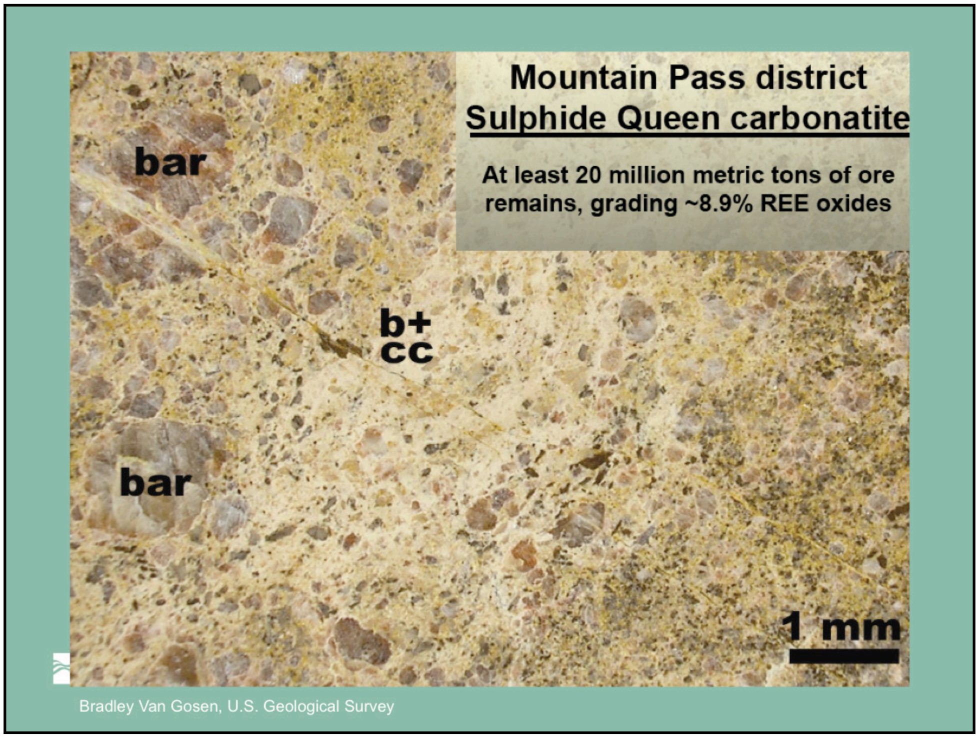
I have allocated global production by deposit types based on my knowledge of the geology of producing rare earth elements (REE) mines. tpy: metric tons per year. REE: rare earth elements. REO: rare earth oxides.



This is a view of the rare earth elements ore at the Mountain Pass mine, California, under a microscope. Scale bar for 1 millimeter is shown in the lower right corner. Labeled minerals are barite (bar) and bastnäsite plus calcite (b+cc). Bastnäsite, a rare earth element carbonate, is the mineral from which rare earth elements are recovered from this mine. Photo courtesy of Bradley Van Gosen, U.S. Geological Survey.

The two black vertical "stripes" with the light-colored "stripe" between comprise the uranium-rare earth elements vein at Bokan Mountain, Alaska. Rock hammer on left for scale. Photo courtesy of Bradley Van Gosen, U.S. Geological Survey.

