ME551/GEO551 Geology of Industrial Minerals Spring 2018

Commodities, Part 4

Nepheline Syenite, Silica, Niobium, Zeolites, Zircon, REE

Safety

Reminders

- Midterms
- April 13 NMGS Spring Meeting
- April 14 Field trip
- April 28 AIPG meeting and Field trip in afternoon (perlite mine or carbonatites)
- Commodity presentation in April
- Research Projects presentations April 30
- Finals, Project written report due May 4
- No class May 7

Field trip schedule, Saturday, April 14

- Leave Socorro at 7:30
- Monticello Point diatomite mine (inactive)
- St. Cloud zeolite mine (active but we will not get an official mine tour)
- Lunch at Cuchillo (Bring your own lunch), visit museum
- Kline clay mine
- Taylor Creek tin deposits (if time)
- Home at Socorro 6 PM

Nepheline syenite

Nepheline syenite

- Light-colored, silica-deficient feldspathic igneous rock
- Sodium and potassium feldspars
- Nepheline, no quartz
- Not mined in US but in Canada

Nepheline syenite—properties

- In glass, alumina from nepheline syenite improves product hardness, durability, and resistance to chemical corrosion
- In ceramics, nepheline syenite is used as a flux, melting at an early stage in the firing process and forming a glassy matrix that bonds together the other components of the system

Nepheline syenite

- Alumina acts as a matrix of stabilizser, enhancing the workability of molten glass, and increasing the resistance for scratching, breaking and chemical protection
- Alkali acts as a flux agent, lowering the melting temperature of the batch (no need for soda ash)

Uses

- Glass
- Ceramics
- Fillers, extenders, paint, coatings, roofing granules
- Dimension stone, aggregate, abrasive
- Alumina source
  - Russia produces most of its alumina from nepheline syenite

Table 3. Production of nepheline syenite, by country, t

Year	Russia	Canada	Norway	Turkey	South Africa*
1980	na†	599,699	217,000	na	na
1981	na	587,565	223,000	na	na
1982	na	552,838	224,000	na	na
1983	na	523,249	219,565	na	na
1984	na	520,640	225,731	na	na
1985	na	467,186	227,465	na	na
1986	na	467,491	218,421	na	na
1987	na	506,415	240,000	na	na
1988	na	539,835	287,000	na	na
1989	na	555,728	na	6,000	na
1990	na	na	306,000	6,000	na
1991	na	486,000	292,000	6,000	20,966
1992	1,500,000	566,000	340,000	6,000	na
1993	1,390,000	549,000	315,000	6,000	na
1994	1,500,000	602,000	279,000	18,000	98,667
1995	1,500,000	616,000	294,000	35,000	145,459
1996	1,300,000	606,000	300,000	na	137,706
1997	940,000	647,000	310,000	114,201	114,201
1998	889,000	636,000	319,835	11,500	104,000
1999	772,000	676,000	304,592	na	82,000
2000	814,000	717,000	330,000	na	na
2001	na	734,000	330,362	na	na
2002	na	724,000	330,461	na	na

Adapted from Guillet 1994; Bolger 1995; Levine 1995, 1996; Minister of Industry 1999, 2001; Levine and Wallace 2000; British Geological Survey 2002; Gurmendi 2002; Kuo 2002; Natural Resources of Canada 2003; Taylor et al. 2003; Chapman et al. 2004.

* Production from South Africa was for crushed and broken stone.

† na = not available.

Table 5. Comparison of chemical compositions of nepheline syenite, %

Oxide	Khibiny, Russia	York River (Nepheline Gneiss), Ontario	Obedjiwan, Quebec	Mount Copeland, British Columbia	Iivaara (Ijolite), Finland	Loch Borolan, Scotland	Norra Karr, Sweden	Jabal Sawda, Saudi Arabia	Jabal Abu Khuruq, Egypt
SiO_2	54.01	41.73	54.65	56.9	46.15	48.19	56.37	50.3	63.49
TiO_2	1.20	0.29	1.07	0.55	0.38	1.75	0.01	0.07	0.03
Al_2O_3	21.05	27.48	20.91	21.0	15.7	18.52	24.95	25.8	20.56
Fe_2O_3	2.60	1.84	2.38	2.6	6.59	4.51	0.31	1.39	1.2
FeO	1.80	4.52	3.79	2.6	na*	1.68	0.20	0.46	na
MgO	0.77	1.24	1.11	0.7	5.52	1.12	0.07	0.18	0.18
CaO	1.80	6.78	0.56	1.6	14.16	10.29	0.25	1.46	0.64
K_2O	5.30	3.16	7.21	6.1	2.61	8.05	5.20	4.48	5.99
Na_2O	9.50	11.05	6.25	7.5	7.24	3.44	11.73	9.38	7.48
MnO	0.17	trace	0.06	0.24	0.18	na	0.05	0.06	0.24
P_2O_5	0.09	0.14	0.05	0.02	0.77	na	0.01	0.03	0.04
CO_2	na	0.93	0.64	0.2	na	na	na	na	na
Loss on ignition (LOI)	1.14	0.52	1.14	0.5	0.93	3.45	0.1	5.93	na
Total	99.43	99.68	99.82	100.51	100.23	101.00	99.25	99.54	99.85

Adapted from Shand 1939; Baragar 1953; Tilley 1953; Lehijarvi 1960; Currie 1976; Liddicoat, Ramsay, and Hedge 1985; Hosterman, Patterson, and Good 1990; Landoll, Foland, and Henderson 1994; *Industrial Minerals* 2003.

* na = not available.

Table 13. Typical glass-grade compositions of nepheline syenite, wt %

Chemical Composition	Unimin Canada A Grade	Unimin Canada B Grade	North Cape	
SiO_2	60.2	60.1	55.9	
Al_2O_3	23.5	23.4	24.2	
Fe_2O_3	0.08	0.35	0.1	
MgO	trace	trace	trace	
CaO	0.3	0.3	1.3	
K_2O	5.1	4.9	9.0	
Na_2O	10.6	10.5	7.9	
P_2O_5			0.1	
LOI	0.4	0.3	1.0	
Sieve Analyses, %	**U.S. Sieve No.**	**U.S. Sieve No.**	**Tyler Sieve No., %**	
On 25 mesh	0.0	0.0	On 28 mesh	0.0
30	0.1	0.1	32	0.1
40	14.5	14.0	53	4.9
50	48.0	46.0	48	30.0
100	86.0	84.0	65	52.0
200	98.0	97.2	200	89.0
Pan	2.0	2.8	Pan	11.0

Adapted from Minnes, Lefond, and Blair 1983; Guillet 1994.

Table 14. Chemical analyses and physical properties of products from Nephton, Ontario

Properties	MATRIX Glassy Phase Promoters (Fiberglass) 131	MATRIX Glassy Phase Promoters (Fiberglass) 134	SPECTRUM Ceramic Fluxes
SiO_2, wt %	60.00	59.70	60.20
Al_2O_3, wt %	23.40	23.40	23.60
Fe_2O_3, wt %	0.1	0.34	0.08
CaO, wt %	0.44	0.56	0.35
MgO, wt %	0.02	0.03	0.02
Na_2O, wt %	10.30	10.30	10.50
K_2O, wt %	5.20	5.10	4.80
LOI, %	0.51	0.61	0.42
Free-silica content	<0.1%	<0.1%	<0.1%
pH	10.1	10.1	10.1
Melting point	1,868°F/1,020°C	1,868°F/1,020°C	1,868°F/1,020°C
Bulk density, loose	83–87 lb/ft^3	83–87 lb/ft^3	38–55 lb/ft^3
Specific gravity	2.61 g/cm^3	2.61 g/cm^3	2.61 g/cm^3

Adapted from Unimin Corp.

Table 1. Major worldwide nepheline syenite mines and deposits

Mine	Company	Mining Method	Startup Date	Capacity, *tpy*	Comments
Khibiny, Kola, Russia	Apatit Production Association	3 open pit, 2 underground	1929	1,500,000	Apatite with by-product nepheline syenite produced
Lovozero massif, Kola, Russia	na*	na	na	na	By-product of REEs production from syenite, urtite
Kiya-Shaltyr and Goryachegorsk, Siberia	na	na	na	na	Aluminum production from urtite and ijolite
Blue Mountain, Havelock, Ontario	Unimin Corporation	Open pit	1955	700,000	Crush, magnetic separation, sizing, fine grinding
Blue Mountain, Nephton, Ontario	Unimin Corporation	Open pit	1936	Included with Havelock Mine	Crush, magnetic separation, sizing, fine grinding
North Cape, Stjernoya, Norway	North Cape Minerals AS (owned by Unimin)	Underground	1961	330,000	Nepheline syenite
Fourche Mountain, Arkansas, United States	3M Company	Open pit	1947		Roofing granules, construction aggregates
Canaan, Rio de Janeiro, Brazil	Unimin Corporation		1980	134,000	Litchfieldite
Sichuan, Shuiye, Anyang, Henan Province, China	Fineton Industrial Minerals Ltd.	Under development	1994	35,000	100,000 t of ore
Bursa Orhaneli, Turkey	Matel Hammade San ve Tic AS	Open pit	na	na	40 Mt of nepheline syenite
South Africa		Quarries	na	na	Crushed stone, nepheline syenite

Adapted from Woolley 1987; *Industrial Minerals* 2003.

* na = not available.

Figure 1. Nepheline syenite mines and deposits worldwide

Silica

Silica

- Quartz
- Citrine—yellow to brown color, similar to topaz
- Tridymite
- Cristobalite
- Coesite
- Stishovite
- Melanophlogite
- Lechatelierite
- Agate—banded, multicolored
- Flint—gray to black, opaque
- Chalcedony—fine grained chert
  - Carnelian—red to reddish brown

Silica—introduction

- SiO_2
- Industrial sand and gravel
- Silicon
- Quartz crystals
- Special silica stone products
- Tripoli (microcrystalline silica)
  - Rottenstone
- Novacullite (whetstones, microcrystalline silica)
- Spiculite

Table 2.—Common products containing 0.1% or more crystalline silica		
At Work	At Home	Everywhere
(in the process of manufacturing or using the following items)	(as a consumer of the following items)	(exposure could be on the job or at home)
Asphalt filler-is usually composed of quartz and stone aggregate. Bricks-have a high concentration of sand. Contains quartz and possibly cristobalite. Concrete-like asphalt filler, contains stone aggregate. Jeweler's rouge-contains cryptocrystalline silica. Jewelry and crystals-amethyst and quartz are crystalline silica. Mortar-contains sand. Municipal water filter beds-are constructed from both sand (crystalline silica) and diatomite (amorphous silica). Plaster-is made from gypsum but sometimes contains silica. Plastic in appliances-can contain clay, talc, crushed limestone, and silica as fillers. Rofing granules-are made from sand and aggregate. Wallboard-is made from gypsum.	Art clays and glazes-contain clay, and sometimes crystalline silica. Cleansers-contain pumice and feldspar as abrasives. Cosmetics-contain talc and clay. Pet litter-is composed priarily of clay. Talcum powder-contains talc. Unwashed root vegetables-(such as potatoes and carrots) are coated with soil, which has a high crystalline silica content. Pharmaceuticals-contain clays and talc as filler. Often the dosage of active ingredient in a medication is so minute that filler (listed as an inert ingredient) must be added to make the substance manageable to take. Sand-is crystalline silica. Beach sand, play sand for sandboxes, and the sand used on golf courses are no different than industrial sand used for construction, in sandblasting, or on icy roads. All are largely crystalline silica.	Caulk and putty-contain clay, which can have a low to moderate crystalline silica content, as a filler. Dust-(whether household or industrial) contains crystalline silica. Fill dirt and topsoil-contain sand. Because the crystalline silica content of common soil is so high, agricultural workers represent the occupational group most at risk for exposure to respirable crystalline silica. Foam in furniture and on rug backings-contain talc and silica. Paint-contains clay, talc, sand, and diatomite. Paper and paper dust contain kaolin and clay.

http://minerals.usgs.gov/minerals/pubs/commodity/silica/780292.pdf

Industrial sand and gravel—introduction

- Silica
- Silica sand
- Quartz sand
- Sand and gravel with a high SiO_2 content

Industrial sand and gravel—uses

- Glassmaking sand, 38%
- Foundry sand, 22% (molds, cores, castings)
- Abrasive sand, 5%
- **Hydraulic fracturing sand**, 5%
- 30% for other uses (flux)

Not more than 0.6% iron oxide

TABLE 1
SALIENT U.S. SILICA STATISTICS 1/

		1997	1998	1999	2000	2001
Industrial sand and gravel: 2/						
Sold or used:						
Sand:						
Quantity	thousand metric tons	26,300	26,400	26,900	26,800	26,900
Value	thousands	$485,000	$491,000	$510,000	$532,000	$559,000
Gravel:						
Quantity	thousand metric tons	2,170	1,790	1,940	1,660	1,060
Value	thousands	$26,300	$22,200	$28,400	$24,400	$17,600
Total:						
Quantity	thousand metric tons	28,500	28,200	28,900	28,400	27,900
Value	thousands	$511,000	$513,000	$538,000	$556,000	$576,000
Exports:						
Quantity	thousand metric tons	980	2,400	1,670	1,660	1,540
Value	thousands	$134,000	$148,000	$133,000	$179,000	$163,000
Imports for consumption:						
Quantity	thousand metric tons	39	44	211	247	172
Value	thousands	$3,200	$2,750	$5,590	$11,800	$11,000
Processed tripoli: 3/						
Quantity	metric tons	81,300	79,600	84,900	72,000	60,500
Value	thousands	$16,400	$16,900	$20,200	$15,900 e/	$15,000
Special silica stone:						
Crude production:						
Quantity	metric tons	843	649	697	553	705
Value	thousands	$224	$184	$183	$158	$234
Sold or used:						
Quantity	metric tons	445	438	475	312	393
Value	thousands	$2,560	$3,440	$3,060	$4,610	$4,040
Electronic and optical-grade quartz crystals, production:						
Mine	thousand kilograms	450	--	--	--	--
Cultured	do.	355	185	192	189	W

e/ Estimated. W Withheld to avoid disclosing company proprietary data. -- Zero.
1/ Data are rounded to no more than three significant digits; may not add to totals shown.
2/ Excludes Puerto Rico.
3/ Includes amorphous silica and Pennsylvania rottenstone.

USGS Commodity Reports

Industrial sand and gravel—uses

- Glassmaking (high specifications, no Fe)
- Foundry (98% SiO_2, low CaO, MgO, grain size and shape)
- Abrasive, blasting sand (clean metal, concrete' angular shape)
- Hydraulic fracturing (frac) applications (well rounded)
- Ceramics
- Chemicals
- Ground silica (fillers, extenders; bright, reflective)
- Filtration (pure)
- Roofing granules
- Flux
- Optical fiber

Industrial sand and gravel—regions

TABLE 2
INDUSTRIAL SAND AND GRAVEL SOLD OR USED IN THE UNITED STATES, BY GEOGRAPHIC REGION 1/

	2000				2001			
Geographic region	Quantity (thousand metric tons)	Percentage of total	Value (thousands)	Percentage of total	Quantity (thousand metric tons)	Percentage of total	Value (thousands)	Percentage of total
Northeast:								
New England	104	(2/)	W	W	138	(2/)	W	W
Middle Atlantic	2,400	8	$51,500	9	2,160	8	$49,600	9
Midwest:								
East north-central	10,100	35	170,000	31	9,960	36	170,000	29
West north-central	1,420	5	28,700	5	1,480	5	31,200	5
South:								
South Atlantic	4,270	15	92,400	17	4,090	15	86,300	15
East south-central	2,260	8	43,100	8	2,240	8	43,200	8
West south-central	4,440	16	96,400	17	4,330	16	118,000	20
West:								
Mountain	1,360	5	22,600	4	1,380	5	24,100	4
Pacific	2,090	7	51,300	9	2,140	8	54,600	9
Total	28,400	100	556,000	100	27,900	100	576,000	100

W Withheld to avoid disclosing company proprietary data; included with "Middle Atlantic."
1/ Data are rounded to no more than three significant digits; may not add to totals shown.
2/ Less than 1/2 unit.

Industrial sand and gravel—regions

FIGURE 1
PRODUCTION OF INDUSTRIAL SAND AND GRAVEL IN THE UNITED STATES IN 2001, BY GEOGRAPHIC DIVISION

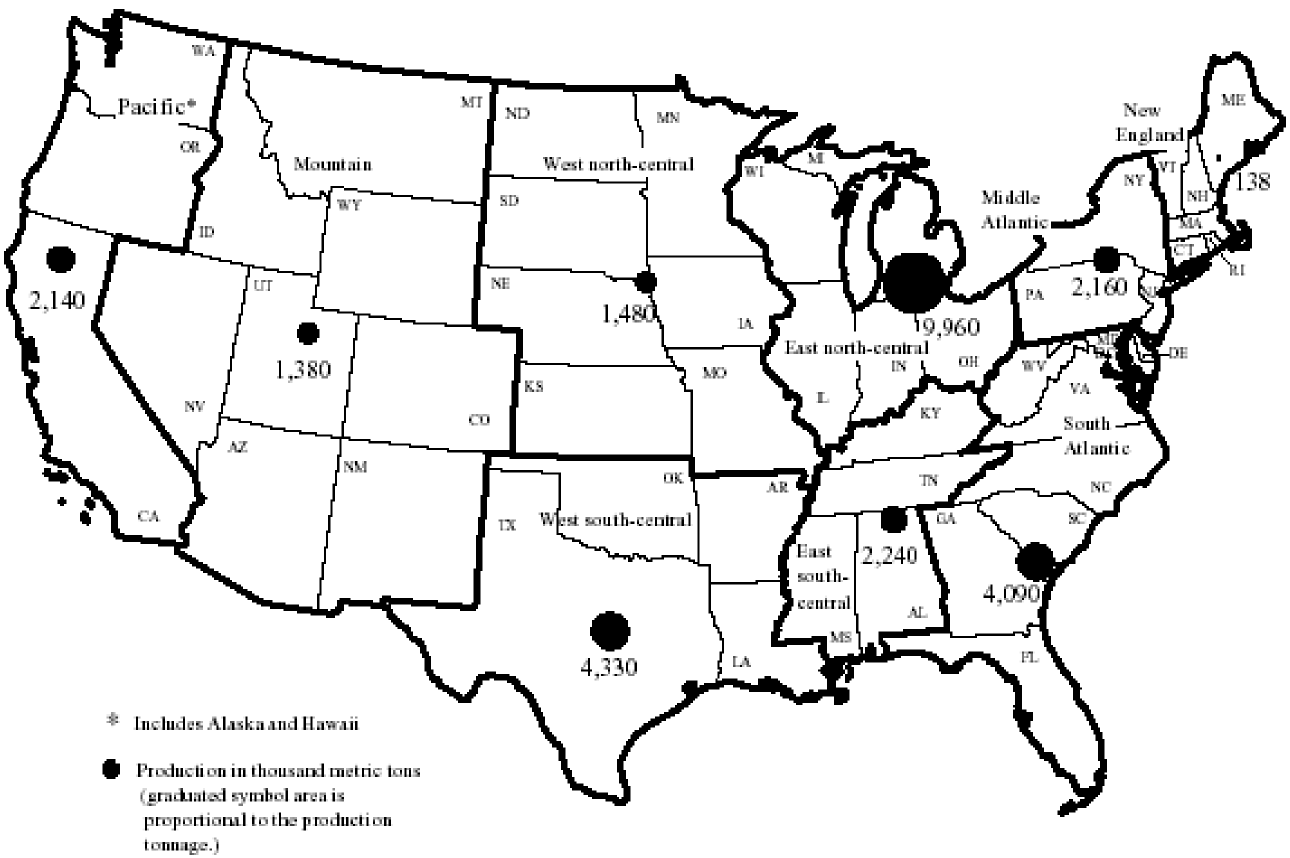


TABLE 6
INDUSTRIAL SAND AND GRAVEL SOLD OR USED BY U.S. PRODUCERS IN 2001, BY MAJOR END USE 1/

	Northeast			Midwest			South		
Major use	Quantity (thousand metric tons)	Value (thousand dollars)	Value 3/ (dollars per metric ton)	Quantity (thousand metric tons)	Value (thousand dollars)	Value 3/ (dollars per metric ton)	Quantity (thousand metric tons)	Value (thousand dollars)	Value 3/ (dollars per metric ton)
Sand:									
Glassmaking:									
Containers	W	W	18.70	1,200	13,800	11.47	1,570	25,100	15.99
Flat (plate and window)	W	W	17.14	1,290	14,000	10.92	1,730	28,100	16.21
Specialty	W	W	26.23	W	W	16.60	311	7,080	22.77
Fiberglass (unground)	--	--	--	397	5,520	13.88	W	W	16.18
Fiberglass (ground)	--	--	--	W	W	46.55	W	W	45.96
Foundry:									
Molding and core	W	W	18.75	4,850	65,900	13.58	627	10,600	16.93
Molding and core (ground)	--	--	--	W	W	80.66	W	W	97.78
Refractory	W	W	27.86	W	W	23.74	W	W	34.36
Metallurgical:									
Silicon carbide	--	--	--	W	W	18.91	--	--	--
Flux for metal smelting	--	--	--	--	--	--	W	W	5.38
Abrasives:									
Blasting	36	2,800	78.51	205	6,080	29.61	1,070	30,300	28.26
Scouring cleansers (ground)	W	W	63.80	W	W	10.92	W	W	116.59
Sawing and sanding	W	W	22.33	--	--	--	--	--	--
Chemicals (ground and unground)	W	W	20.60	W	W	13.46	315	8,920	28.31
Fillers (ground), rubber, paints, putty, etc.	W	W	13.43	146	10,200	69.47	W	W	108.77
Whole grain fillers/building products	221	6,710	30.29	515	12,700	24.56	1,120	21,100	18.95
Ceramic (ground), pottery, brick, tile, etc.	W	W	56.86	W	W	74.05	116	5,680	48.90
Filtration:									
Water (municipal, county, local, etc.)	34	1,430	41.77	73	3,180	43.71	186	5,410	29.06
Swimming pool, other	31	1,330	43.13	W	W	79.48	47	686	14.66
Petroleum industry:									
Hydraulic fracturing	--	--	--	1,030	33,900	32.98	W	W	54.97
Well packing and cementing	--	--	--	W	W	730.40	W	W	65.77
Recreational:									
Golf course (greens and traps)	W	W	16.35	254	3,620	14.24	415	4,430	10.65
Baseball, volleyball, play sand, beaches	72	1,260	17.64	W	W	34.98	W	W	10.29
Traction (engine)	33	603	18.10	79	921	11.64	47	686	14.66
Roofing granules and fillers	W	W	24.12	W	W	16.22	129	2,520	19.58
Other (ground silica)	W	W	49.10	130	7,510	57.71	442	27,000	61.15
Other (whole grain)	1,870	35,400	19.05	1,160	22,100	19.04	1,840	57,200	29.15
Total or average	2,290	49,600	21.61	11,300	199,000	17.60	9,970	235,000	23.57

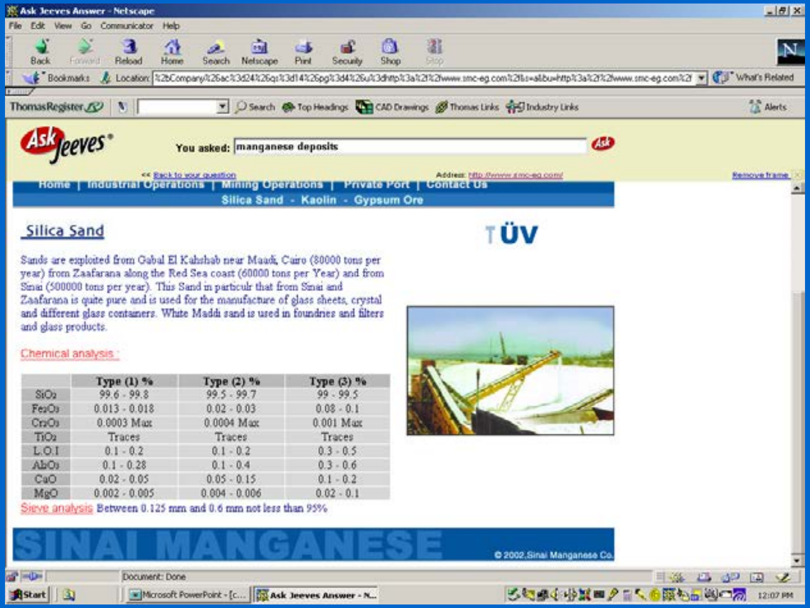
See footnotes at end of table.