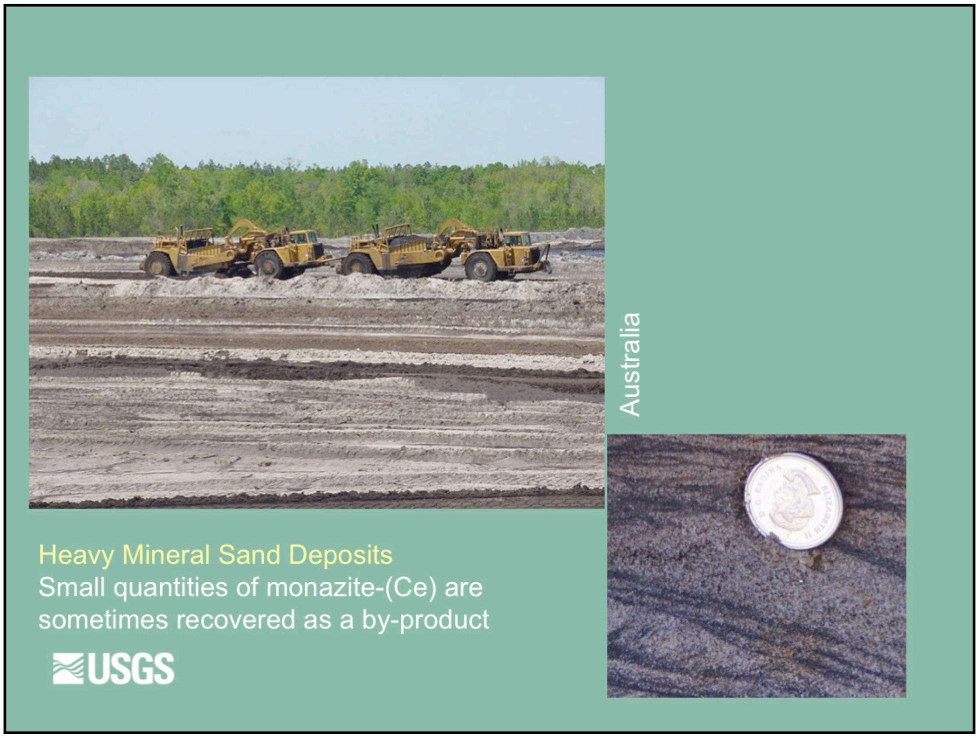


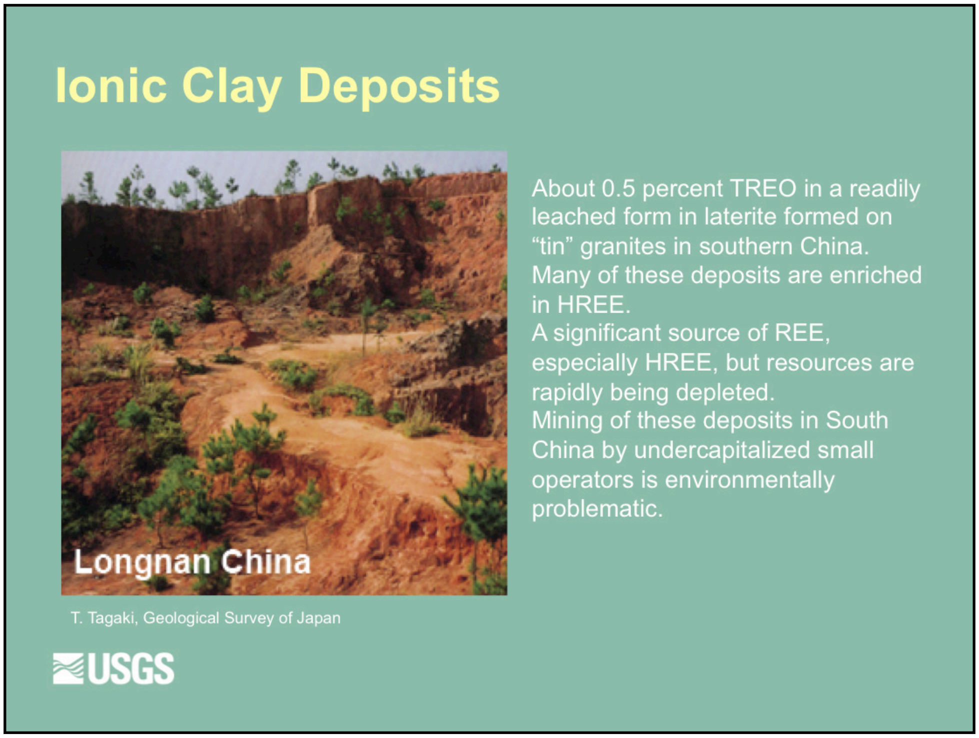
Photo on upper left is of a heavy mineral sands mine in Australia. The photo on the lower right is a close up of the heavy mineral sand with a coin for scale. The principal minerals recovered from these sands are ilmenite and rutile, which are sources of titanium. Monazite, a rare earth elements-bearing mineral, occurs in small quantities in these sands, but is not currently being recovered in Australia. It is recovered from heavy mineral sands in India.