Industrial sand and gravel—geology

- Sedimentary, especially where multiple cycles of erosion and deposition has upgraded the deposits
  - What geologic environments are we looking at?

Silica sand—geology

- White Maddi sand is used in foundries, filters, and glass products, Gabal El Kahshab near Maadi, Cairo



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Silica Sand - Kaolin - Gypsum Ore

Silica Sand

Sands are exploited from Gabal El Kahshab near Maadi, Cairo (80000 tons per year) from Zaafarana along the Red Sea coast (60000 tons per Year) and from Sinai (500000 tons per year). This Sand in particulr that from Sinai and Zaafarana is quite pure and is used for the manufacture of glass sheets, crystal and different glass containers. White Maddi sand is used in foundries and filters and glass products.

Chemical analysis :

	Type (1) %	Type (2) %	Type (3) %
SiO_2	99.6 - 99.8	99.5 - 99.7	99 - 99.5
Fe_2O_3	0.013 - 0.018	0.02 - 0.03	0.08 - 0.1
Cr_2O_3	0.0003 Max	0.0004 Max	0.001 Max
TiO_2	Traces	Traces	Traces
L.O.I	0.1 - 0.2	0.1 - 0.2	0.3 - 0.5
Al_2O_3	0.1 - 0.28	0.1 - 0.4	0.3 - 0.6
CaO	0.02 - 0.05	0.05 - 0.15	0.1 - 0.2
MgO	0.002 - 0.005	0.004 - 0.006	0.02 - 0.1

Sieve analysis Between 0.125 mm and 0.6 mm not less than 95%

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Industrial sand and gravel—substitutions

- For glass, foundry, molding
  - Zircon
  - Olivine
  - Staurolite
  - Chromite sands

FRAC SAND

- A quartz sand of a specific grain size and shape used in the oil industry.
- Mixed with fluid and pumped into oil and gas wells during fracturing operation.
- The sand keeps the fracture opened to unlock the natural gas and oil that is trapped within the shale.
- Name (frac sand)-as a result of its use in the hydraulic fracturing process.
- The best frac sand is almost pure silica with very round, large grains of a uniform size.


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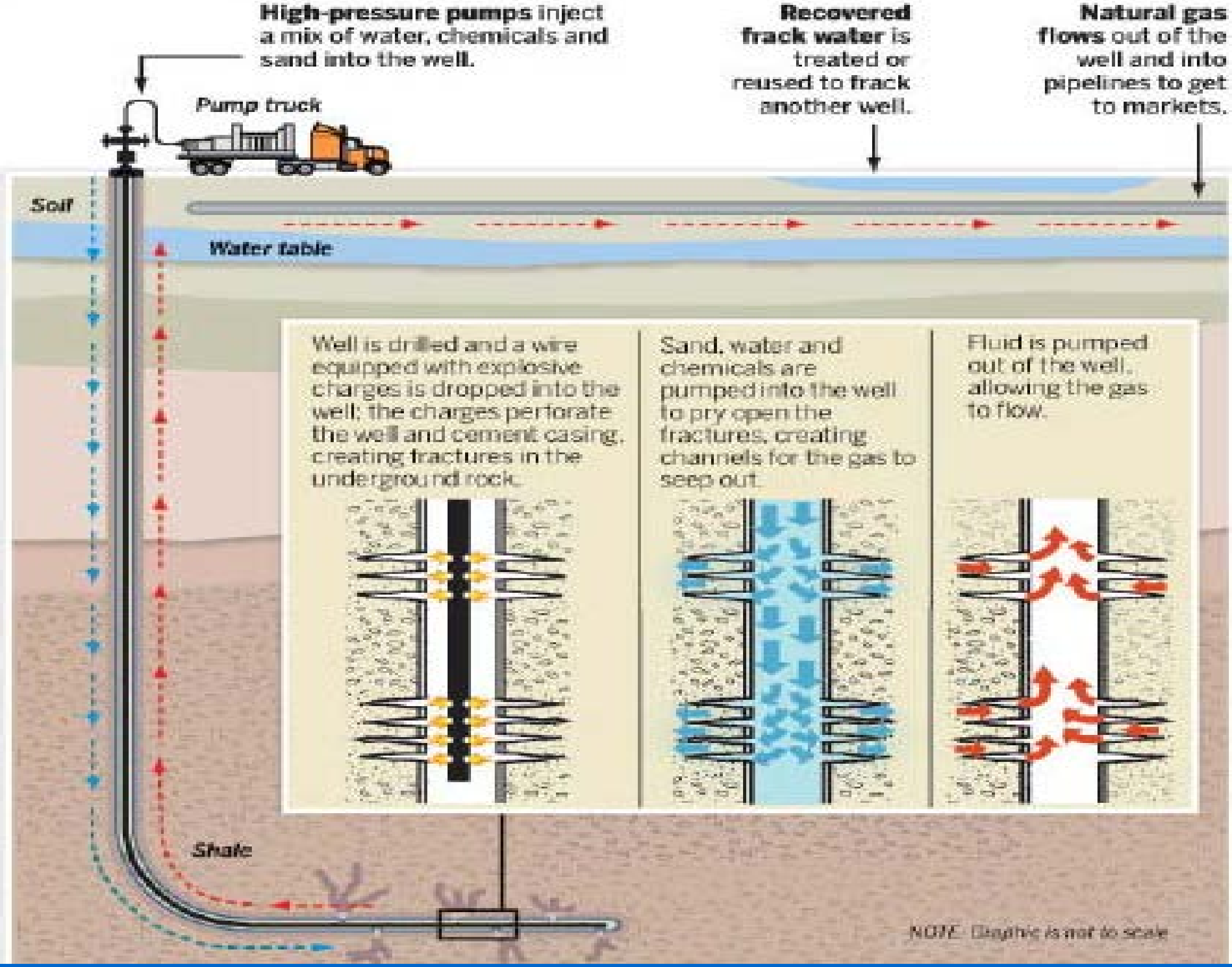
Hydraulic fracturing

Also known as "fracking," it unlocks natural gas from rock that would otherwise be uneconomical to tap. Sand keeps cracks open to allow the gas to escape. The chemicals used in the process have come under fire for potentially polluting air and water.



TYPES AND PROPERTIES

TYPES

1. White Sand (Ottawa or Ontario sand)
2. Brown or Brady Sand (Texas Brown Sand)

GENERAL PROPERTIES

- Silica minerals
- A common size of 20/40
- 40/140 – Also used in the natural gas industry

TYPES AND PROPERTIES

WHITE FRAC SAND

- White in color.
- Silica concentration around 95%.
- Spherical in shape and the size varies from 12 to 270 on the Tyler mesh scale.
- Sustain the openings in the rock layers better than the brown sand.

BROWN FRAC SAND

- Brown or pale yellow in color.
- 99% silica content
- Irregular in shape.

PROPERTIES

- Sizes range from 8 to 100 on the Tyler mesh scale.

USES

- Used by the oil and gas industry during the exploration of new oil and gas reserves.
- For making glass.

GEOLOGIC DESCRIPTION

- Produced from sandstone deposits.
- Large resources throughout the world.
- Resources are locally uneconomic because of its geographic distribution and environmental restrictions.
- Geologically the white frac sand was deposited after the last ice age by glaciers.
- White sand is normally found at the northern part of America and the brown in southern part of America.

GEOLOGIC DESCRIPTION

DOMESTIC PRODUCTION (USA)

- Sand and gravels produced by 68 companies from 116 operations in 33 States was 30 million metric tons.
- In 2011, about 41% of the total sand tonnage (12.3 million Mt) was used as hydraulic fracturing sand.
- Leading States were Illinois, Texas, Wisconsin, Minnesota, Oklahoma, North Carolina, California, and Michigan.

PROCESSING

- Washed or scrubbed to remove silt and clay size particles, carbonate cement, iron coatings and other minerals.

TRANSPORTATION

- Haulage truck
- Railway
- Shipping

Silicon

Silicon—introduction

- Silicon metal and alloys
- Ferrosilicon

Silicon—uses

- ferrous foundry
- steel industries
- aluminum and aluminum alloys
- chemical industry
- semiconductor industry, which manufactures chips for computers from high-purity silicon

Silicon—substitutions

- ferrosilicon
  - aluminum
  - silicon carbide
  - silicomanganese
- semiconductors and infrared
  - gallium arsenide
  - germanium

Silicon—production

Salient Statistics—United States:	**2013**	**2014**	**2015**	**2016**	**2017[e]**
Production:					
Ferrosilicon and silicon metal[1, 2]	392	401	411	384	405
Imports for consumption:					
Ferrosilicon, all grades[1]	157	186	162	155	150
Silicon metal	118	139	140	122	140
Exports:					
Ferrosilicon, all grades[1]	10	9	9	7	10
Silicon metal	38	45	37	60	62
Consumption, apparent:[3]					
Ferrosilicon, all grades[1]	W	W	W	W	W
Silicon metal[2]	W	W	W	W	W
Total	631	670	661	601	625
Price, average, cents per pound:					
Ferrosilicon, 50% Si[4]	103	108	101	83	92
Ferrosilicon, 75% Si[5]	94	98	88	71	83
Silicon metal[2, 5]	122	140	127	91	110
Stocks, producer, yearend:					
Ferrosilicon and metal[1, 2]	25	27	33	27	25
Net import reliance[6] as a percentage of apparent consumption:					
Ferrosilicon, all grades[1]	<50	<50	>50	>50	<50
Silicon metal[2]	<50	<50	<50	<50	<50
Total	39	42	38	36	35

Recycling: Insignificant.

World Production and Reserves:

	Production[6,7] 2016	Production[6,7] 2017
United States	[9]384	405
Bhutan[10]	69	69
Brazil	110	110
Canada	51	51
China	5,000	4,800
France	120	120
Iceland[10]	79	79
India[10]	59	59
Malaysia[10]	82	110
Norway	380	380
Russia	750	750
South Africa	85	85
Spain	81	75
Ukraine[10]	66	61
Other countries	310	280
World total (rounded)	7,600	7,400

Reserves[8]

The reserves in most major producing countries are ample in relation to demand. Quantitative estimates are not available.

Silicon—production

- Norway, 27%
- South Africa, 15%
- Russia, 11%
- Canada, 10%

Quartz crystal

Quartz crystal—introduction

- Hardness 7
- any color
- common mineral
- cultured quartz crystals became important in 1971, no natural production

Quartz crystal—properties

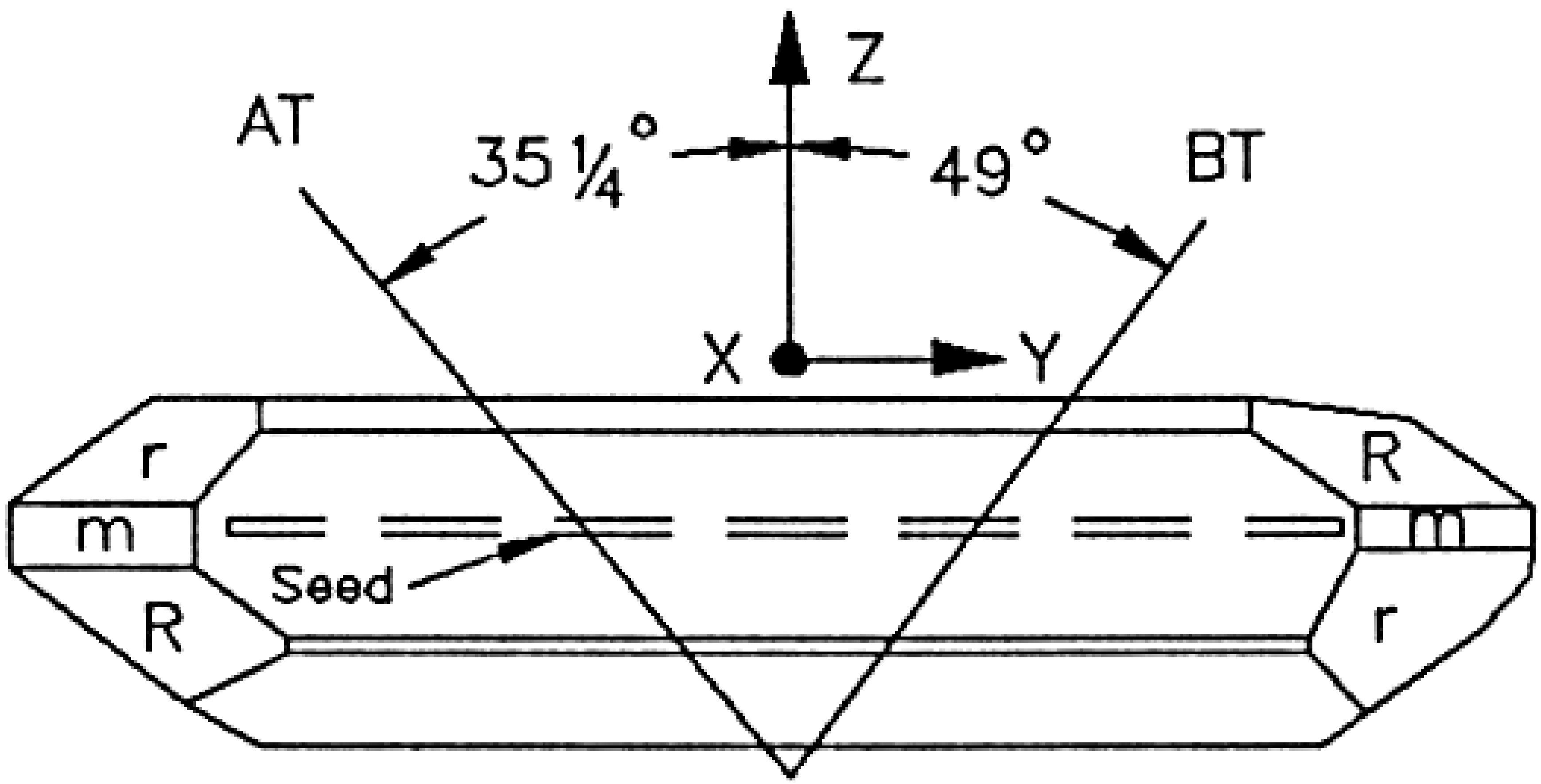
- Piezoelectric effect
- when compressed or bent, it generates a charge or voltage on its surface
- if a voltage is applied, quartz will bend or change its shape very slightly
- hardness
- high electrical resistance
- dimensional stability

Growing quartz crystal

- Process in Germany 50 years ago
- grown in pressure vessels containing quartz dissolved in an aqueous alkaline solution at temperatures of 375 degrees centigrade and pressures of 800 to 2000 atmospheres
- Seed crystals are placed near the top of the container
- nutrient in the form of broken chunks of natural Brazilian quartz (lascas) as a nutrient are placed on the bottom
- Convection currents move dissolved material from the bottom of the chamber to the cooler upper section where it deposits on the seed crystals

http://www.itme.edu.pl/z18/syn...

Figure 3: Cultured Quartz Crystal



http://www.corningfrequency.com/library/qcao.html

Quartz crystal—uses

- single-crystal silica
- Electronic applications
- optical applications
- filters, frequency controls, and timers in electronic circuits
- carvings
- gem stone

Quartz crystal—geology

- Pegmatites
- in Arkansas veins filled cavities or fractures in the Crystal Mountain and Blakely Sandstones
  - 5 feet long and weighing over 500 pounds and clusters up to 15 feet long by 10 feet wide, weighing over 10 tons
  - end of the Ouachita Mountain orogenic cycle in Late Pennsylvanian to Early Permian (Ar/Ar)

Quartz—production

TABLE 11
SALIENT U.S. ELECTRONIC- AND OPTICAL-GRADE QUARTZ CRYSTAL STATISTICS 1/

(Thousand kilograms and thousand dollars)

	1997	1998	1999	2000	2001
Production:					
Mine	450	--	--	--	--
Cultured e/	355	185	192	189	W
Exports (cultured): 2/					
Quantity	74	63	90	74	38
Value	31,100	24,300	25,400	22,800	10,600
Imports (cultured): 2/					
Quantity	63	47	26	31	14
Value	11,700	12,200	11,000	14,300	8,390
Consumption, apparent e/	343	169	128	146	W

e/ Estimated. W Withheld to avoid disclosing company proprietary data. -- Zero.
1/ Data are rounded to no more than three significant digits.
2/ Excludes mounted piezoelectric crystals.

Special silica stone products

Special silica stone products—introduction

- abrasive tools
  - deburring media
  - grinding pebbles
  - grindstones, hones,
  - oilstones
  - stone files
  - tube-mill liners
  - whetstones
- Fillers
- extenders
- flux

Special silica stone products—introduction

- Sandstone
- quartzite
- vein quartz
- silica pebble
- novaculite
- microcrystalline quartz
- speculite
- tripoli
- tripolite or diatomaceous earth
- amorphous silica

Novaculite

- Sedimentary microcrystaline quartz
- homogeneous
- more compact than porous tripoli
- whetstones
- dense, hard, white to grayish-black in color, translucent on thin edges, and has a dull to waxy luster
- resistant to erosion, it forms prominent ridges
- Dev to Miss Novaculite Formation in Ark
  - 250-900 ft thick

Rottenstone

- Common variety of tripoli
- Penn--weathering of siliceous shale

Spiculite

- Siliceous sponge spicules
- replacement of spicule-bearing limestone
- Texas

Tripoli

- 1 to 10 micrometers
- 98% to 99% silica, minor Al and Fe
- white to cream
- brown
- red
- yellow
- abrasive
- diatomaceous earth (different origin)

Tripoli—geology

- alteration of chert, chalcedony, or novaculite, or leaching of highly siliceous limestones
- Paleozoic chert bearing limestones in Arkansas and Oklahoma, Illinois
  - NE Ar cherty limestones of the Boone Formation (Mississippian)
  - Ouachita Mountains leaching of a limy phase within the Upper Division of the Arkansas Novaculite
- Arkansas tripoli is >99% SiO_2

Special silica stone products—source

- Arkansas
- Wisconsin

Special silica stone products—uses

- Craft
- household
- industrial
- leisure uses

Special silica stone products

TABLE 10
U.S. PRODUCERS OF SPECIAL SILICA STONE PRODUCTS IN 2001

Company and location	Type of operation	Product
B&C Abrasives, Inc., Hot Springs, AR	Stone cutting and finishing	Whetstones and oilstones.
Blue Mountain Whetstone Co., Hot Springs, AR	do.	Do.
Buffalo Stone Corp., Hot Springs, AR	Tumbling and sizing novaculite	Metal finishing media deburring media.
Dan's Whetstone Co., Inc., Hot Springs, AR	Stone cutting and finishing	Whetstones and oilstones.
Do.	Quarry	Crude novaculite.
Hall's Arkansas Oilstones, Inc., Pearcy, AR	Stone cutting and finishing	Whetstones and oilstones.
The Kraemer Co., Baraboo, WI	Crushing and sizing	Deburring media.
Do.	Quarry	Crude silica stone.
Norton Company Oilstones:		
Hot Springs, AR	do.	Do.
Littleton, NH	Stone cutting and finishing	Whetstones and oilstones.
Smith Abrasives, Inc., Hot Springs, AR	do.	Do.
Do.	Quarry	Crude novaculite.
Taylor Made Crafts Inc.:		
Hot Springs, AR	Stone cutting and finishing	Whetstones and oilstones.
Pearcy, AR	Quarry	Crude novaculite.

Environmental regulations of quartz

- regulation of crystalline silica
  - hours workers exposure
  - water well monitoring
  - noise and dust control
  - water discharge
  - archaeological surveys
  - carcinogen

Niobium and tantalum

Niobium and tantalum—introduction

- Columbium
- Nb
- found with tantalum Ta

Niobium—uses

- Carbon steels, 33%
- Superalloys, 23%
- Stainless and heat-resisting steels,18%
- High-strength low-alloy steels, 16%
- Alloy steels, 9%
- Other, 1%

Tantalum—uses

- capacitors
  - automotive electronics
  - pagers
  - personal computers
  - portable telephones
- electrical applications

TABLE 4

REPORTED CONSUMPTION, BY END USE, AND INDUSTRY STOCKS OF FERROCOLUMBIUM AND NICKEL COLUMBIUM IN THE UNITED STATES 1/

(Metric tons of contained columbium)

End use	2000	2001
Steel:		
Carbon	1,370	1,300
Stainless and heat-resisting	682	660
Full alloy	(2/)	(2/)
High-strength low-alloy	1,090	1,030
Electric	(2/)	(2/)
Tool	(2/)	(2/)
Unspecified	--	--
Total	3,140	2,990
Superalloys	942	1,230
Alloys (excluding alloy steels and superalloys)	(3/)	(3/)
Miscellaneous and unspecified	10	11
Grand total	4,090	4,230
Stocks, December 31:		
Consumer	NA	NA
Producer 4/	NA	NA
Total	NA	NA

NA Not available. -- Zero.

1/ Data are rounded to no more than three significant digits; may not add to totals shown.

2/ Included with "Steel: High-strength low-alloy."

3/ Included with "Miscellaneous and unspecified."

4/ Ferrocolumbium only.

USGS Commodity Summaries

Niobium—uses (USGS OF01-348)

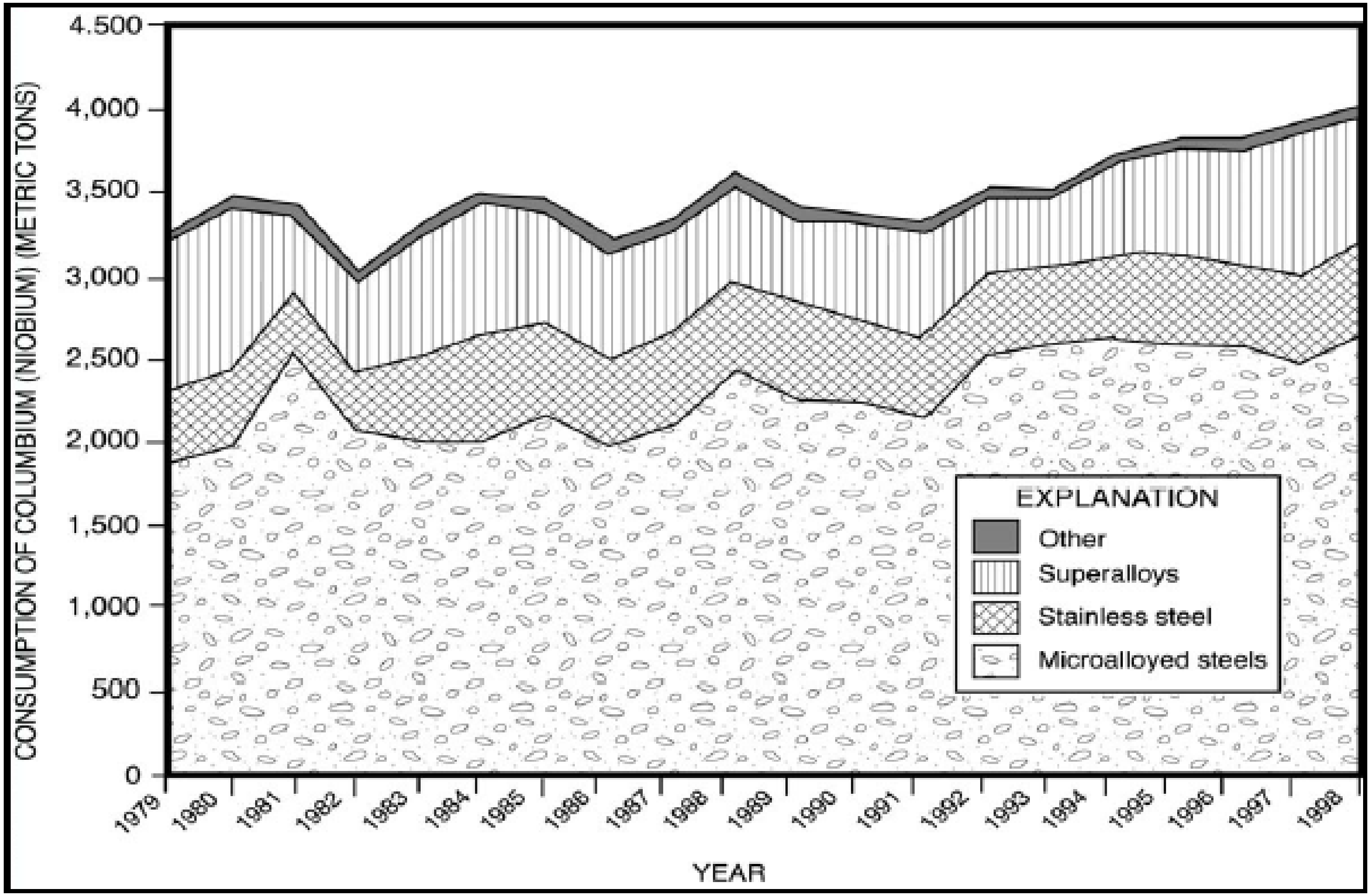


Figure 2. U.S. columbium end-use patterns, 1979-98, in metric tons contained columbium.

Production—niobium

Salient Statistics—United States:	2013	2014	2015	2016	2017[e]
Production, mine	—	—	—	—	—
Imports for consumption[e, 1]	8,580	11,100	8,520	9,580	11,300
Exports[e, 1]	435	1,110	1,430	841	1,500
Government stockpile releases[2]	—	—	—	—	—
Consumption:[e]					
Apparent[3]	8,140	10,000	7,080	8,740	9,800
Reported[4]	7,500	8,210	7,510	7,370	6,510
Unit value, ferroniobium, dollars per kilogram[5]	27	26	24	21	18
Net import reliance[6] as a percentage of apparent consumption	100	100	100	100	100

Recycling: Niobium was recycled when niobium-bearing steels and superalloys were recycled; scrap recovery, specifically for niobium content, was negligible. The amount of niobium recycled is not available, but it may be as much as 20% of apparent consumption.

World Mine Production and Reserves:

	Mine production 2016	Mine production 2017[e]	Reserves[9]
United States	—	—	—
Brazil	57,000	57,000	4,100,000
Canada	6,100	6,000	200,000
Other countries	800	800	NA
World total (rounded)	63,900	64,000	>4,300,000

USGS Mineral Yearbooks Metric tons

Production—tantalum

Salient Statistics—United States:	2013	2014	2015	2016	2017[e]
Production:					
Mine	—	—	—	—	—
Secondary	NA	NA	NA	NA	NA
Imports for consumption[e, 1]	1,110	1,230	1,240	1,060	1,290
Exports[e, 1]	844	725	657	604	630
Government stockpile releases[e, 2]	—	—	—	—	—
Consumption, apparent[3]	263	508	586	458	660
Price, tantalite, dollars per kilogram of Ta_2O_5 content[4]	260	221	193	193	193
Net import reliance[5] as a percentage of apparent consumption	100	100	100	100	100

Recycling: Tantalum was recycled mostly from new scrap that was generated during the manufacture of tantalum-containing electronic components and from tantalum-containing cemented carbide and superalloy scrap.

Salient Statistics—United States:	2013	2014	2015	2016	2017[e]
Production:					
Mine	—	—	—	—	—
Secondary	NA	NA	NA	NA	NA
Imports for consumption[e, 1]	1,110	1,230	1,240	1,060	1,290
Exports[e, 1]	844	725	657	604	630
Government stockpile releases[e, 2]	—	—	—	—	—
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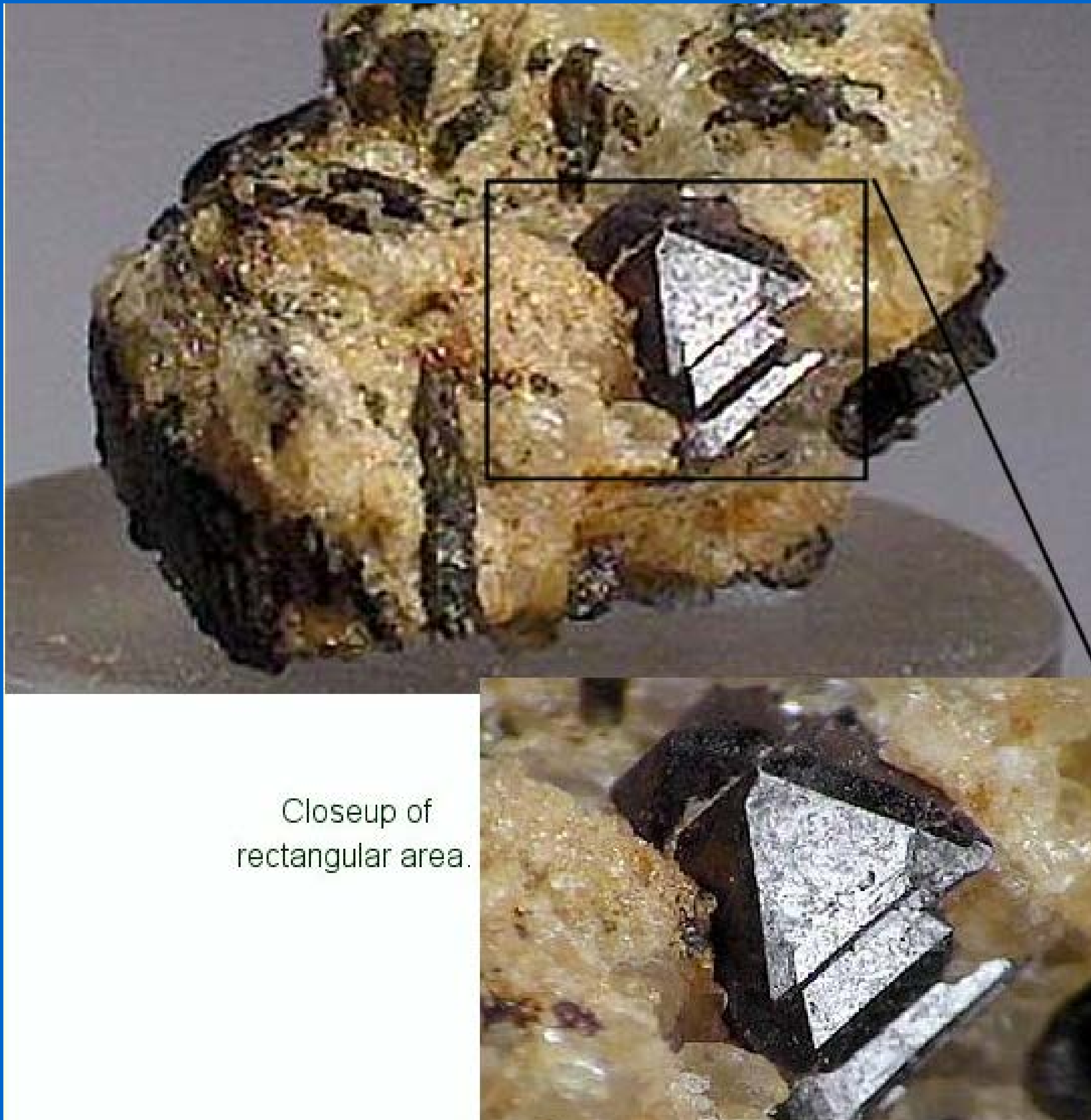
Niobium—geology

http://www.tanb.org/niobium1.html

- pyrochlore [$(Ca,Na)_2 Nb_2(O,OH,F)_7$] in carbonatite and alkaline igneous deposits
- pegmatites (Columbite and tantalite)
- alluvial deposits
- largest deposit in Araxá, Brazil, owned by Companhia Brasileira de Metalurgia e Mineração (CBMM) (460 million tons of 3.0% Nb_2O_5, or 500 yrs reserves)
- Niobec mine in Quebec
- tin slags produced from the smelting of cassiterite ores



Lauzon Farm, Oka, Quebec, Canada. 3.9 x 2.9 cm. http://www.webmi

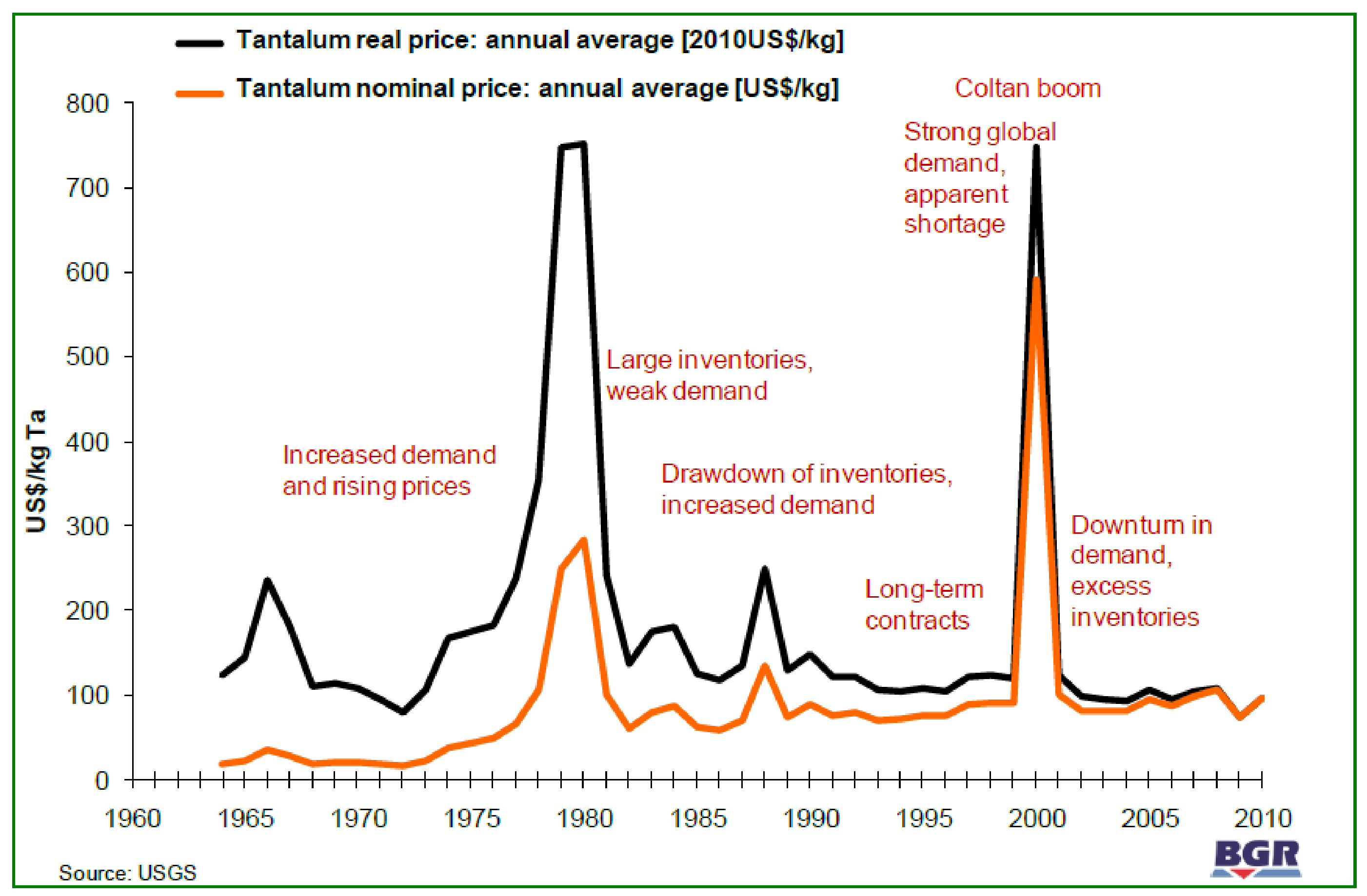
Companhia Brasileira de Metalurgia e Mineração (CBMM), open pit mine for Nb, Minas Gerais, Brazil

http://www.us.cbmm.com.br/english/sources/mine/operat/f_operat.htm

Tantalum

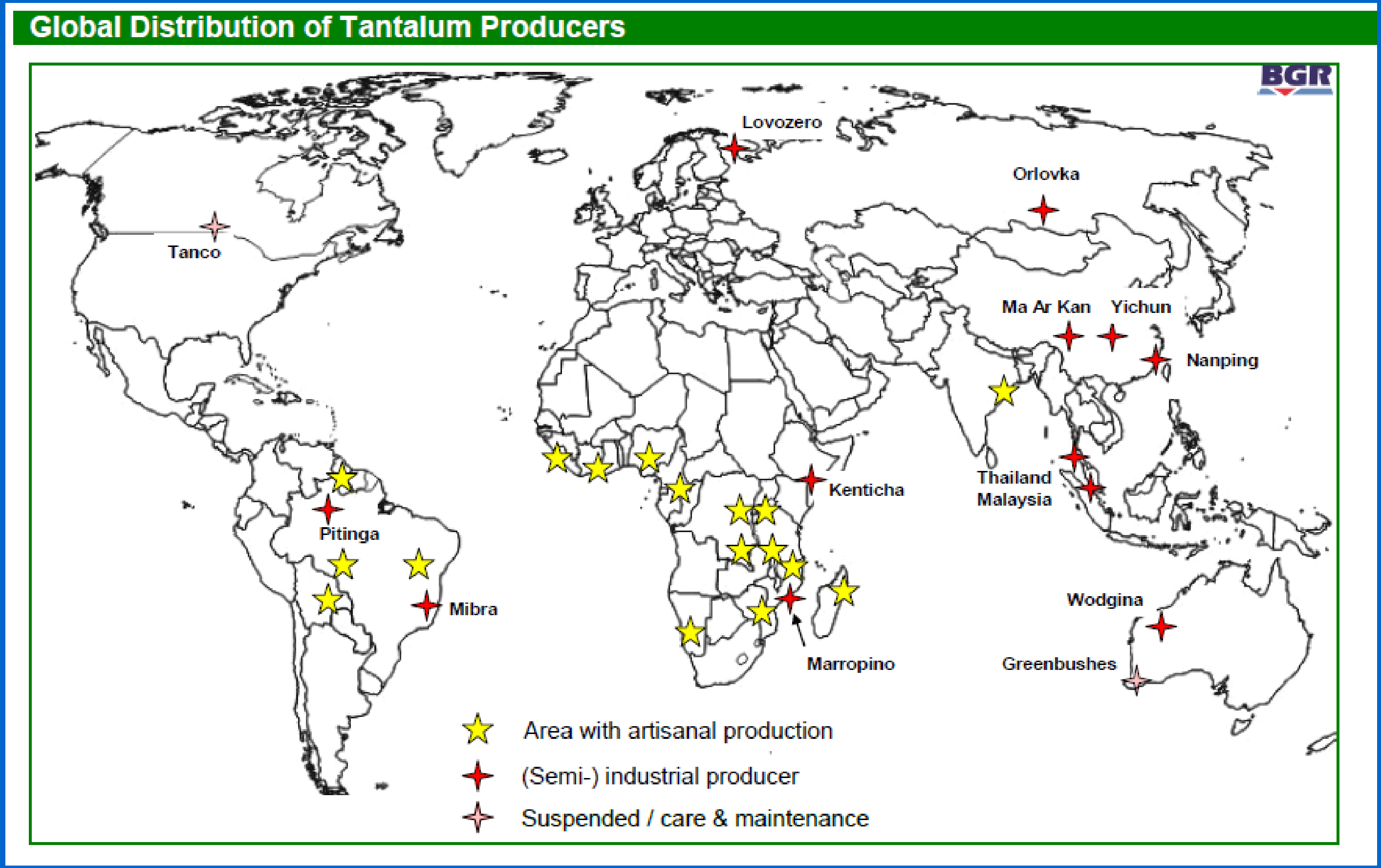
- Minerals--tantalite and columbite or niobite
- Best deposits--Granitic rare-metal pegmatites and rare-metal granites
- Grades--0.015 - 0.02 % Ta_2O_5

Tantalium—price



http://www.polinares.eu/docs/d2-1/polinares_wp2_annex2_factsheet2_v1_10.pdf

Tantalium—deposits



http://www.polinares.eu/docs/d2-1/polinares_wp2_annex2_factsheet2_v1_10.pdf

Zeolites

What is a zeolite?

- A zeolite is a crystalline hydrated aluminosilicate whose framework structure encloses cavities (or pores) occupied by cations and water molecules, both of which have considerable freedom of movement, permitting ion exchange and reversible dehydration. This definition places it in the class of materials known as "molecular sieves."
- The pores in dehydrated zeolite are 6 Å in size, while those of a typical silica gel average about 50 Å, and activated carbon averages 105 Å.

Source of definition=http://palimpsest.stanford.edu/byorg/abbey/an/an20/an20-7/an20-702.html

Zeolite facts

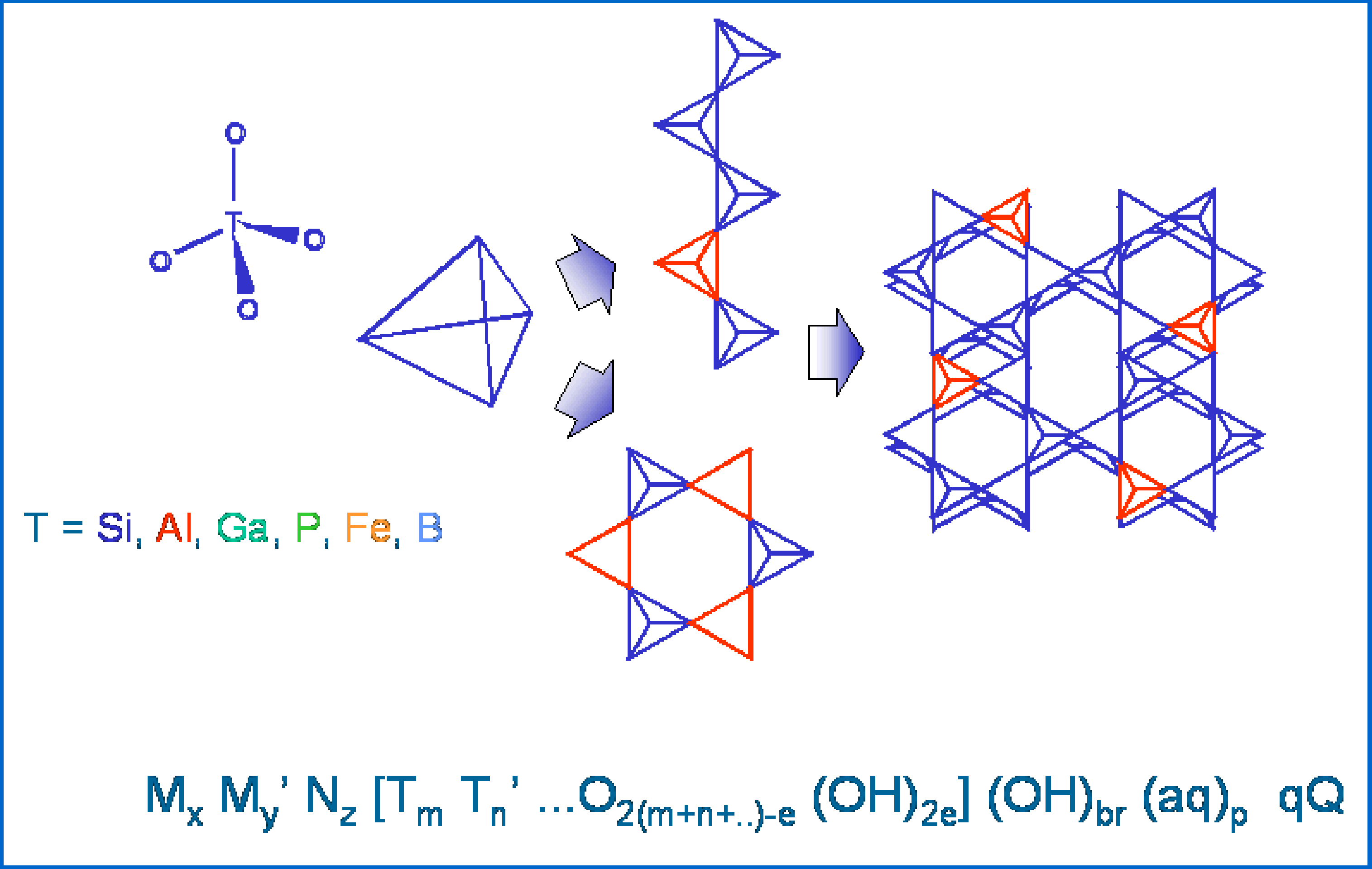
- Tektosilicates, networks of SiO4 tetrahedrons with some Al substituting for Si
- Strong bonds support framework
- Hydrated aluminosilicates with particularly open frameworks of $(Si,Al)0_4$ tetrahedrons
- Open cavities contain cations (Ca, K, Na, Ba)
- Cations balance negative charge of framework
- Ions are easily exchanged, move freely through framework
- Remain stable after losing water from structure
- Heating causes water loss at a continuous rate
- Form by chemical reaction between volcanic glass and saline water