Image on upper left from:

http://project-geo.org/Spring_05/heavy_minerals/.

Image on lower right from:

http://grandriverironsands.com/index-3.html.



TREO: total rare earth oxides.

HREE: heavy rare earths (terbium to lutetium).

REE: rare earth elements.

Photo from Tetsuichi Tagaki, Geological Survey of Japan.

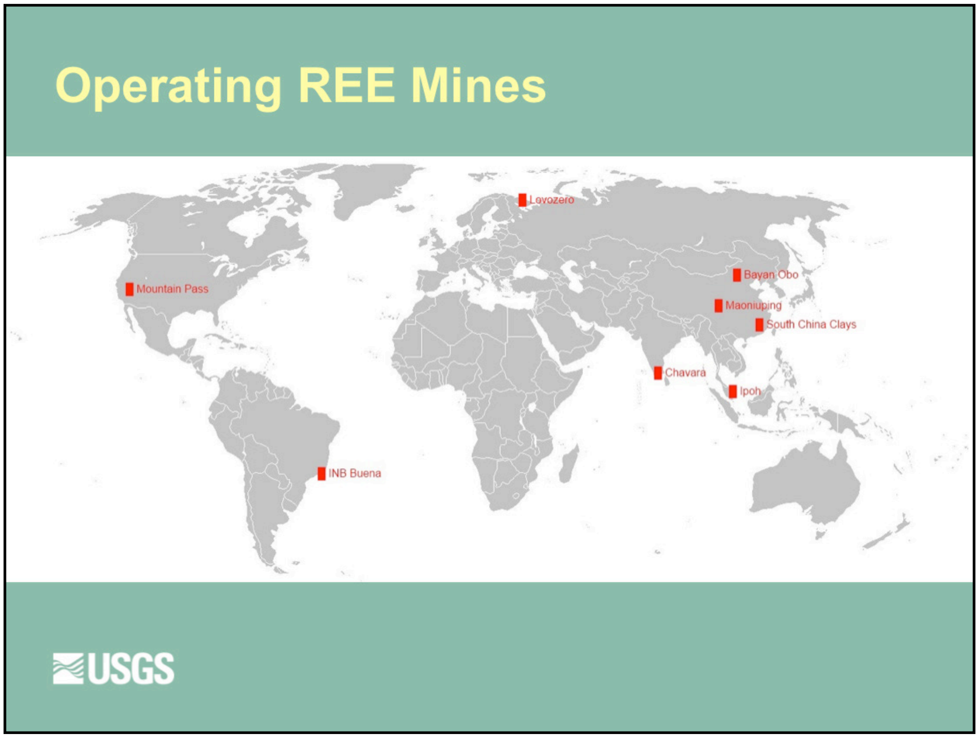


Figure by author.

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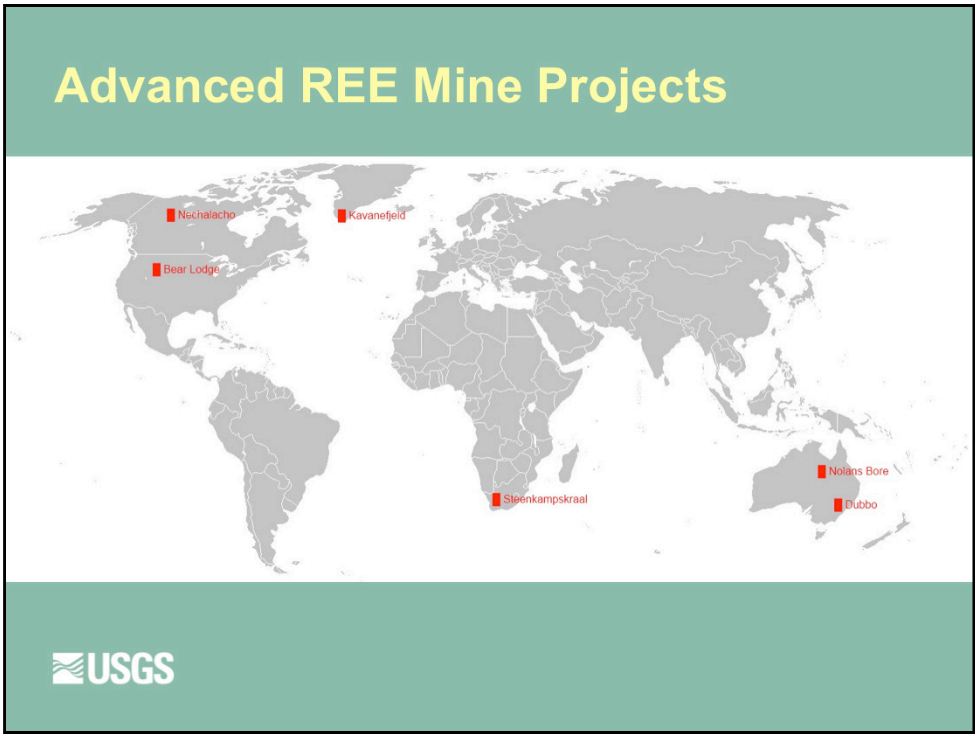

Figure by author.

Reserves and Resources

As reported according to SEC, NI 43-101, JORC, or SAMREC standards except for figures in italics

Country	Reserves metric t TREO	Resources metric t TREO
Australia	1,434,000	1,588,000
Brazil	*48,000*	
Canada		8,083,000
Greenland		875,000
India	*3,100,000*	
Kyrghyzstan		49,000
Malawi		107,000
Malaysia	*30,000*	
Russia		*1,700,000*
South Africa		977,000
Sweden		447,000
United States	1,009,000	589,000

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China is excluded from these figures because we do not have any reliable data on Chinese reserves and resources for rare earth elements. The resources for Russia are those in various deposits at the Lovozero mining complex. We do not have data for any other rare earth elements deposits in Russia. Reserves for India include the Chavara mine and other heavy mineral sands operations. TREO: total rare earth oxides.

Mining

Mountain Pass, CA

Mining of rare earth deposits is by conventional open pit and underground methods.

Pea Ridge, MO

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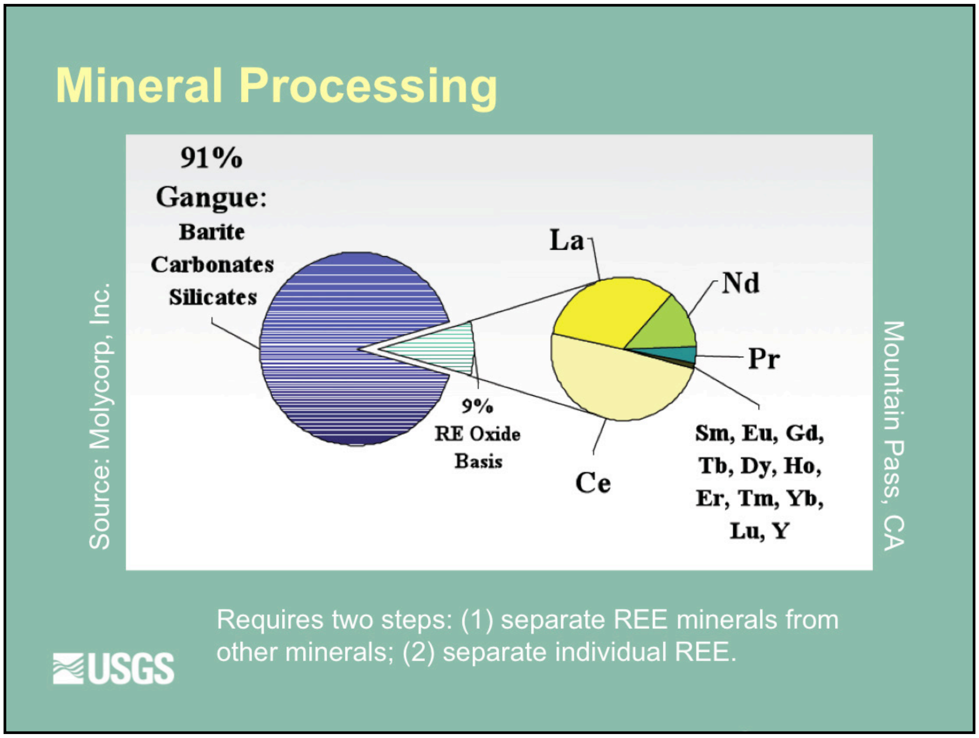
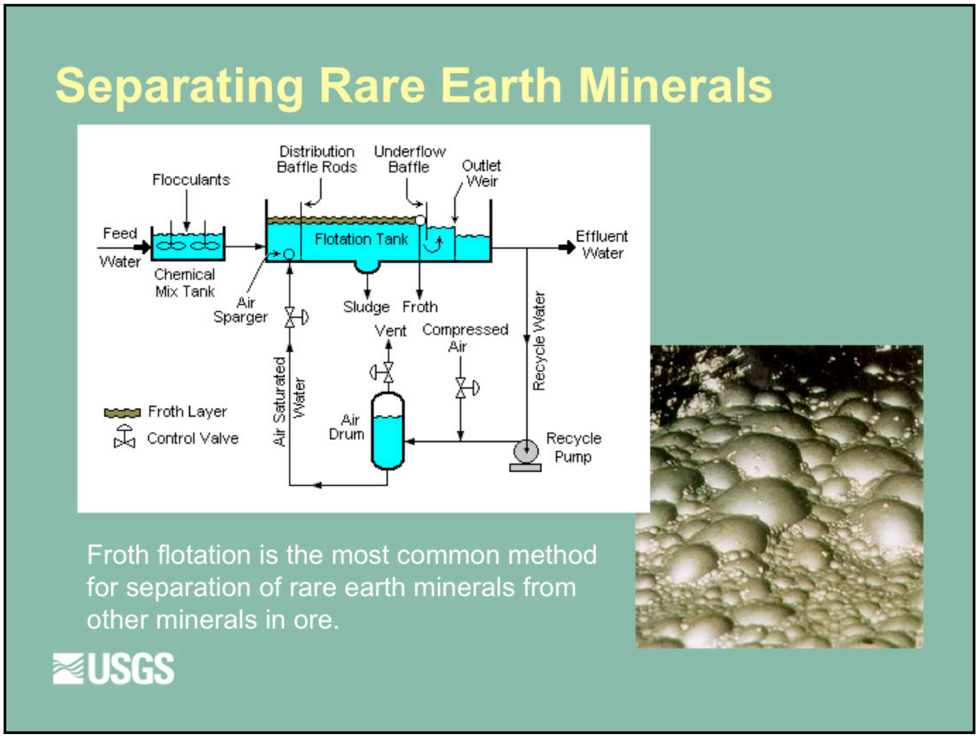
Photo of Mountain Pass, California, open pit mine from Molycorp, Inc. Photo of headrame on Pea Ridge shaft, Missouri. from Bradley Van Gosen, U.S. Geological Survey.