Zeolite Physical Properties

- Soft to moderately hard, H=4-5
- Low density
- Transparent to translucent
- 48 natural Zeolites
- Over 120 synthetic Zeolites
- Industrially speaking, the term zeolite includes natural silicate zeolites, synthetic materials, and phosphate minerals that have a zeolite like structure

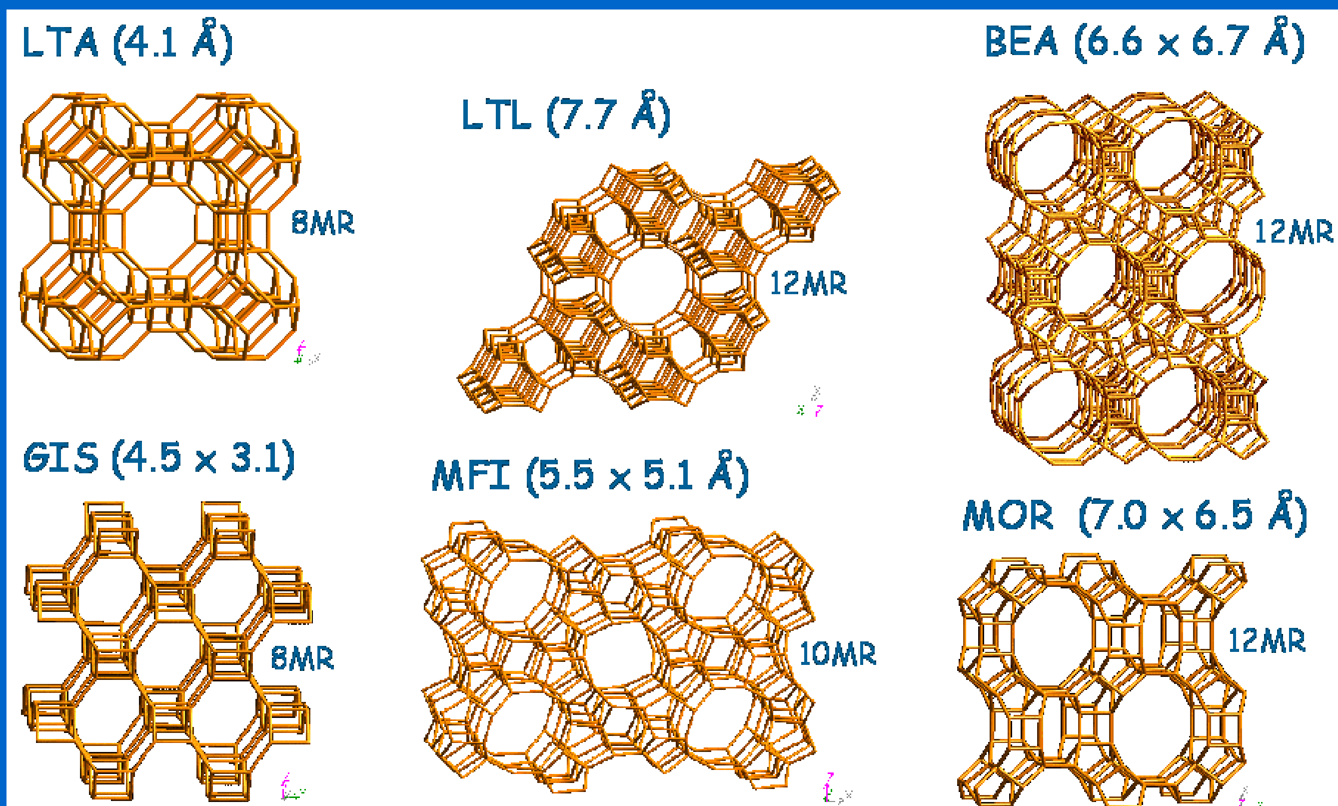
Zeolite structure

- The primary building unit of zeolites are cations coordinated tetrahedrally by oxygen. These tetrahedra are connected via corners, thus forming the crystal structure of the specific zeolite.



Source of diagram: lheim.mpg.de/. ../zeolites_c2.html

Properties of Zeolites

- All commercially useful zeolites owe their value to one or more of three properties: adsorption, ion exchange, and catalysis
- 

Source of structures: eim.mpg.de/. ../zeolites_c2.html

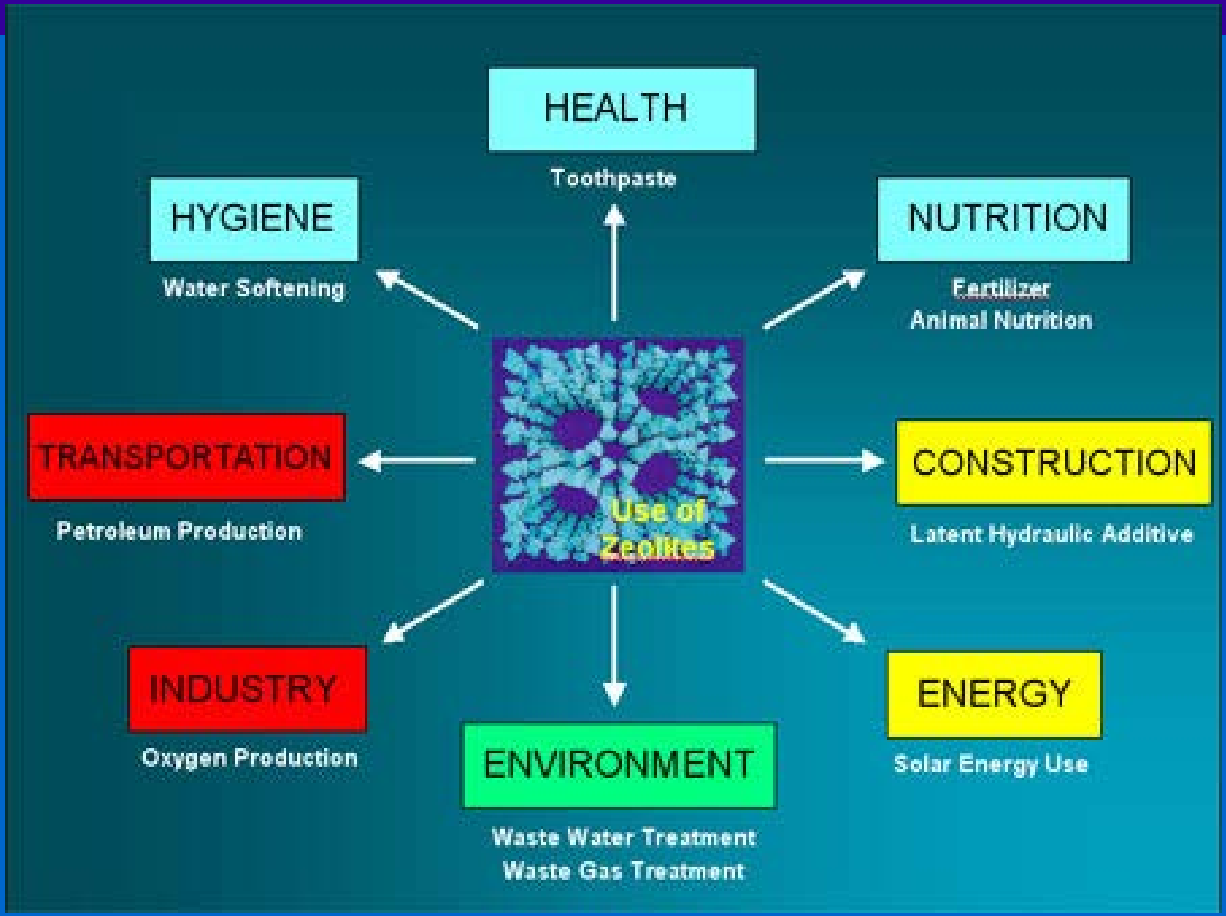
Formation of Zeolites

- Formed by alteration reactions
- Temperatures range from 27°C - 55°C
- pH is typically between 9 and 10
- Nature requires 50 - 50,000 years to complete the reaction
- Mostly altered volcanic glasses
- Fine-grained volcanic ashes or pumice particles are especially susceptible to alteration
- Starting materials can also be minerals, like nepheline, leucite, and feldspars
- Alteration in different environments: hydrothermal, saline or alkaline lakes, and groundwater
- The alteration conditions of these three environments are completely different with respect to chemistry, concentration, and pH of the reacting solution, solid/liquid ratio, temperature, reaction in closed or open system.

Uses of Zeolites

- Natural and synthetic zeolites are used commercially because of their unique adsorption, ion-exchange, molecular sieve, and catalytic properties. Major markets for natural zeolites are pet litter, animal feed, horticultural applications (soil conditioners and growth media), and wastewater treatment. Major use categories for synthetic zeolites are catalysts, detergents, and molecular sieves.

Uses of Zeolites



Source: www.egam.tugraz.at/ app_min/sci_topics/zeolithe/

Zeolite Applications: Gas Adsorption

- Zeolites adsorb many gases on a selective basis
- Specific channel size (2.5 to 4.3A) enables zeolites to act as molecular gas sieves
- Selectively adsorb ammonia, hydrogen sulfide, carbon monoxide, carbon dioxide, sulfur dioxide, water vapor, oxygen, nitrogen, formaldehyde, and others.
- Public toilets, horse stables, chicken houses, and feed lots, pet litter trays release ammonia fumes
- Adding zeolites can minimize odors

Zeolite Applications: Water Adsorption/Desorption

- **Adsorbing and desorbing** water without damage to the crystal structure, make excellent **desiccants**
- Low cost, efficient media for **heat storage** (to include storage of waste and/or off-peak heat energy like solar systems) and solar refrigeration applications.

Zeolite Applications: Ion Exchange

- Water Treatment uses include water softening, remove metals (Cu^{+2}, Pb^{+2}, Zn^{+2}), and radioactive waste treatment (Sr^{90}, Ce^{137}), and wastewater treatment (sequester pollutants)
- Remove ammonia in aquaculture tanks
- In agriculture, control high nitrogen levels and reduce pollution caused by field runoff.

Which Zeolites have commercial value?

- Chabazite and clinoptilolite are the 2 out of the 48 minerals in the zeolite group which have the most commercial applications.
- Occur in Cenozoic age tuffaceous sediments principally in the Western US.
- Chabazite and Clinoptilolite formed over a long period of time are the end product of the chemical reaction between volcanic ash glass shards and alkaline water.
- Because of their high silica to alumina ratios ranging from 2:1 for chabazite to 5:1 for clinoptilolite, these minerals are stable and less likely to dealuminate in acidic solutions than are synthetic zeolites.

Zeolites Deposits of the Western US

showing the location and mineral species of principal domestic economic deposits.

St. Cloud Zeolite Mine
Winston, NM

Source=http://books.smenet.org/Ind_Min_Rcks/imar-ch93-sc00-pt00-bod.cfm

ZeoliteProduction in the US

TABLE 1	
DOMESTIC ZEOLITE PRODUCERS AND SUPPLIERS IN 2003	
State and company	Type of zeolite
Arizona:	
GSA Resources, Inc.	Chabazite.
UOP Inc.	Do.
California:	
Ash Meadows Zeolite, LLC	Clinoptilolite.
KMI Zeolite, Inc.	Do.
Steelhead Specialty Minerals, Inc.	Do.
Idaho:	
Bear River Zeolite, LLC	Do.
Steelhead Specialty Minerals, Inc.	Do.
Nevada, Moltan Co.	Clinoptilolite/mordenite.
New Mexico, St. Cloud Mining Co.	Clinoptilolite.
Oregon, Teague Mineral Products Co.	Do.
Texas, Zeotech Corp.	Do.
Wyoming, Addwest Minerals International Ltd.	Do.

Source= http://minerals.usgs.gov/minerals/pubs/commodity/zeolites/

Salient Statistics—United States:	2013	2014	2015	2016	2017[e]
Production, mine	69,500	62,800	75,100	73,400	79,000
Sales, mill	68,300	62,500	73,200	69,500	77,000
Imports for consumption[e]	<1,000	<1,000	<1,000	<1,000	<1,000
Exports[e]	<1,000	<1,000	<1,000	<1,000	<1,000
Consumption, apparent[e, 1]	68,300	62,500	73,200	69,500	77,000
Price, range of value, dollars per metric ton[2]	50–800	110–440	110–950	100–400	100–400
Employment, mine and mill[e, 3]	105	95	100	115	110
Net import reliance[4] as a percentage of estimated consumption	E	E	E	E	E

Recycling: Zeolites used for desiccation, gas absorbance, wastewater cleanup, and water purification may be reused after reprocessing of the spent zeolites. Information about the quantity of recycled natural zeolites was unavailable.

	Mine production[e] 2016	2017	Reserves[5]
United States	[6]73,400	79,000	World reserve data are unavailable but are estimated to be large.
China	300,000	300,000	
Cuba	51,000	55,000	
Jordan	13,000	13,000	
Korea, Republic of	191,000	200,000	
New Zealand	80,000	80,000	
Turkey	55,000	60,000	
Other countries	350,000	350,000	
World total (rounded)	1,100,000	1,100,000	

World Resources: Recent estimates for domestic and global resources of natural zeolites are not available. Resources of chabazite, clinoptilolite, erionite, mordenite, and phillipsite within the Basin and Range province in the United States are sufficient to satisfy foreseeable domestic demand.

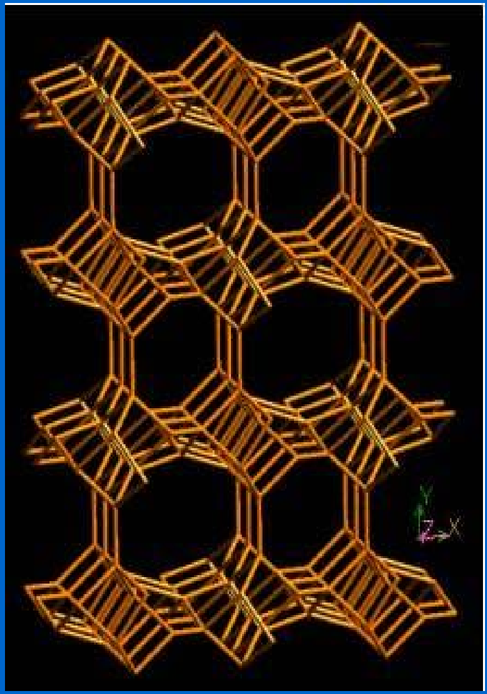
USGS Mineral Yearbooks   Metric tons

Zeolites in New Mexico

- Buckhorn clinoptilolite deposit 2 clinoptilolite–bearing ash–fall tuff and reworked tuff beds of Pliocene–Pleistocene age. Zeolitized ash–fall tuff 1 to 1.6 m and consisting of 60 to 90% clinoptilolite, with chabazite, heulandite and analcime locally, not mined (Eyde, 1982).
- Tertiary volcanic rocks near Winston in Sierra County comprise the Winston clinoptilolite deposit; ash–flow tuffs and related tuffaceous breccias; predominantly clinoptilolite–heulandite. St. Cloud Mining Company currently mines, processes, and markets Winston deposit zeolites

Clinoptilolite Studies at NMT

- NMT Hydrology study under Rob Bowman has focused on the natural zeolite clinoptilolite
- Formula $(Ca,Na_2,K_2)(Al_6\ SiO)\cdot 24H_2O$.
- Clinoptilolite from the [St. Cloud Mining Company]
- Mine located near Winston, New Mexico
- St. Cloud is the largest producer of natural zeolite in North America.
- Mineralogy of St. Cloud material:
  74% clinoptilolite
  10% feldspar
  10% quartz + cristobalite
  5% smectite



http://www.ees.nmt.edu/bowman/research/SMZ/ZeoProp.html

St. Cloud Zeolite Mine

The Cuchillo Negro clinoptilolite deposit mined by the St. Cloud campany is shown here.

St. Cloud Zeolite Plant

St. Cloud Mining Company has emerged as the largest producer of natural zeolite in North America. The zeolite mineral, clinoptilolite, is an absorbent volcanic ash with unique physical, chemical, and cation exchange properties used in agriculture, industrial and environmental applications.

Source=http://www.stcloudmining.com/

Mining St. Cloud Zeolite

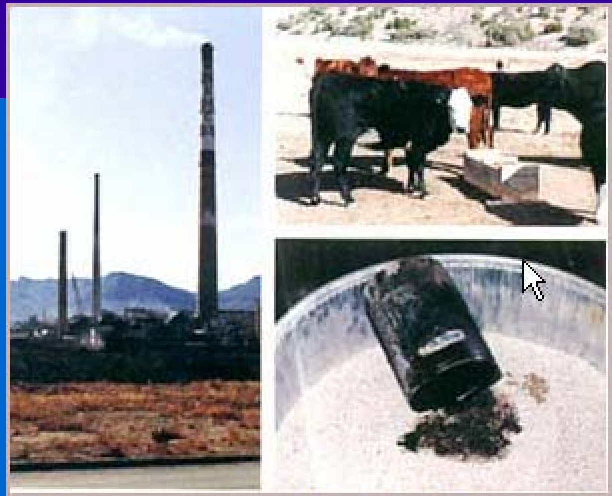
St. Cloud's zeolite deposit contains an estimated 18.3 million tons of clinoptilolite resources and the production facility has a capacity in excess of 100,000 tons per annum. The operation includes facilities for custom sizing, bagging, blending and manufacturing of added value products. St. Cloud sells zeolite primarily through a network of brokers, distributors and manufacturers.

Source=http://www.stcloudmining.com/

Lighter color is the altered volcanic ash with clinoptilolite at the St. Cloud zeolite mine

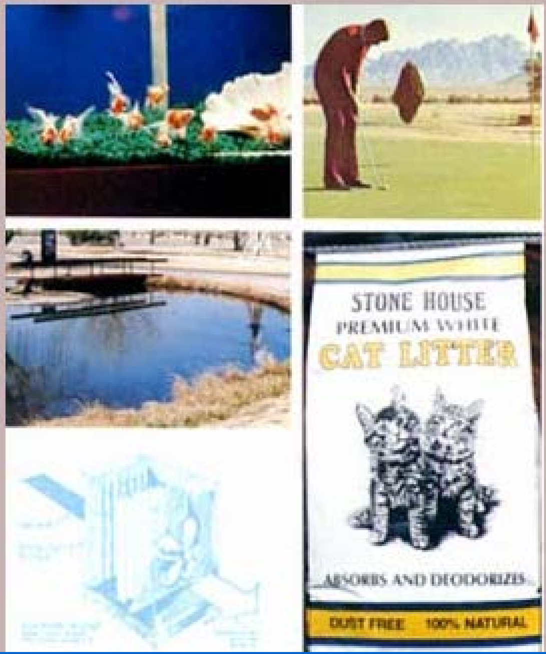
Source= http://www.ees.nmt.edu/~ranck/zeolite.html

Uses of St. Cloud Zeolite



Zeolites are used in many different applications including animal feed supplements, water and air filtration and pollution control media, animal hygiene, odor control, oil absorbing floor drying material, aquaculture and pond filtration, soil amendments, and industrial fillers.

Other applications for natural zeolites include paper and paint fillers, thermal storage, natural gas purification, ground water and sewage effluent treatment, removal of ammonia, heavy metals and radioactive ions from industrial and municipal effluents.



Zeolite Markets

- Relatively new, since1960s
- Most consumed within country produced
- Diverse markets
- Steady growth is anticipated for the rest of the 1990s for agricultural, industrial, and consumer applications. The strongest areas of market growth in North America are expected to be in sewage treatment, deodorants, pet litter, soil treatment, and nuclear waste treatment and containment.

Foreign Zeolite Sources

- Antigua, Argentina©, Australia©, New South Wales, Bulgaria, Canada (Nova Scotia, British Columbia), Chile, China©, Czechoslovakia ©, France, Germany©, Hungary©, Iceland, Indonesia©, Italy©, Japan©, Korea©, Mexico©, New Zealand, Poland, S. Africa©, Romania©, Spain©, UK, USSR©, Yugoslavia©.

  (The © means commercial development)

Value of Zeolites

- Usually determined by cost of processing and added value
- Mining costs $3-6/Ton
- Processed $30-120/Ton
- Pet litter, fish tank, deodorant $.50-4.50 kg
- Special apps = $1000s /ton (radioactive waste filter media or catalysts in petroleum refining, etc)

Transporting Zeolites

- Generally transported by highway or rail carriers in bulk, in one–ton super–sacks or in multi–wall paper bags, usually palletized.
- Do not require special handling
- Costs affected by distance must transport
- Currently economical to ship from western US to eastern US for agricultural uses
- May change in future when imports from Cuba & Antigua become cheaper for eastern US to use
- Specialty zeolites worth shipping farther

Alternates

- Synthetic zeolites (customized molecular sieves) are the major alternate materials to natural zeolites.
- Synthetic zeolites can tailor physical and chemical characteristics to serve many applications more closely and they are more uniform in quality than their natural equivalents.
- Natural zeolites advantage over synthetic materials: Ce and Sr adsorption in radioactive waste cleanup, able to function at lower pH levels, much lower in cost than synthetic zeolite products.
- Activated carbon, silica gel, & similar materials are more effective than zeolites for many ion–exchange applications and are not disproportionately more expensive.
- Bentonite, attapulgite, and others show selective high absorbency, available in a competitive price range.

Problems with Zeolites

- The synthetic zeolites pose no problems, readily made from abundant raw materials, present no toxic or environmental problems.
- Naturally occurring zeolites are excluded from many important commercial applications where uniformity and purity are essential
- Natural zeolites must penetrate markets where other materials are already used and accepted
- Natural zeolites were over-marketed in the 70's, created stigma, must now overcome
- Some zeolites are fibrous, all are silicates
- No industrial standards exist for natural zeolites, harder to market, need ASTM or other standards published

Future of Zeolites

- A healthy, growing industry with continued expansion into new applications and steady demand in industrial markets
- Most of the activity and growth has been in the synthetic zeolite field.
- Natural zeolite market likely to continue on a slow and steady basis.
- Natural zeolites domestic market for catalysis and petroleum refining, nuclear waste treatment, and odor control, pollution control, and energy cost and efficiency issues will continue and expand.
- Higher energy costs and greater environmental demands will spur zeolite production and sales significantly.
- For the next decade, natural zeolites should emerge as a better–defined mineral commodity, and North America will become a leading producer.

Zircon

Zircon—introduction

- $ZrSiO_4$
- Baddeleyte ZrO_2
- Highly resistant to weathering
- High specific gravity 4.6-4.7
- Other potential minerals
  - Eudialyte
  - Gittinsite

Zircon—introduction

- Zr resistant to corrosion by acids and other chemicals
- Alloyed with Nb it becomes superconductive (conduct electricity with very little loss of energy to electric resistance)
- Does not absorb neutrons

Zircon—uses

- zircon ceramics
- opacifiers
- refractories
- foundry applications
- abrasives
- chemicals
- metal alloys
- welding rod
- coatings
- sandblasting

Production

Salient Statistics—United States:	2013	2014	2015	2016	2017[e]
Production, zircon (ZrO_2 content)[1]	W	W	[2]50,000	W	[2]30,000
Imports:					
Zirconium, ores and concentrates (ZrO_2 content)	8,050	32,800	20,800	24,900	28,000
Zirconium, unwrought, powder, and waste and scrap	395	843	1,140	1,040	840
Zirconium, wrought	321	257	171	195	240
Hafnium, unwrought, powder, and waste and scrap	10	21	72	180	160
Exports:					
Zirconium ores and concentrates (ZrO_2 content)	19,000	4,850	3,200	3,280	11,000
Zirconium, unwrought, powder, and waste and scrap	599	534	515	363	550
Zirconium, wrought	1,140	913	1,020	788	630
Consumption, apparent, zirconium ores and concentrates, (ZrO_2 content)[3]	W	W	[2]70,000	W	[2]50,000
Prices:					
Zircon, dollars per metric ton (gross weight):					
Domestic[4]	1,050	1,050	1,025	1,025	1,025
Imported[5]	996	1,133	1,061	877	881
Zirconium, unwrought, import, France, dollars per kilogram[6]	75	59	50	46	46
Hafnium, unwrought, import, France, dollars per kilogram[6]	578	561	607	[7]NA	[7]NA
Hafnium, unwrought, dollars per kilogram[8]	NA	NA	NA	1,088	912
Net import reliance[9] as a percentage of apparent consumption:					
Zirconium	E	<50	<25	<50	<50
Hafnium	NA	NA	NA	NA	NA

Recycling: Companies in Oregon and Utah recycled zirconium from new scrap generated during metal production and fabrication and (or) from post-commercial old scrap. Zircon foundry mold cores and spent or rejected zirconia refractories are often recycled. Hafnium metal recycling was insignificant.

USGS Mineral Yearbooks metric tons

	Zirconium concentrates, mine production (thousand metric tons, gross weight)		Zirconium reserves[10] (thousand metric tons, ZrO_2)
	2016	**2017[e]**	
United States	W	[2]50	500
Australia	450	600	47,000
China	140	140	500
India	40	40	3,400
Indonesia	110	120	NA
Mozambique	68	75	1,800
Senegal	53	60	NA
South Africa	360	400	14,000
Other countries	96	110	7,200
World total (rounded)	[11]1,320	1,600	74,000

World Resources: Resources of zircon in the United States included about 14 million tons associated with titanium resources in heavy-mineral-sand deposits. Phosphate rock and sand and gravel deposits could potentially yield substantial amounts of zircon as a byproduct. World resources of hafnium are associated with those of zircon and baddeleyite. Quantitative estimates of hafnium resources are not available.

Zircon—geology

- Beach sands in Florida, Virginia and South Carolina (with Ti)

REE

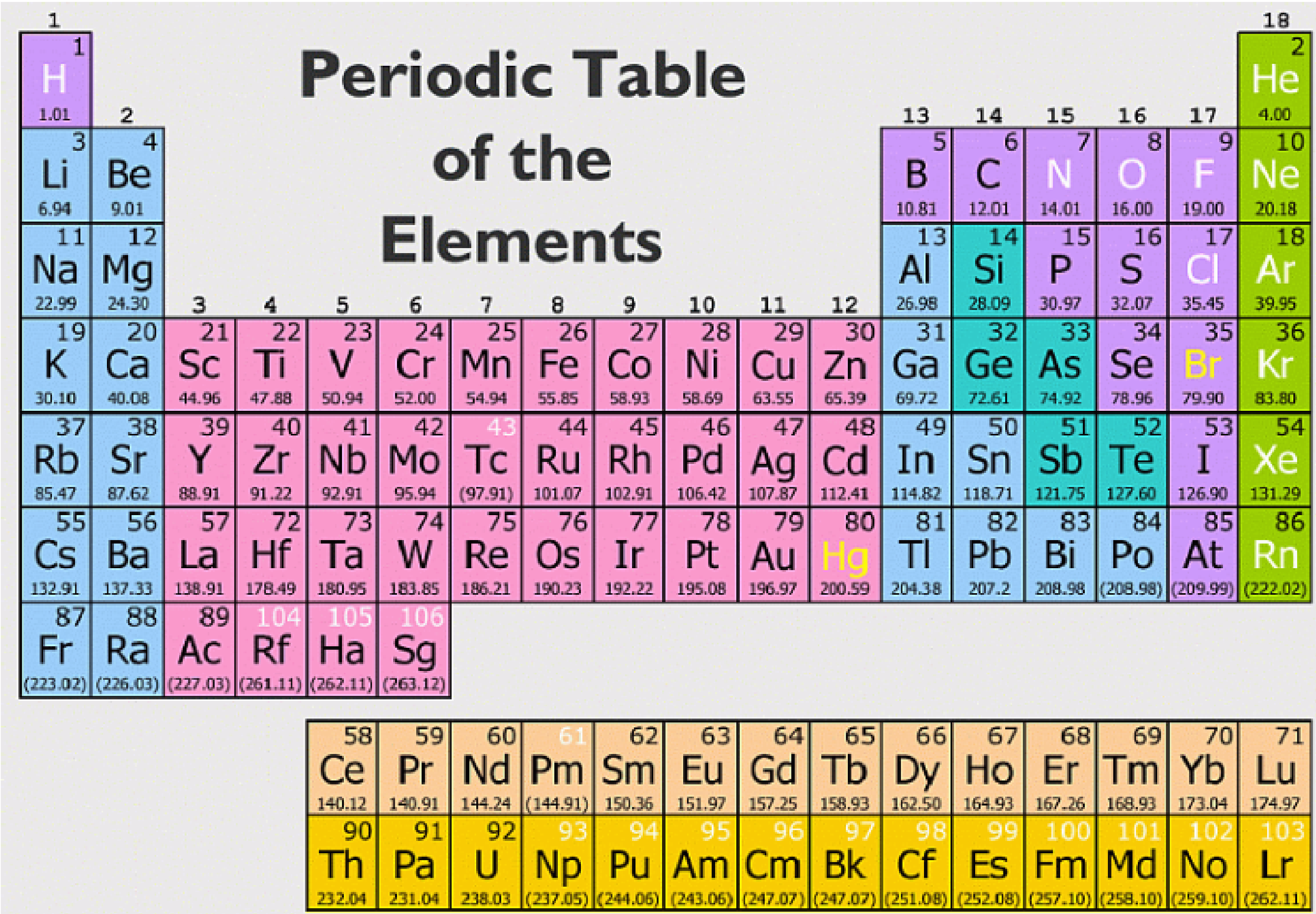


Figure 1. Periodic table of the elements. The rare earth elements comprise 15 elements, which range in atomic number from 57 to 71, including lanthanum (La) to lutetium (Lu). The elements are also commonly referred to as "lanthanides." Yttrium (Y, atomic number 39) is also typically included with the rare earth elements group because it shares chemical, physical, and application properties with the lanthanides.

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

REE

- Lithophile elements (or elements enriched in the crust)
- Similar physical and chemical properties
- Occur together in nature
- Classified as metals
- Soft, malleable, ductile and usually quite reactive metals
- MP range from 798 to 1663 deg C

57	58	59	60	62	63	64	65	66	67	68	69	70	71	39
La	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**	**Y**
138.91	140.12	140.91	144.24	150.36	151.96	157.25	158.93	162.5	164.93	167.26	168.93	173.04	174.97	88.906

Light rare earths (La, Ce, Pr, Nd, Sm) | **Heavy rare earths** (Eu – Y)

La - Lanthanum
Ce - Cerium
Pr - Praseodymium
Nd - Neodymium
Sm - Samarium

Eu - Europium
Gd - Gadolinium
Tb - Terbium
Dy - Dysprosium
Ho - Holmium

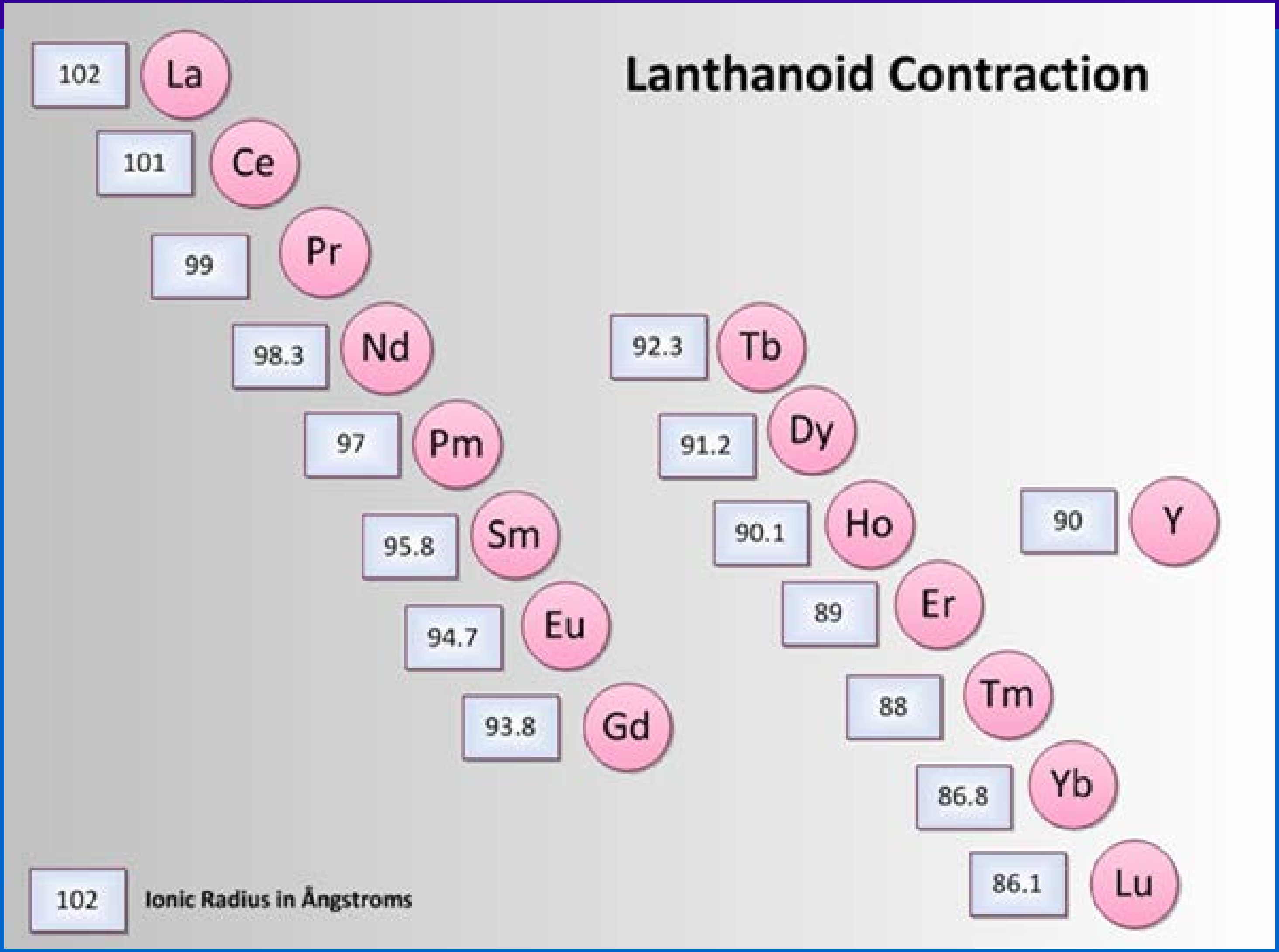
Er - Erbium
Tm - Thulium
Yb - Ytterbium
Lu - Lutetium
Y - Yttrium

Figure 2.2: Sub-groups of the rare-earth metals, per industry (not scientific) norms (sources: TMR, industry sources).

ISSUE

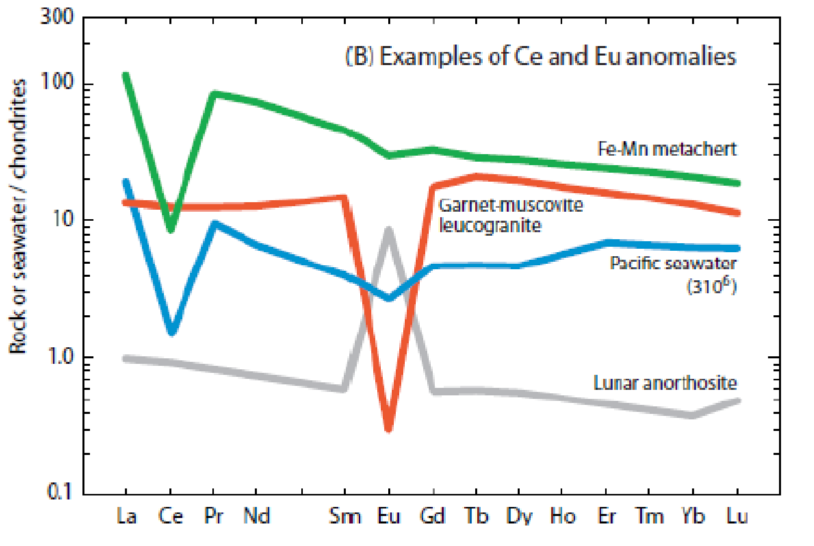
- In 2010, China announced it would significantly restrict REE exports to ensure supply for Chinese domestic manufacturing
- 72% REE export reduction in 2010
- 35% REE export reduction in 2011
- Quota reduction officially to curb rampant and unregulated REE production over the last few years, which has caused significant environmental problems

Ionic radius decreases with increasing number

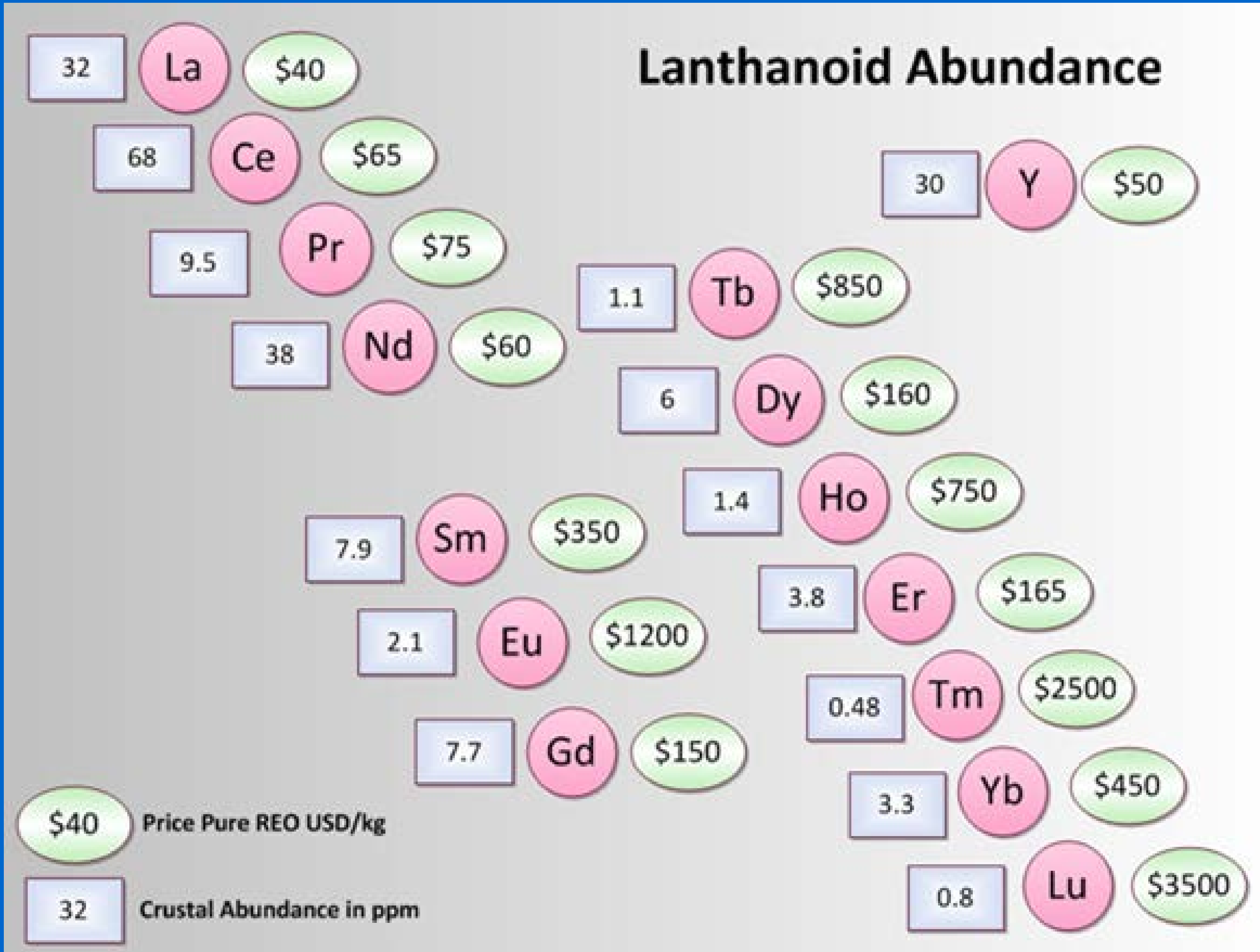


Oxidation state

- All REE occur in 3+ state
- Eu also occurs in 2+ state
  - Substitutes for 2+ cations such as Ca2+
- Ce also occurs in 4+ state
  - insoluble



From: Haxel (2005)


Lanthanoid Abundance
32 La $40
68 Ce $65
9.5 Pr $75
38 Nd $60
7.9 Sm $350
2.1 Eu $1200
7.7 Gd $150
30 Y $50
1.1 Tb $850
6 Dy $160
1.4 Ho $750
3.8 Er $165
0.48 Tm $2500
3.3 Yb $450
0.8 Lu $3500
$40 Price Pure REO USD/kg
32 Crustal Abundance in ppm

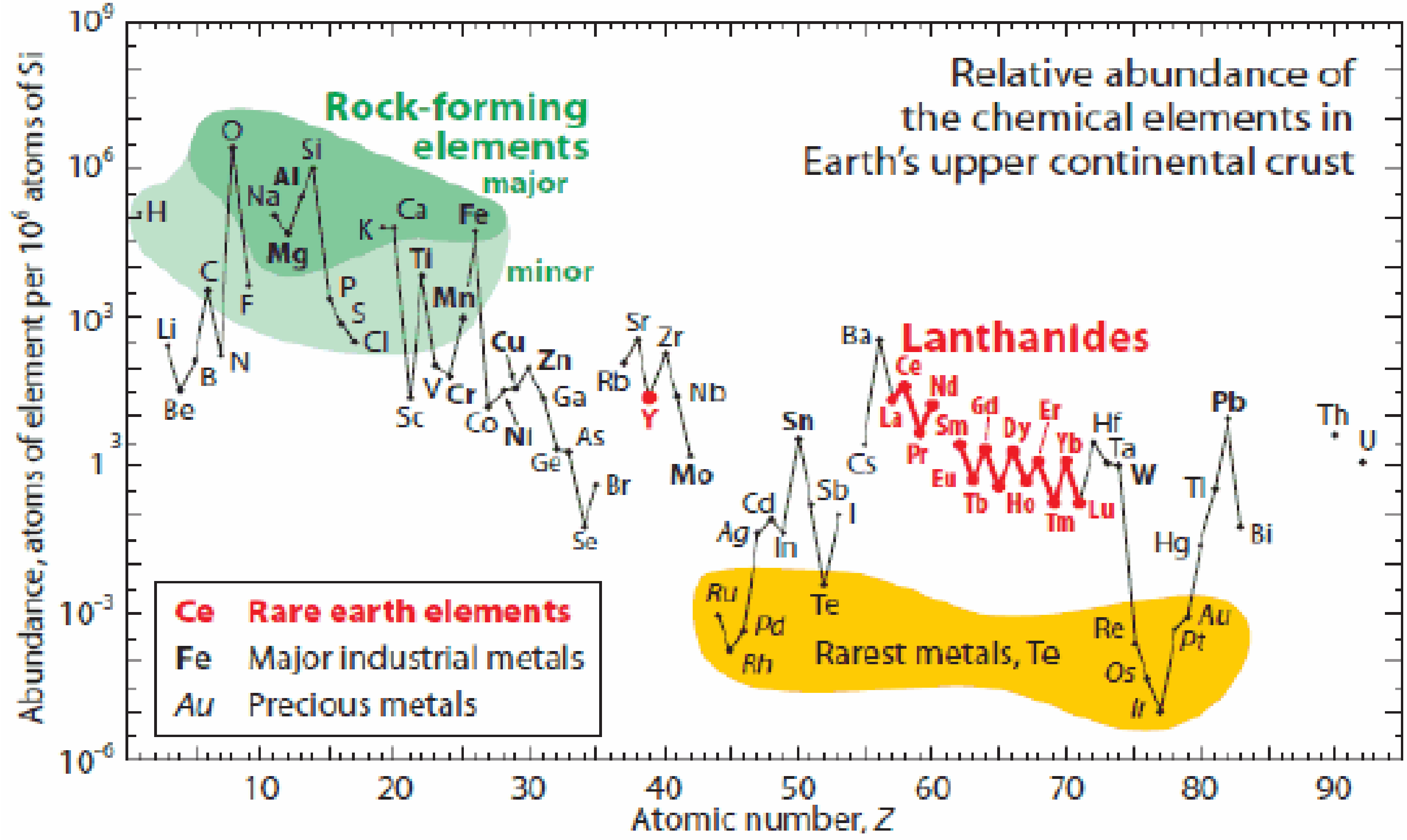


Figure 1 Relative abundance of rare earths (highlighted in red). Figure courtesy of Gordon Haxel, USGS.

- Less abundant than rock forming minerals
- More abundant than precious metals
- Oddo-Harkins rule
  - greater abundance of even-numbered elements relative to their odd-numbered neighbors
- easily smoothed out by “normalizing” the measured concentrations of REEs to some reference REE
  - REE abundances normalized to the primitive mantle values
  - chondritic meteorites

"The estimated average concentration of the rare earth elements in the Earth's crust, which ranges from around 150 to 220 parts per million (table 1), exceeds that of many other metals that are mined on an industrial scale, such as copper (55 parts per million) and zinc (70 parts per million)."

"Although rare earth elements are relatively abundant in the Earth's crust, they are rarely concentrated into mineable ore deposits."

(Long et al., 2010)

Table 1. Estimates of the crustal abundances of rare earth elements.