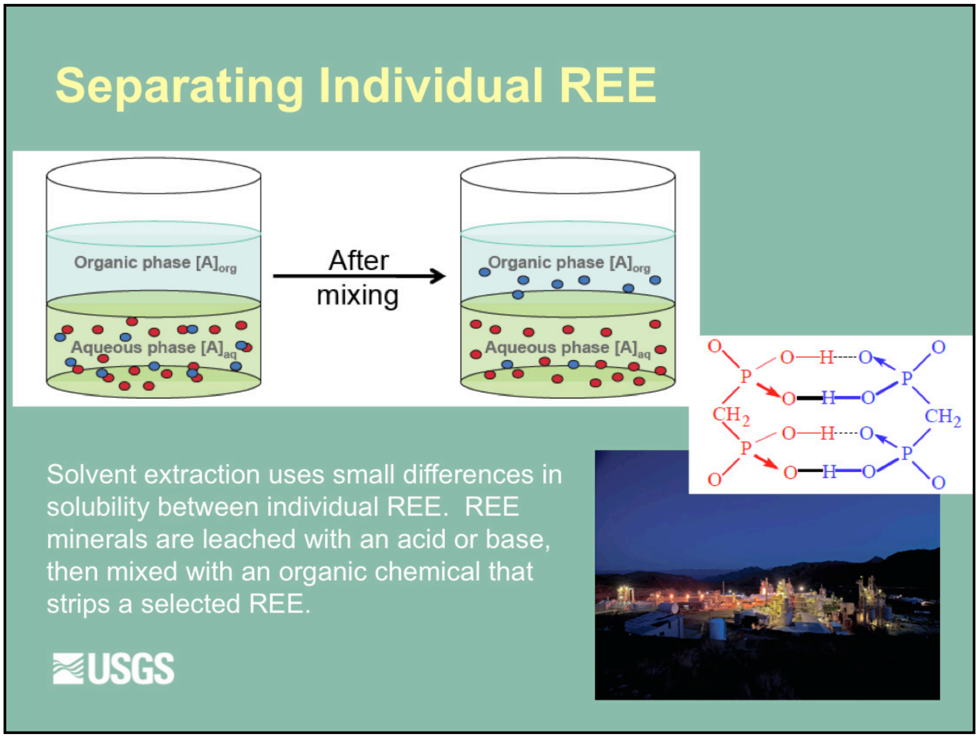


Graphic from Molycorp, Inc.



Graphic from : http://www.thefullwiki.org/Dissolved_air_flotation.

Image from:
http://www3.imperial.ac.uk/newsandeventspggrp/imperialcollege/newssummary/news_23-5-2008-10-37-3?newsid=36894.



Graphics from John Klaehn and Mark Ogden, Department of Energy, Idaho National Laboratory and John Hyrn, Department of Energy, Argonne National Laboratory. Photo of Mountain Pass, California processing plant from Molycorp, Inc.

REE: rare earth elements.

Cost to Produce REO

Reported Operating Costs at Full Production

Operation	Operating Cost USD/kg TREO	Source
Mountain Pass	2.77	Molycorp
China	5.58	Molycorp
Mount Weld	7.00	Molycorp
Nechalacho	3.70*	Avalon Rare Metals
Strange Lake	*0.51***	Quest Rare Minerals

*Calculated from data reported in preliminary economic assessment.
**Calculated from data reported in a preliminary economic assessment after deducting co-product revenue from costs.

USGS

Sources:

Molycorp: A Molycorp, Inc., corporate presentation as of January 2011 accessed June 14, 2011 at :

http://www.slideshare.net/RareEarthsRareMetals/molycorp-corporate-presentation-jan-2011.

Avalon Rare Metals: Bakker, F., and others, March 13, 2011, Technical report on the Nechalacho deposit, Thor Lake Project, Northwest Territories, Canada, prepared by Avalon Rare Metals, Inc., NI 43-101 report.

Quest Rare Minerals: Mclaughlin, M., and others, September 24, 2010, Preliminary economic assessment on the Strange Lake B Zone, Quebec, by Wardrop for Quest Rare Minerals, Ltd., NI 43-101 Report.

The USGS cannot verify the accuracy of these operating cost estimates.

Principal Operating Costs

- **Reagents** – Chemicals used to leach REE from concentrates, usually sulfuric or hydrochloric acid
- **Power** – Electrical power required for mineral processing operations
- **Fuel** – Diesel fuel used for blasting and for operating mine equipment
- **Common Element:** Cost of energy

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Based on reviews of preliminary economic assessments and feasibility studies for rare earth elements (REE) mining projects.

Cost to Develop a New REO Mine

Operation	Capital Cost USD millions	Capital Cost USD per metric t REO capacity
Mount Weld	566	71,000
Nolans Bore*	499	23,000
Nechalacho*	895	45,000
Strange Lake*	548	55,000
Kvanefjeld*	2,310	62,000
Bear Lodge**	87	?
Mountain Pass	681	17,000

Exchange rates used: AUD:USD 1.0616:1; CAD:USD 1.0286:1.
*Operation with significant co-product production.
**Capital cost for mine and flotation plant only.

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Estimated capital costs as reported by the companies that are developing or studying the feasibility of developing these rare earth elements deposits. I have calculated the capital cost per unit capacity using planned output capacities as reported by these firms. USD: United Stated Dollar. AUD: Australian Dollar. CAD: Canadian Dollar. REO: rare earth oxides.

Time to Develop a New Mine United States

- 14 major metal mines started production in the USA since 2000
- Minimum time from permit application to commercial production was six years
- Maximum time was 23 years
- Average around 10 years
- Excludes pre-permitting exploration, environmental baseline studies, and feasibility studies

USGS

Results of research by author as reported in Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, D., 2010, The principal rare earth elements deposits of the United States, A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220 . The report can be obtained at: http://pubs.usgs.gov/sir/2010/5220/.

Time to Develop a New Mine Elsewhere

- Have not yet done a detailed analysis of lead times for mines in other countries
- Nolans Bore, Australia – Plans to submit its permit application this year and start production later this year with full commercial production by end 2012
- Projects in northern Canada constrained by short exploration seasons and logistical difficulties

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See Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, D., 2010, The principal rare earth elements deposits of the United States, A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220 for an analysis of the time required to develop a new nickel laterite mine outside of the United States as a situation comparable in complexity to developing a rare earth elements mine outside of the United States. The report can be obtained at: http://pubs.usgs.gov/sir/2010/5220/.

Scenario Analysis Future REO Capacity

Country	Operation	2011	2012	2013	2014	2015-2016
Australia	Dubbo	0	0	3,800	3,800	3,800
	Mount Weld	11,000	22,000	22,000	22,000	22,000
	Nolans Bore	0	20,000	20,000	20,000	20,000
Canada	Nechalacho	0	0	0	0	8,000
	Strange Lake	0	0	0	0	10,000
Greenland	Kvanefjeld	0	0	0	0	37,000
India	Chavara	2,700	2,700	2,700	2,700	2,700
Malaysia	Ipoh	450	450	450	450	450
Russia	Lovozero	3,000	3,000	3,000	3,000	3,000
South Africa	Steenkampskraal	0	0	5,000	5,000	5,000
United States	Bear Lodge	0	0	0	0	10,000
	Mountain Pass	3,000	19,050	40,000	40,000	40,000
Total:		20,150	67,200	96,950	96,950	161,950

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An example of a scenario analysis for future rare earth oxides (REO) supplies as completed by the author. Here, the projected supply from sources outside of China is examined. There are many assumptions made to complete this kind of analysis which must be considered when using these figures. If these assumptions prove incorrect, the projected scenarios may not be realized. Figures shown in red have a significant risk of not being realized by the times indicated due to uncertainties in obtaining governmental approvals, financing, construction timeframes, and whether, once built, a mine will perform as planned. Capacity figures (supply) are as reported by the companies that are developing or studying the feasibility of developing the rare earth elements deposits shown.

Scenario Analysis REO Supply

	2011	2012	2013	2014	2015-2016
			Supply		
China	115,000	95,000	95,000	95,000	95,000
ROW Max	20,000	67,000	97,000	97,000	162,000
ROW Min	9,000	47,000	68,000	68,000	68,000
World Max	135,000	162,000	192,000	192,000	257,000
World Min	124,000	142,000	163,000	163,000	163,000
			Demand		
Demand Max	140,000	150,000	170,000	190,000	210,000
Demand Min	130,000	130,000	150,000	170,000	190,000

Major uncertainties include Chinese production, scheduling of new capacity after 2014, and future demand for REO.