[Rare earth elements listed in order of increasing atomic number; yttrium (Y) is included with these elements because it shares chemical and physical similarities with the lanthanides. Unit of measure, parts per million]

Rare earth element	Mason and Moore (1982)	Jackson and Christiansen (1993)	Sabot and Maestro (1995)	Wedephol (1995)	Lide (1997)	McGill (1997)
Lanthanum	30	29	18	30	39	5 to 18
Cerium	60	70	46	60	66.5	20 to 46
Praseodynium	8.2	9	5.5	6.7	9.2	3.5 to 5.5
Neodymium	28	37	24	27	41.5	12 to 24
Samarium	6	8	6.5	5.3	7.05	4.5 to 7
Europium	1.2	1.3	0.5	1.3	2	0.14 to 1.1
Gadolinium	5.4	8	6.4	4	6.2	4.5 to 6.4
Terbium	0.9	2.5	0.9	0.65	1.2	0.7 to 1
Dysprosium	3	5	5	3.8	5.2	4.5 to 7.5
Holmium	1.2	1.7	1.2	0.8	1.3	0.7 to 1.2
Erbium	2.8	3.3	4	2.1	3.5	2.5 to 6.5
Thulium	0.5	0.27	0.4	0.3	0.52	0.2 to 1
Ytterbium	3.4	0.33	2.7	2	3.2	2.7 to 8
Lutetium	0.5	0.8	0.8	0.35	0.8	0.8 to 1.7
Yttrium	33	29	28	24	33	28 to 70
Scandium	22		10	16	22	5 to 10
Total	206.1	205.2	159.9	184.3	242.17	

(Long et al., 2010)

Sc

At A Glance: Sc

Atomic Number:	21
Atomic Symbol:	Sc
Atomic Weight:	44.9559
Electron Configuration:	[Ar]4s23d1
Atomic Radius:	216 pm (Van der Waals)
Melting Point:	1541 °C
Boiling Point:	2836 °C
Oxidation States:	3

Sources: It is widely distributed on earth, occurring in very minute quantities in over 800 mineral species.**Uses:** High-intensity lights; tracing agent in refinery crackers for crude oil; highly efficient light source. *Content provided by Los Alamos National Laboratory. Used with permission.*

- 20 kg/yr produce high-intensity lights
- 46Sc used in refinery cracking for crude oil
- Used in mercury vapor lamps (resembles sunlight)
- Recovered from thortveitite or a by-product of U mill tailings

At A Glance: Y

Atomic Number:	39
Atomic Symbol:	Y
Atomic Weight:	88.9059
Electron Configuration:	[Kr]5s24d1
Atomic Radius:	219 pm (Van der Waals)
Melting Point:	1522 °C
Boiling Point:	3345 °C
Oxidation States:	3

Sources: Improves efficiency of fuels; microwave and cellular communications devices for defense, satellites and phones; jet engine turbines; laser crystals specific to spectral characteristics for military communications; red color in televisions and computer screens. Yttrium stabilized cubic zirconia produces simulated diamonds.
Uses: While yttrium occurs in nearly all of the rare earth minerals, ion-adsorption ores provide the bulk of the world's Yttrium. Recovered commercially from monazite sand, which contains about 3%, and from bastnasite, which contains about 0.2%. Analysis of lunar rock samples obtained during the Apollo missions show a relatively high yttrium content.

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Y

- Yttrium Iron Garnets (YIG) are used as resonators for use in frequency meters, magnetic field measurement devices, tunable transistors Gunn oscillators, cellular communications devices
- stabilizer and mold former for exotic light-weight jet engine turbines and other parts, and as a stabilizer material in rocket nose cones
- Other uses
- Recovered from monazite

At A Glance: La

Atomic Number:	57
Atomic Symbol:	La
Atomic Weight:	138.9055
Electron Configuration:	[Xe]6s25d1
Atomic Radius:	240 pm (Van der Waals)
Melting Point:	918 °C
Boiling Point:	3464 °C
Oxidation States:	2

Sources: Found in rare-earth minerals such as cerite, monazite, allanite, and bastnasite. Monazite and bastnasite are principal ores in which lanthanum occurs in percentages up to 25 percent and 38 percent respectively. **Uses:**hybrid vehicle batteries, fluid cracking catalysts, glass polishing, fuel cells.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Ce

Atomic Number:	58
Atomic Symbol:	Ce
Atomic Weight:	140.12
Electron Configuration:	[Xe]6s24f15d1
Atomic Radius:	235 pm (Van der Waals)
Melting Point:	798 °C
Boiling Point:	3,443 °C
Oxidation States:	4,3

Sources: Cerium is the most abundant rare earth element. Monazite and bastnasite ores are presently the more important sources of cerium.**Uses:**Pollution control technologies such as catalytic converters and fuel additives, glass polishing and UV shielding, water filtration, fluorescent lighting.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Pr

Atomic Number:	59
Atomic Symbol:	Pr
Atomic Weight:	140.9077
Electron Configuration:	[Xe]6s24f3
Atomic Radius:	239 pm (Van der Waals)
Melting Point:	931 °C
Boiling Point:	3520 °C
Oxidation States:	3

Sources: Monazite and bastnasite are the two principal commercial sources of praseodymium.**Uses:** Paired with neodymium in permanent magnets, also used in photographic filters, airport signal lenses, pigment in ceramic tile and glass, pollution control catalysts.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Nd

Atomic Number:	60
Atomic Symbol:	Nd
Atomic Weight:	144.24
Electron Configuration:	[Xe]6s24f4
Atomic Radius:	229 pm (Van der Waals)
Melting Point:	1021 °C
Boiling Point:	3074 °C
Oxidation States:	3

Sources: It is present in significant quantities in the ore minerals monazite and bastnäsite.
Uses: High powered neodymium-iron-boron permanent magnets used in smartphones, computer hard drives, audio speakers, and many other consumer electronics, hybrid and electric vehicle motors, wind turbine generators, MRI machines, and defense equipment; also used in lasers and glass production.
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At A Glance: Pm

Atomic Number:	61
Atomic Symbol:	Pm
Atomic Weight:	145
Electron Configuration:	[Xe]6s24f5
Atomic Radius:	236 pm (Van der Waals)
Melting Point:	1042 °C
Boiling Point:	~3000 °C
Oxidation States:	3, 2

Sources: Promethium is man-made and does not occur in nature.
Uses: Few known uses of promethium.

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At A Glance: Sm

Atomic Number:	62
Atomic Symbol:	Sm
Atomic Weight:	150.4
Electron Configuration:	[Xe]6s24f6
Atomic Radius:	229 pm (Van der Waals)
Melting Point:	1074 °C
Boiling Point:	1794 °C
Oxidation States:	3, 2

Sources: Found along with other rare earth elements in many minerals, including monazite and bastnasite, which are commercial sources. Samarium metal can be produced by reducing the oxide with lanthanum.
Uses: Used in making permanent magnet material that maintains its performance at high temperatures, primarily used in defense-related equipment; also used in optical glass, infrared absorbing glass, and lasers. *Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Eu

Atomic Number:	63
Atomic Symbol:	Eu
Atomic Weight:	151.96
Electron Configuration:	[Xe]6s24f7
Atomic Radius:	233 pm (Van der Waals)
Melting Point:	822 °C
Boiling Point:	1529 °C
Oxidation States:	3, 2

Sources: Bastnasite and monazite are the principal ores containing europium.**Uses:** Phosphors in LCD screens, compact fluorescent lightbulbs, lasers.
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At A Glance: Gd

Atomic Number:	64
Atomic Symbol:	Gd
Atomic Weight:	157.25
Electron Configuration:	[Xe]6s24f75d1
Atomic Radius:	237 pm (Van der Waals)
Melting Point:	1313 °C
Boiling Point:	3273 °C
Oxidation States:	3

Sources: Bastnasite and monazite are the principal ores containing gadolinium.
Uses: Phosphors in television, microwave applications, heat resistant metals and alloys.

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At A Glance: Tb

Atomic Number:	65
Atomic Symbol:	Tb
Atomic Weight:	158.9254
Electron Configuration:	[Xe]6s24f9
Atomic Radius:	221 pm (Van der Waals)
Melting Point:	1356 °C
Boiling Point:	3230 °C
Oxidation States:	3

Sources: Terbium is never found in nature as a free element, but it is contained in many minerals, including cerite, gadolinite, monazite, xenotime and euxenite.**Uses:** Energy efficient fluorescent lighting, magneto-optic recording of data, solid-state devices, and fuel cells.
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At A Glance: Dy

Atomic Number: 66

Atomic Symbol: Dy

Atomic Weight: 162.50

Electron Configuration: [Xe]6s24f10

Atomic Radius: 229 pm (Van der Waals)

Melting Point: 1413 °C

Boiling Point: 2567 °C

Oxidation States: 3

Uses:A key additive to NdFeB magnets to maintain their magnetic properties at high temperatures; consumer electronics.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Ho

Atomic Number: 67

Atomic Symbol: Ho

Atomic Weight: 164.9304

Electron Configuration: [Xe]6s24f11

Atomic Radius: 216 pm (Van der Waals)

Melting Point: 1474 °C

Boiling Point: 2700 °C

Oxidation States: 3

Sources: Holmium is found in the minerals monazite and gadolinite, and is usually commercially extracted from monazite using ion exchange techniques.
Uses: Holmium is one of the least abundant Rare Earth elements and has few commercial uses.

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At A Glance: Er

Atomic Number: 68

Atomic Symbol: Er

Atomic Weight: 167.26

Electron Configuration: [Xe]6s24f12

Atomic Radius: 235 pm (Van der Waals)

Melting Point: 1529 °C

Boiling Point: 2868 °C

Oxidation States:

Uses: Fiber optic data transmission, lasers for medical and dental uses, glass coloration used in sunglasses and decorative crystal glassware. *Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Tm

Atomic Number:	69
Atomic Symbol:	Tm
Atomic Weight:	168.9342
Electron Configuration:	[Xe]6s24f13
Atomic Radius:	227 pm (Van der Waals)
Melting Point:	1545 °C
Boiling Point:	1950 °C
Oxidation States:	3, 2

Sources: The element is never found in nature in pure form, but it is found in small quantities in minerals with other rare earths.**Uses:** Because of the relatively high price of the metal, thulium has not yet found many practical applications.*Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Yb

Atomic Number:	70
Atomic Symbol:	Yb
Atomic Weight:	173.04
Electron Configuration:	[Xe]6s24f14
Atomic Radius:	242 pm (Van der Waals)
Melting Point:	819 °C
Boiling Point:	1196 °C
Oxidation States:	3, 2

Sources: A soft silvery metallic element, ytterbium is a rare earth element of the lanthanide series and is found in the minerals gadolinite, monazite, and xenotime.**Uses:** Improves the grain refinement, strength, and other mechanical properties of stainless steel. *Content provided by Los Alamos National Laboratory. Used with permission.*

At A Glance: Lu

Atomic Number:	71
Atomic Symbol:	Lu
Atomic Weight:	174.97
Electron Configuration:	[Xe]6s24f145d1
Atomic Radius:	221 pm (Van der Waals)
Melting Point:	1663 °C
Boiling Point:	3402 °C
Oxidation States:	3

Sources: Found with almost all other rare-earth metals but never by itself, lutetium is very difficult to separate from other elements.**Uses:** Catalysts in cracking, alkylation, hydrogenation, and polymerization; detectors in positron emission tomography (PET). Virtually no other commercial uses have been found yet for lutetium. *Content provided by Los Alamos National Laboratory. Used with permission.*

Government documents

USGS
science for a changing world

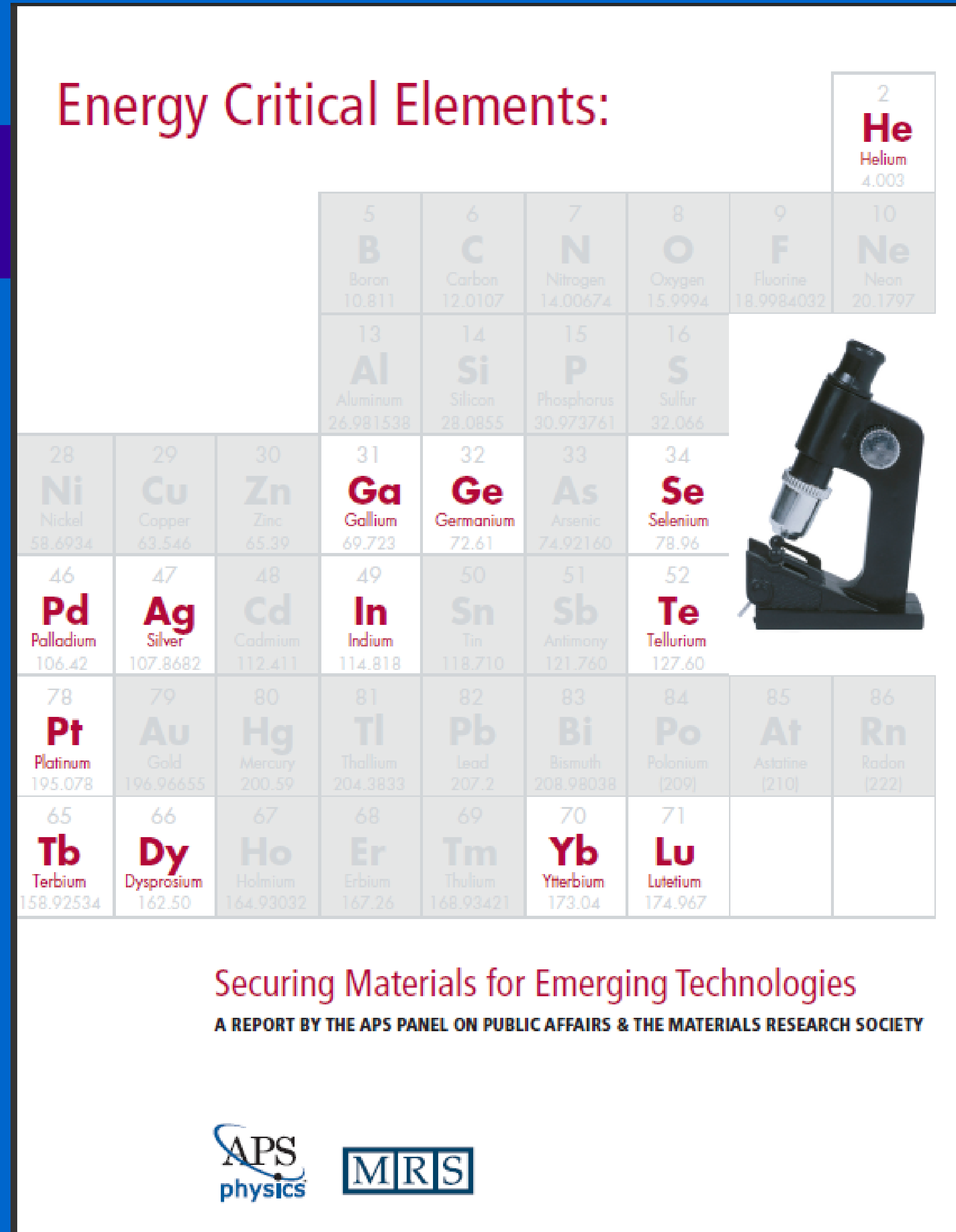
2014 Minerals Yearbook

RARE EARTHS [ADVANCE RELEASE]

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

December 2016

https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2014-raree.pdf



Energy Critical Elements:

								2 He Helium 4.003
			5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
			13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066		
28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96		
46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60		
78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967		

Securing Materials for Emerging Technologies

A REPORT BY THE APS PANEL ON PUBLIC AFFAIRS & THE MATERIALS RESEARCH SOCIETY

APS physics MRS

http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=236337

Congressional Research Service

Rare Earth Elements: The Global Supply Chain

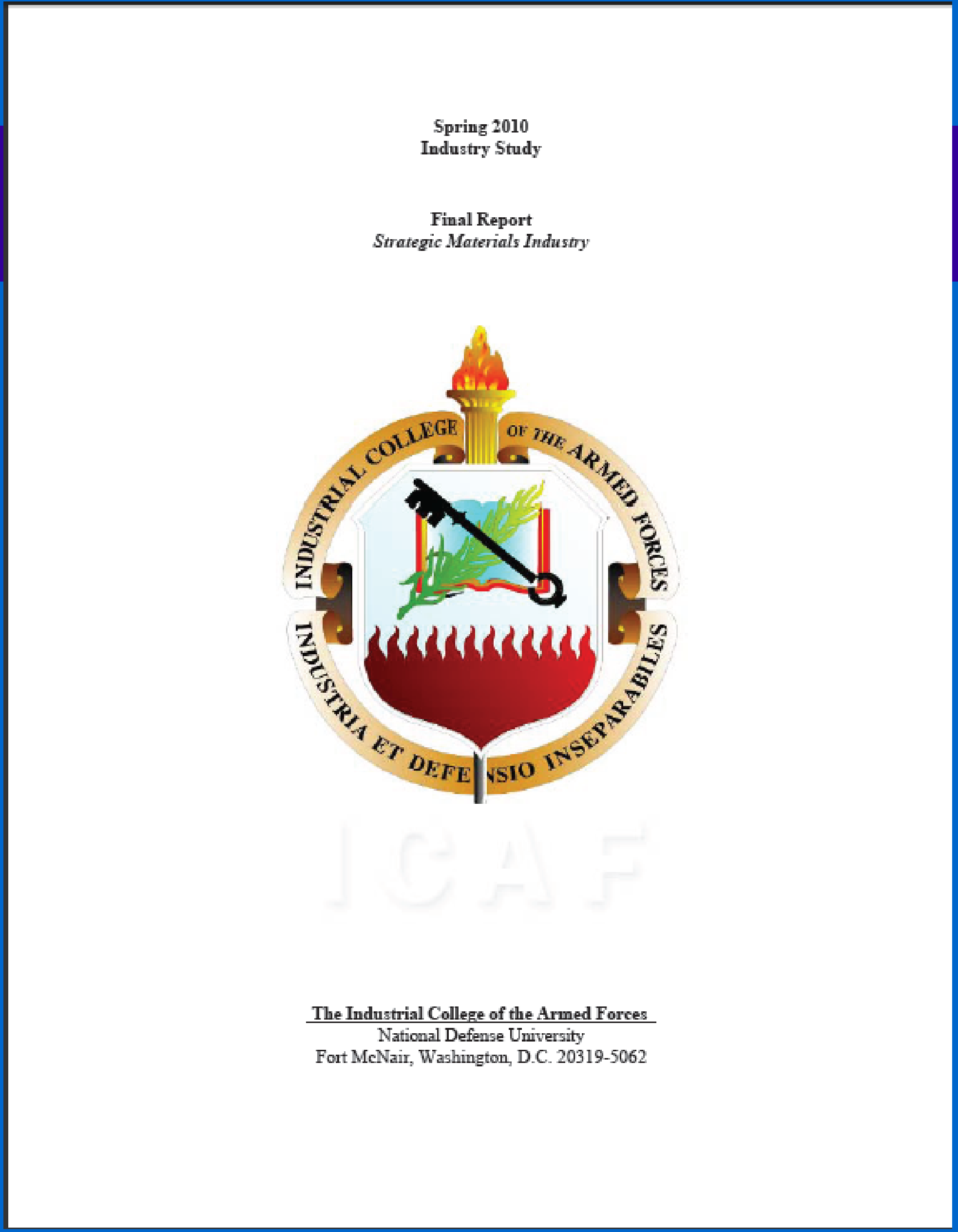
Marc Humphries
Specialist in Energy Policy

June 8, 2012

Congressional Research Service
7-5700
www.crs.gov
R41347

CRS Report for Congress
Prepared for Members and Committees of Congress

http://www.fas.org/sgp/crs/natsec/R41347.pdf



Spring 2010
Industry Study

Final Report
Strategic Materials Industry

The Industrial College of the Armed Forces
National Defense University
Fort McNair, Washington, D.C. 20319-5062

http://www.ndu.edu/es/programs/academic/industry/reports/2010/pdf/icaf-is-report-strategic-mat-2010.pdf

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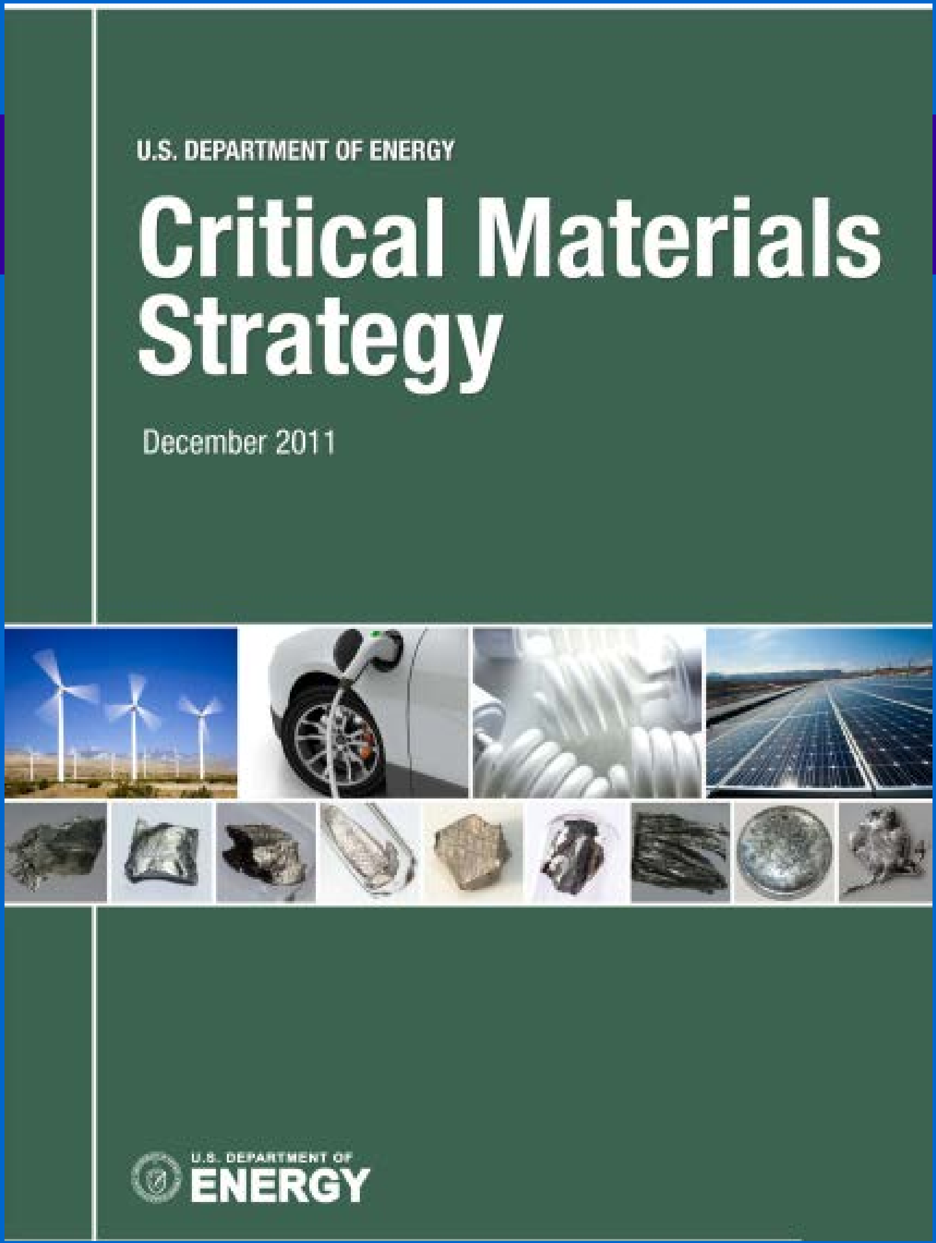
Rare Earth Materials in the Defense Supply Chain

Briefing for Congressional Committees
April 1, 2010

http://www.gao.gov/new.items/d10617r.pdf



http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Rare Earth Elements

November 2011

MineralsUK
Centre for sustainable mineral development

Mineral profile

Definitions, mineralogy and deposits

Definitions and characteristics

The rare earth elements (REE) (sometimes referred to as the rare earth metals) are a group of 17 chemically similar metallic elements, including the 15 lanthanides, scandium and yttrium. The lanthanides are elements spanning atomic numbers 57 (lanthanum, La) to 71 (lutetium, Lu) (Table 1). The lanthanides all occur in nature, although promethium[1], the rarest, only occurs in trace quantities in natural materials as it has no long-lived or stable isotopes (Castor and Hedrick, 2006). Scandium and yttrium are considered REE as they have similar chemical and physical properties. Separation of the individual REE was a difficult challenge for chemists in the 18th and 19th centuries, and consequently it was not until the 20th century that they were all identified. On account of their chemical similarity the REE can very easily substitute for one another making refinement to pure metal difficult.