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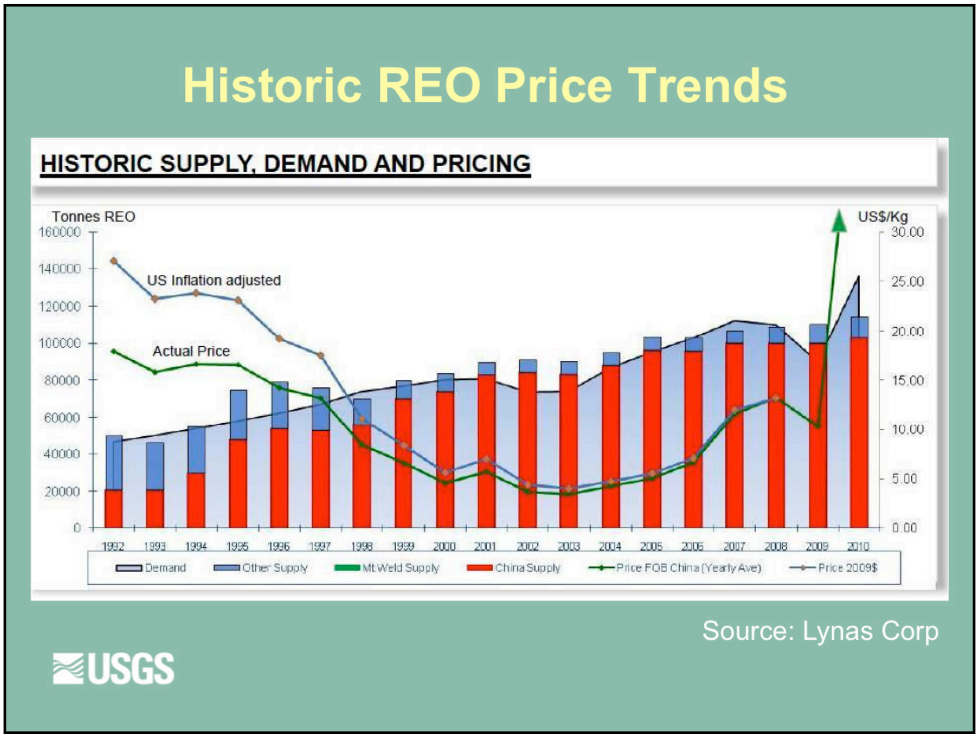
An example of a scenario analysis for future rare earth oxides (REO) supplies as complete by the author. Here, projected global supplies, including those in China, are examined along with global demand. There are many assumptions made to complete this kind of analysis which must be considered when using these figures. If these assumptions prove incorrect, the projected scenarios may not be realized. These particular scenarios suggest a realistic chance of a sufficient surplus in capacity by 2015–2016 to meet projected demand with significant price competition between producers. The most uncertain figures are those for projected demand, which are estimated by IMCOA (Industrial Minerals Co. of Australia). Supply figures (supply) for ROW are as reported by the companies that are developing or studying the feasibility of developing the rare earth elements deposits shown in the previous slide. Data for Chinese supply are based on Chinese production quotas assuming that illegal Chinese production and exports will not be a factor in 2012 and that production quotas will be maintained at the 2012 rate.



This, or a similar graph is shown in most investor presentations by Lyans Corp. The most recent version (5/2011) can be found at:

http://www.lynascorp.com/content/upload/files/Presentations/Investor_Presentation_May_2011.pdf.

The Raventhorpe story can be found on Wikipedia: http://en.wikipedia.org/wiki/Ravensthorpe_Nickel_Mine.

Image is from:

http://www.watoday.com.au/business/bhp-sells-ravensthorpe-mine-for-376-million-20091209-kio7.html.

Conclusions

- REE will continue to find increasing use due to their unique properties.
- There is a realistic possibility around 2015–2016 of sufficient REE capacity to meet demand under conditions of healthy price competition.
- REE supplies will be tight and prices high for a few years.
- There is significant downside risk that newly developed mines will not perform as planned.

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Location of principal rare earth elements deposits in the United States. See Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, D., 2010, The principal rare earth elements deposits of the United States, A summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220 for more information on these deposits and associated resources. The report can be obtained at: http://pubs.usgs.gov/sir/2010/5220/.

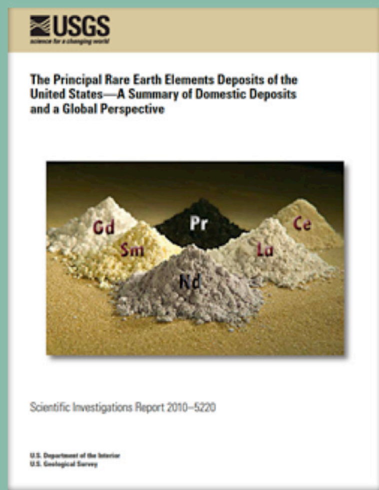
USGS REE Resources & Activities

- NMIC REE Page http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/
- NMIC REE Specialist
  Dan Cordier dcordier@usgs.gov
  (703) 648-7723
- Minerals at Risk and For Emerging Technologies Project (ends this year)
- Future Project?

USGS

Basic sources of information on rare earth elements (REE) at the U.S. Geological Survey.

USGS REE Publications



The Principal Rare Earth Elements Deposits of the United States

http://pubs.usgs.gov/sir/2010/5220/

USGS

This recent USGS publication reviews the geology and resource status of domestic rare earth elements (REE) deposits in a global context.