The term rare earth is a misnomer arising from the rarity of the minerals from which they were originally isolated (Figures 1 and 2). In contrast REEs are relatively plentiful in the Earth's crust having an overall crustal abundance of 9.2 ppm (Rudnick et al. 2003). The crustal abundance of individual REE varies widely, from cerium the most abundant at 43 ppm (exceeding other important metals including copper — 27 ppm and lead — 11 ppm) to 0.28 ppm for thulium (Taylor and McLennan, 1985; Rudnick et al. 2003).

The lanthanides are commonly divided into: lower atomic weight elements, lanthanum through to europium, referred to as the light rare earth elements (LREE) and the heavy rare earth elements (HREE) — gadolinium through to lutetium and yttrium (Table 1). Yttrium is usually grouped with the HREE because of its chemical similarity. The division is somewhat arbitrary and the term middle REE (MREE) is sometimes used to refer to those elements between europium to dysprosium (Samson and Wood, 2004). The relative abundance of the REE varies

1 Promethium is a radioactive element.

Element	Symbol	Atomic number	Atomic weight	Density (gcm^{-3})	Melting Point (°C)	Vicker's hardness, (10 kg load, kg/mm^2
Scandium	Sc	21	44.95	2.989	1541	85
Yttrium	Y	39	88.90	4.469	1522	38
Lanthanum	La	57	138.90	6.146	918	37
Cerium	Ce	58	140.11	6.160	798	24
Praseodymium	Pr	59	140.90	6.773	931	37
Neodymium	Nd	60	144.24	7.008	1021	35
Promethium[1]	Pm	61	145.00	7.264	1042	-
Samarium	Sm	62	150.36	7.520	1074	45
Europium	Eu	63	151.96	5.244	822	17
Gadolinium	Gd	64	157.25	7.901	1313	57
Terbium	Tb	65	158.92	8.230	1356	46
Dysprosium	Dy	66	162.50	8.551	1412	42
Holmium	Ho	67	164.93	8.795	1474	42
Erbium	Er	68	167.26	9.066	1529	44
Thulium	Tm	69	168.93	9.321	1545	48
Ytterbium	Yb	70	173.04	6.966	819	21
Lutetium	Lu	71	174.97	9.841	1663	77

Table 1 Selected properties of the REE. Compiled from Gupta and Krishnamurthy (2005).

Figure 1 Elongate prismatic fergusonite in an open cavity associated with albite and quartz, Arran, Scotland. Photograph: Fergus MacTaggart, BGS © NERC.

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=7&ved=0CHAQFjAG&url=http%3A%2F%2Fwww.bgs.ac.uk%2Fdownloads%2Fstart.cfm%3Fid%3D1638&ei=PbwvUd3IMOryigK-g4DYAg&usg=AFQjCNHv3zX_vBeh3VCZkL5RYzQyWymvBg&sig2=N4NSi7WNik2vt_XKY_2dfA

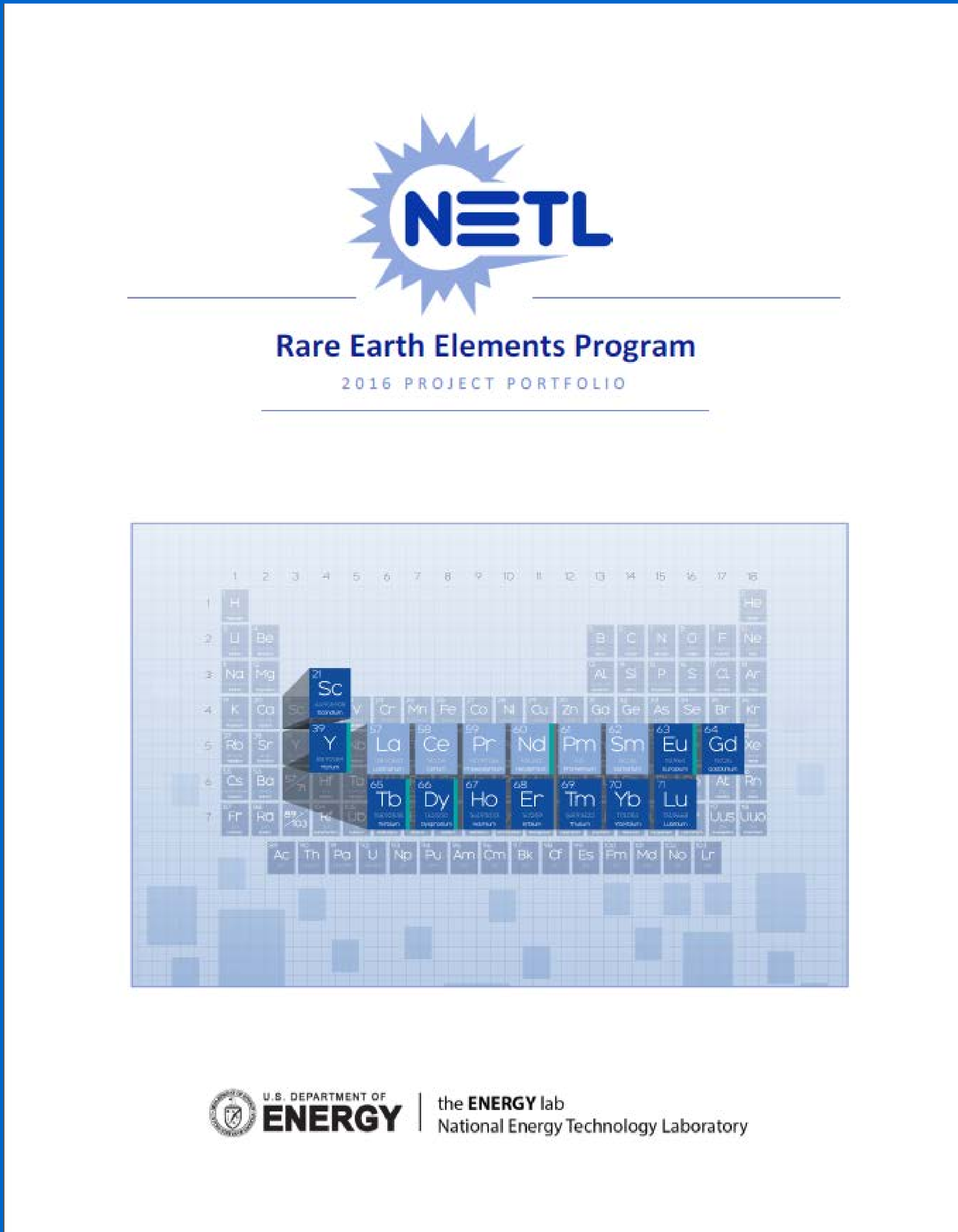
USGS
science for a changing world

The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective

Scientific Investigations Report 2010–5220

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

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


NETL

Rare Earth Elements Program

2016 PROJECT PORTFOLIO

U.S. DEPARTMENT OF ENERGY | the ENERGY lab National Energy Technology Laboratory

https://www.netl.doe.gov/File%20Library/Research/Coal/Rare%20Earth%20Elements/REE-Project-Portfolio-2016.pdf

USES

- 1970s: Rare earth mineral concentrates.
- 1980s: Mixed rare earth chemical concentrates.
- Early1990s: Separated rare earth oxides and metals.
- Late 1990s: Magnets, phosphors, polishing powders.
- 2000s: Electric motors, computers, batteries, LCDs, mobile phones.

Off Road Vehicles

Electric Diesels

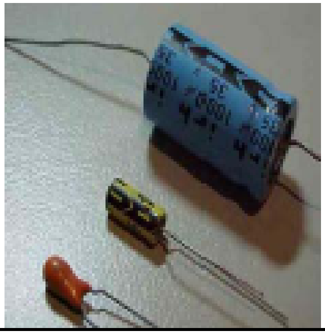
Electric Motor Scooters

JSF and More Electric Aircraft

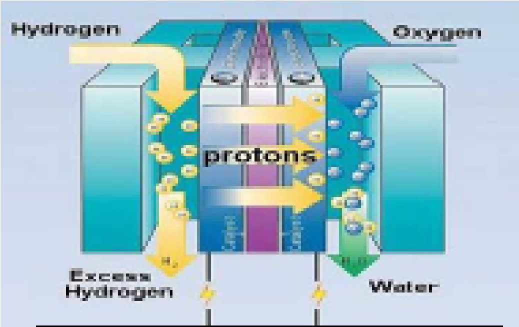
CHPS Future Combat Systems

Zumwalt DDG 1000

Maglev Trains



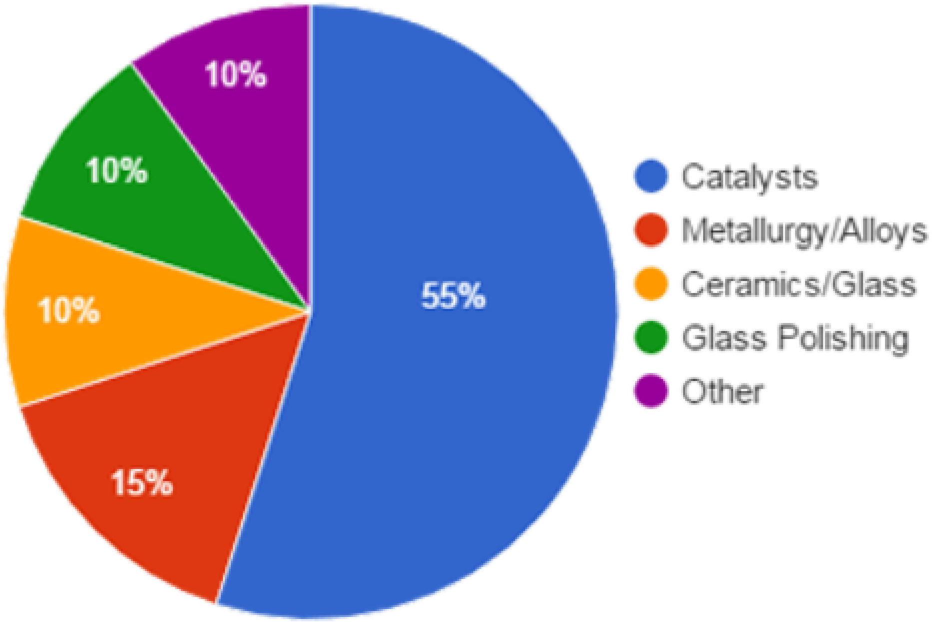
High Energy Density Capacitors



Fuel Cell Systems

REE are so important because each atom of these elements is able to readily give up or accept electrons, which is an important property required to allow magnets, optics, electronics and other applications to work.

Uses of Rare Earth Elements



Uses in the United States as reported by the United States Geological Survey Mineral Commodity Summary, 2017

Uses of rare earth elements: This chart shows the use of rare earth elements in the United States during 2013. Many vehicles use rare earth catalysts in their exhaust systems for air pollution control. A large number of alloys are made more durable by the addition of rare earth metals. Glass, granite, marble, and gemstones are often polished with cerium oxide powder. Many motors and generators contain magnets made with rare earth elements. Phosphors used in digital displays, monitors, and televisions are created with rare earth oxides. Most computer, cell phone, and electric vehicle batteries are made with rare earth metals.

Table 2. Examples of common applications of rare-earth elements.

Application	Chemical element[1]																
	Sc	Y	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Alloys and metallurgical uses	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Batteries			X	X	X	X	X				X						
Catalysts		X	X	X	X	X		X		X							X
Ceramics	X	X	X	X	X	X		X	X	X		X	X	X	X		X
Electronics		X	X	X	X	X					X	X		X			
Fertilizers			X	X		X											
Glass	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
Lamps	X	X	X	X	X			X	X		X	X	X	X	X		
Lasers	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Magnets				X	X	X		X	X	X	X	X	X				
Medical and pharmaceutical uses			X	X		X		X	X	X			X	X			X
Neutron absorption		X		X				X	X	X		X	X	X			
Phosphors	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X

[1]The symbols used for chemical elements in this table include the following (in order of atomic number): Sc, scandium; Y, yttrium, La, lanthanum; Ce, cerium; Pr, praseodymium; Nd, neodymium; Pm, promethium; Sm, samarium; Eu, europium; Gd, gadolinium; Tb, terbium; Dy, dysprosium; Ho, holmium; Er, erbium; Tm, thulium; Yb, ytterbium; and Lu, lutetium.

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

USES

- Chemical—unique electron configuration
- Catalytic—O storage and release
- Magnetic—high magnetic anisotropy and large magnetic moment
- Optical—fluorescence, high refractive index
- Electrical—high conductivity
- Metallurgical—efficient H storage in REE alloys

REE can not be substituted in most applications

USES THAT DEPEND UPON VALENCE AND SIZE

Mixed rare earths

- Petroleum cracking catalyst (also La, Ce)
- Mischmetal
  - lighter flints
  - alloy additive

Individual rare earth elements

- Nickel-metal(La)-hydride batteries
- Alloying agent (La, Ce, Nd, Y)

USES THAT DEPEND ON 4*f* ELECTRONS

Permanent Magnets

Nd, Pr, Sm, Dy

Phosphors

Eu (red, blue)

Tb (green)

fluorescent lamps

optical displays (TV, etc.)

Fiber optics

Er

USES THAT DEPEND ON THE ABSENCE OF ELECTRONIC TRANSITIONS IN UV, OPTICAL AND IR WAVE LENGTHS

- Optical lenses
  - La, Gd, Lu
- Phosphor hosts
  - Y, Gd
- Artificial gem stones
  - Y

USES THAT DEPEND UPON VALENCE CHANGES

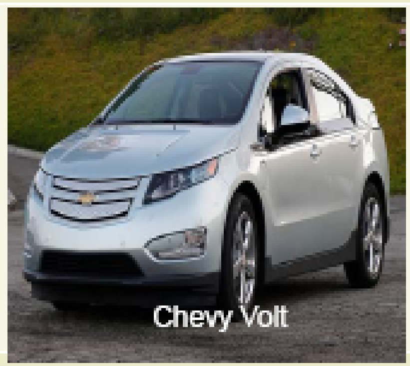
$Ce^{3+} \leftrightarrow Ce^{4+}$ $4f^1 \leftrightarrow 4f^0$

Automotive 3-way emission catalysts

UV light absorption

Polishing compounds

Clean energy

Applications		Typical Quantity of REO per unit
Traditional – disc drives, personal electronic devices, etc.		Grams
Hybrid and electric vehicles – direct drives and electric assist motors		Kilograms
Direct Drive Wind Turbines		Metric Ton

http://www.reitausa.org/storage/Challenges%20Facing%20New%20Global%20Rare%20Earth%20Separation%20Plants.pdf

Toyota Prius

2.2 lbs Nd in magnets

22-33 lbs La in batteries

http://www.molycorp.com/hybrid_ev.asp

Enabling digital technology

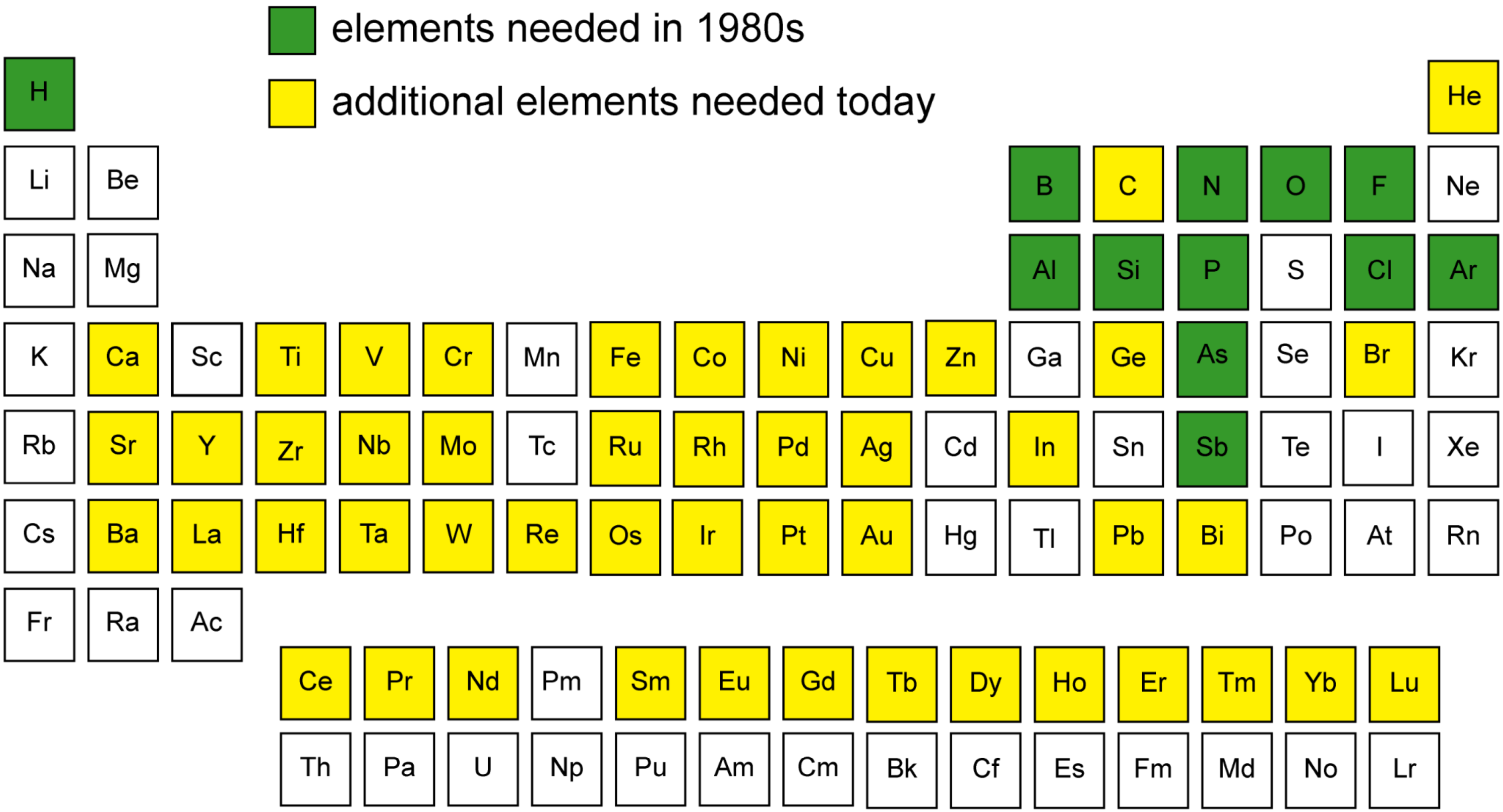
Demand of Rare Earths for Phosphors and Polishing Powders:

Tonnes per annum	2004	2005	AAGR% 2005-10	2010
Total REO Consumption Phosphors	3,652	4,007	13.0%	7,512
Total REO Consumption Polishing Powders	14,100	15,150	9.2%	23,500

AAGR is the Annual Average Growth Rate

http://www.lynascorp.com/Pages/what-are-rare-earths.aspx

Elements in Computer Chips
(National Research Council, 2007)

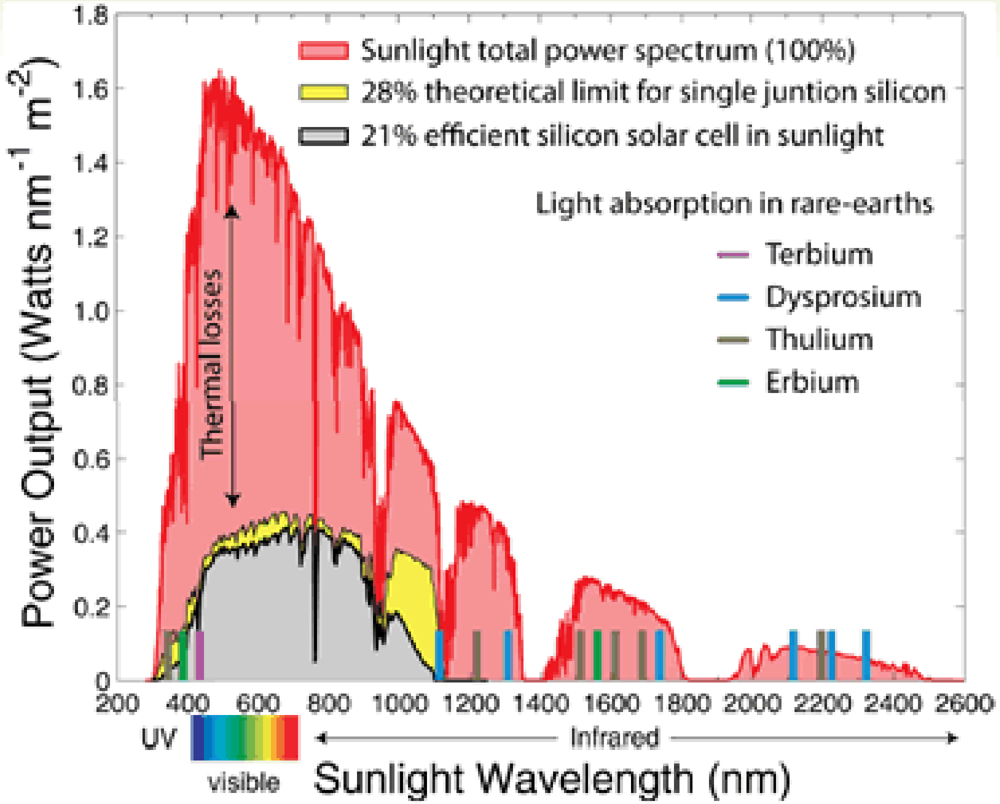


Improving energy efficiency

Fluid Cracking Catalysts (FCC) are used in the refining operation of crude oil and is the major contributor to "value-add" in the refining process. The process enables the transformation of heavy molecules into lighter compounds that make up gasoline and other fuels such as gas, jet fuel and diesel.

Application	Rare Earths	Demand Drivers
Magnets	**Nd, Pr,** Sm, Tb Dy	Drives for computers, mobile phones, mp3 players, cameras. Hybrid vehicle electric motors. Electric motors for luxury vehicles. Mag-lev trains.
LaNiH Batteries	**La,** Ce, Pr, Nd	Hybrid vehicle batteries. Hydrogen absorption alloys for re-chargeable batteries
Phosphors	**Eu, Y, Tb,** La, Dy, Ce, Pr, Gd	LCDs. PDPs. LEDs. Energy efficient fluorescent lights/lamps.
Fluid Cracking Catalysts	**La,** Ce, Pr, Nd	Petroleum production – greater consumption by 'heavy' oils and tar sands
Polishing Powders	**Ce,** La, Nd	Mechano-chemical polishing powders for TVs, monitors, mirrors and (in nano-particulate from) silicon chips.
Auto Catalysts	**Ce,** La, Nd	Tighter NO_x and SO_2 standards – platinum is re-cycled, but for rare earths it is not economic
Glass Additive	**Ce, La,** Nd, Er	Cerium cuts down transmission of uv light. La increases glass refractive index for digital camera lens.
Fibre Optics	**Er,** Y, Tb, Eu	Signal amplification

SOLAR POWER OUTPUT VS SOLAR SPECTRUM



- Conventional Silicon solar cell conversion limited to a small window of solar photon energies close to the band-gap energy of silicon – single junction limitation
- Using patented 'rare earth oxide' materials → conversion efficiency increased by harnessing a far greater fraction of available energy in the solar spectrum

http://www.australianrareearths.com/what-are-rare-earths.html

China: world's leading consumer? (Brown, 2005).

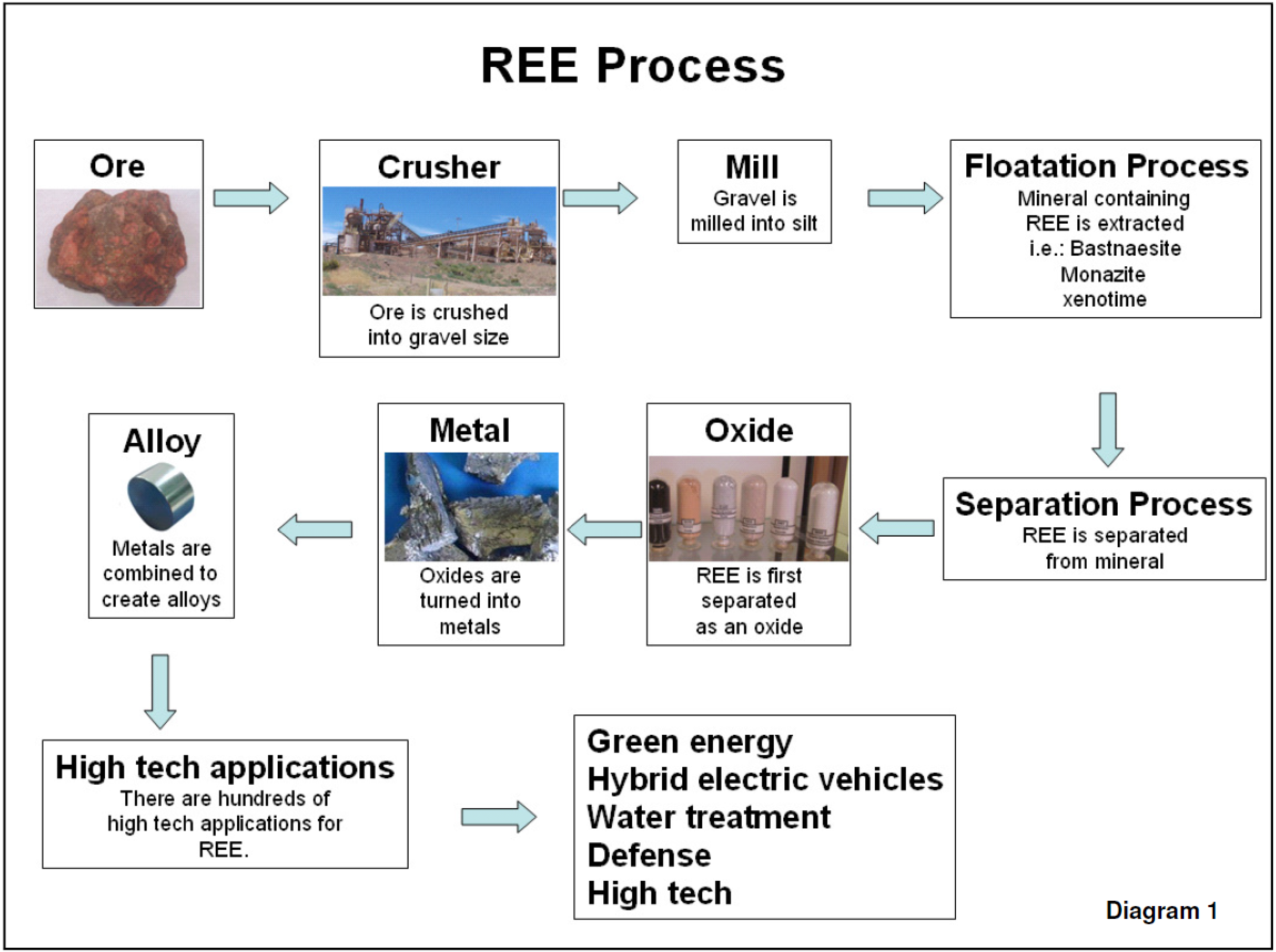
Cell phones — 7 million (1996) to 269 million (2003) in China vs. 44 million (1996) to 159 million (2003) in the United States.

Personal computers and laptops in 2002 — 36 million in China vs. 190 million in the United States, but China's number doubles every 28 months.

Televisions — 374 million in China vs. 243 million in the United States in 2000.

Refrigerators — China surpassed the United States in 2000.

Cars — 24 million in China vs. 226 million in the United States in 2003.



http://fmso.leavenworth.army.mil/documents/rareearth.p

How much REE are needed?

Table 3. Estimated weight (in metric tons) of rare-earth oxides contained in selected manufactured products that entered service in the United States in 2010 and in material containing rare-earth metals that was imported into the United States in 2010.

[Estimates are rounded to two significant figures. t, metric tons; dashes (--), no data; Do., ditto.; LED, light-emitting diode; OEM, original equipment manufacturer. Rare-earth oxides: CeO_2, cerium oxide; Dy_2O_3, dysprosium oxide; Er_2O_3, erbium oxide; Eu_2O_3, europium oxide; Gd_2O_3, gadolinium oxide; La_2O_3, lanthanum oxide; Lu_2O_3, lutetium oxide; Nd_2O_3, neodymium oxide; Pr_6O_{11}, praseodymium oxide; Sm_2O_3, samarium oxide; Tb_4O_7, terbium oxide; Y_2O_3, yttrium oxide]

General application	Product	CeO_2	Dy_2O_3	Er_2O_3	Eu_2O_3	Gd_2O_3	La_2O_3	Lu_2O_3	Nd_2O_3	Pr_6O_{11}	Sm_2O_3	Tb_4O_7	Y_2O_3	Undetermined rare-earth oxides
Mass of compound in manufactured products that entered service in 2010, in metric tons														
Alloys	Zinc-based coatings for light-gage steel supports[1]	5.6	--	--	--	--	2.4	--	--	--	--	--	--	--
Batteries	Electric and hybrid vehicles		--	--	--	--	4,000	--	--	--	--	--	--	--
Catalysts	Automotive catalytic converters	1,400	--	--	--	--		--	--	--	--	--	--	--
Do.	Fluid catalytic cracking (FCC) catalysts for petroleum refining	210	--	--	--	--	3,400	--	640	--	--	--	--	--
Magnets	Automotive (general applications)	--	4.5	--	--	--	--	--	76	--	--	--	--	--
Do.	Cell phone and other mobile devices	--	--	--	--	--	--	--	86	4.2	--	--	--	--
Do.	Electric and hybrid vehicle motors	--	40	--	--	--	--	--	300	--	--	--	--	--
Do.	Electronic power steering in vehicles	--	--	--	--	--	--	--	26	1.7	--	--	--	--
Do.	External disc drives for servers	--	--	--	--	--	--	--	61	4.2	--	--	--	--
Do.	Game consoles	--	--	--	--	--	--	--	64	4.5	--	--	--	--
Do.	OEM speakers in vehicles	--	--	--	--	--	--	--	7	5	--	--	--	--
Do.	Personal computers and laptops	--	--	--	--	--	--	--	440	30	--	--	--	--

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

How much REE are needed?

Table 3. Estimated weight (in metric tons) of rare-earth oxides contained in selected manufactured products that entered service in the United States in 2010 and in material containing rare-earth metals that was imported into the United States in 2010.—Continued

[Estimates are rounded to two significant figures. t, metric tons; dashes (--), no data; Do., ditto.; LED, light-emitting diode; OEM, original equipment manufacturer. Rare-earth oxides: CeO_2, cerium oxide; Dy_2O_3, dysprosium oxide; Er_2O_3, erbium oxide; Eu_2O_3, europium oxide; Gd_2O_3, gadolinium oxide; La_2O_3, lanthanum oxide; Lu_2O_3, lutetium oxide; Nd_2O_3, neodymium oxide; Pr_6O_{11}, praseodymium oxide; Sm_2O_3, samarium oxide; Tb_4O_7, terbium oxide; Y_2O_3, yttrium oxide]

General application	Product	CeO_2	Dy_2O_3	Er_2O_3	Eu_2O_3	Gd_2O_3	La_2O_3	Lu_2O_3	Nd_2O_3	Pr_6O_{11}	Sm_2O_3	Tb_4O_7	Y_2O_3	Undetermined rare-earth oxides
Mass of compound in manufactured products that entered service in 2010, in metric tons—Continued														
Phosphors	Fluorescent bulbs[2]	130	--	--	50	--	200	--	--	--	--	56	740	--
Phosphors and diodes	LED televisions[3]	0.0057	--	--	0.0049	--	--	--	--	--	--	--	0.11	--
Solutions	Imaging contrast dye	--	--	--	--	23 to 70	--	--	--	--	--	--	--	--
TOTAL		1,700	45		50	23 to 70	7,600		1,700	50		56	740	--
Mass of compound in materials imported in 2010, in metric tons														
Catalysts, electronics, fuel additives, glass, imaging contrast dyes, magnets, nuclear fuel rods, phosphors, polishing powders, and others	Imported refined metal and oxides, impure, and intermediate products[4, 5]	3,600	25	33	25	80	7,900	27	590	94	8.8	4.2	670	1,500[6]

[1]Includes only GALFAN®, which contains approximately 0.1 percent rare-earth oxide in a hot-dip coat that makes up about 2 percent of the total weight of the steel.

[2]Includes phosphors used in tube-type and compact fluorescent lights.

[3]Estimates are based on the number of LED televisions sold in the United States in 2010 and assumes a 42-inch screen.

[4]Some material may be exported in various forms. Estimate does not include finished products, such as contrast dye.

[5]Based on United Business Media Global Trade Port Import/Export Reporting Service (PIERS) data for 2010.

[6]Based on limited data. The material was assumed to be bastnäsite and was estimated to contain 740 t CeO_2, 510 t La_2O_3, 170 t Nd_2O_3; 62 t Pr_6O_{11}, and a small amount of other rare-earth oxides.

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

PRODUCTION

Salient Statistics—United States:	**2013**	**2014**	**2015**	**2016**	**2017e**
Production, bastnäsite concentrates	5,500	5,400	5,900	—	—
Imports:[2]					
Compounds:					
Cerium compounds	1,110	2,990	1,440	1,830	2,700
Other rare-earth compounds	7,330	9,260	7,720	9,650	9,300
Metals:					
Ferrocerium, alloys	313	371	356	269	290
Rare-earth metals, scandium, and yttrium	393	348	385	404	400
Exports:[2]					
Compounds:					
Cerium compounds	734	608	440	309	220
Other rare-earth compounds	5,570	3,780	4,540	281	420
Metals:					
Ferrocerium, alloys	1,420	1,640	1,220	943	1,300
Rare-earth metals, scandium, and yttrium	1,050	140	60	103	140
Consumption, apparent[3]	5,870	12,200	9,550	10,500	11,000
Price, dollars per kilogram, yearend[4]					
Cerium oxide, 99.5% minimum	5–6	4–5	2	2	3
Dysprosium oxide, 99.5% minimum	440–490	320–360	215–240	185–193	180–190
Europium oxide, 99.99% minimum	950–1,000	680–730	90–110	62–70	75–80
Lanthanum oxide, 99.5% minimum	6	5	2	2	3
Mischmetal, 65% cerium, 35% lanthanum	9–10	9–10	5–6	5–6	6
Neodymium oxide, 99.5% minimum	65–70	56–60	39–42	38–40	56–59
Terbium oxide, 99.99% minimum	800–850	590–640	410–470	410–425	470–480
Employment, mine and mill, annual average	380	391	351	—	—
Net import reliance[5] as a percentage of apparent consumption	6	56	38	100	100

Recycling: Limited quantities, from batteries, permanent magnets, and fluorescent lamps.

USGS Mineral Commodities Yearbook
metric tons

World Mine Production and Reserves:

	Mine production[8] 2016	Mine production[8] 2017	Reserves[7]
United States	—	—	1,400,000
Australia	15,000	20,000	[8]3,400,000
Brazil	2,200	2,000	22,000,000
Canada	—	—	830,000
China	[9]105,000	[9]105,000	44,000,000
Greenland	—	—	1,500,000
India	1,500	1,500	6,900,000
Malawi	—	—	140,000
Malaysia	300	300	30,000
Russia	2,800	3,000	[10]18,000,000
South Africa	—	—	860,000
Thailand	1,600	1,600	NA
Vietnam	220	100	22,000,000
World total (rounded)	129,000	130,000	120,000,000

World Resources: Rare earths are relatively abundant in the Earth's crust, but minable concentrations are less common than for most other ores. Resources are primarily in four geologic environments: carbonatites, alkaline igneous systems, ion-adsorption clay deposits, and monazite-xenotime-bearing placer deposits. Carbonatites and placer deposits are the leading sources of production of light rare-earth elements. Ion-adsorption clays are the leading source of production of heavy rare-earth elements.

USGS Mineral Commodities Yearbook
metric tons

Operating REE Mines

USGS

China

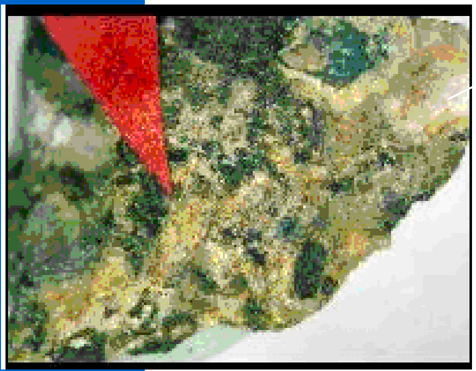
There are about 24 Chinese rare earth mining companies and 100 rare earth enterprises for separating, smelting and refining in China (Schüler et al. 2011). The Chinese industry is undergoing consolidation – mergers and acquisitions by large companies and the closing of small plants. Important rare earth mining companies in China are:

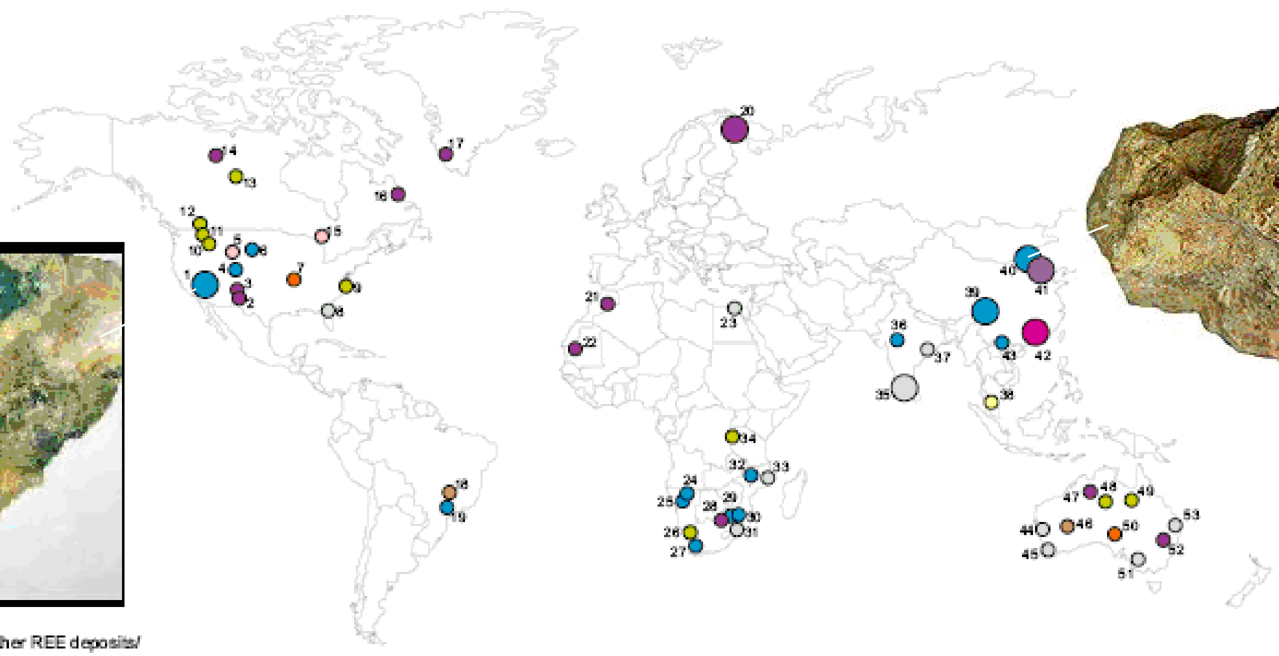
Companies in China	**Share of world production [%]**
Baotou Iron and Steel and Rare Earth Co. (Baogang Group)	~ 40
Minmetals Ganzhou Rare Earth Co. Ltd.	~ 25
Guangdong Zhujiang Rare Earths Co., Ltd.	~ 4
Hezhou Jinguang Rare Earth New Materials	~ 2
Shanghai Yaolong Nonferrous Metals Co.	~ 1.5
Jiangxi Rare Earths Co. (<1%)	< 1
Aluminum Corporation of China Limited (Chinalco)	

Important rare earth mining companies apart from China are:

Companies	**Share of world production [%]**
Molycorp Minerals LLC (Rare Earths Acquisitions LLC) **(USA)**	1.4
Lovozerskaya GOK **(Russia)**	1.4
Indian Rare Earths Limited **(India)**	< 1
Indústrias Nucleares do Brasil (INB) **(Brazil)**	

Rare Earth Elements





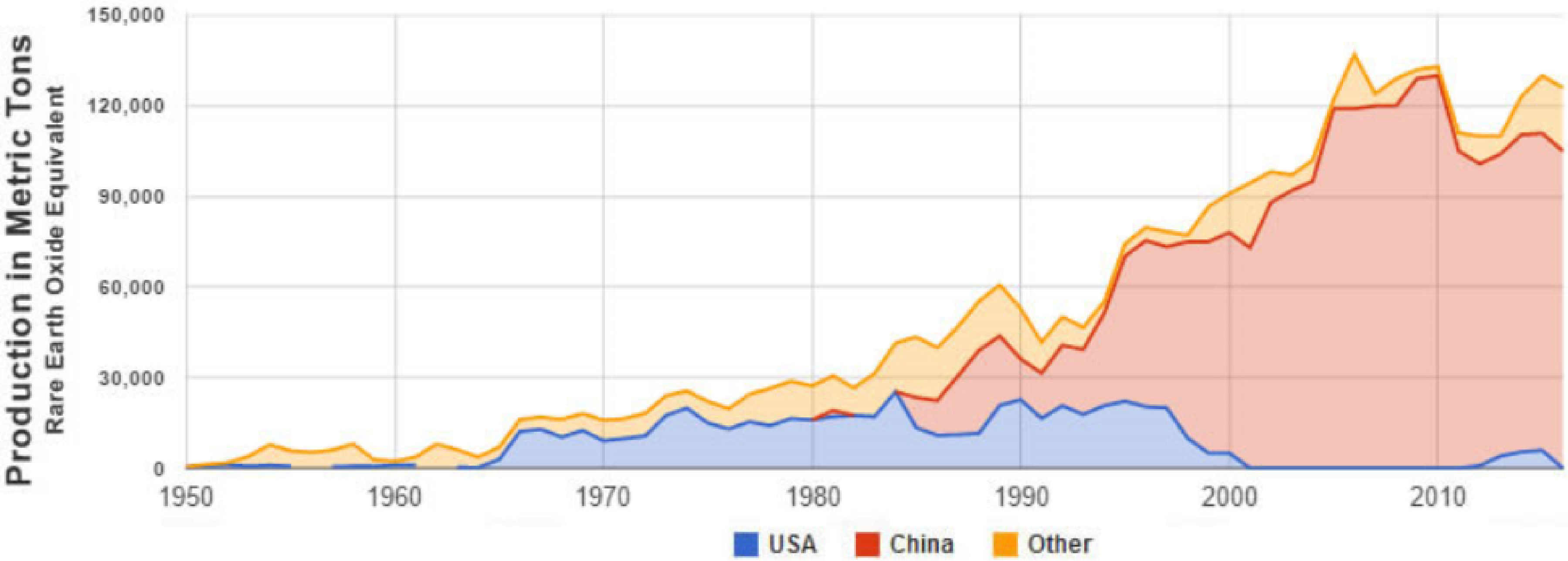
REE mines	Other REE deposits/ occurences		
●	●	Carbonatite-associated	Primary deposits
●	●	Alkaline igneous rock-associated	Primary deposits
	●	Iron-REE deposits	Primary deposits
	●	Hydrothermal deposits exclusive alkaline settings	Primary deposits
●	●	Marine placers	Secondary deposits
	●	Alluvial placers	Secondary deposits
	●	Paleoplacers	Secondary deposits
	●	Lateritic deposits	Secondary deposits
●	●	Ion-adsorption clays	Secondary deposits

1 Mountain Pass, USA
2 Pajarito Mountain, USA
3 Gallinas Mountains, USA
4 Iron Hill, USA
5 Bald Mountain, USA
6 Bear Lodge, USA
7 Pea Ridge, USA
8 Green Cove Springs, USA
9 Carolina placers, USA
10 Lemhi Pass, USA
11 Snowbird, USA
12 Rock Canyon Creek, Canada
13 Hoidas Lake, Canada
14 Thor Lake, Canada
15 Elliot Lake, Canada
16 Strange Lake, Canada
17 Ilimaussaq complex, Greenland
18 Araxa, Brazil
19 Barro do Itapirapua, Brazil
20 Lovozero and Khibina complexes, Russia
21 Tamazeght complex, Morocco
22 Bou Naga, Mauritania
23 Nile Delta and Rosetta, Egypt
24 Etaneno, Namibia
25 Okorusu, Namibia
26 Steenkampskraal, South Africa
27 Zandkopsdrift, South Africa
28 Pilanesberg Complex, South Africa
29 Naboomspruit, South Africa
30 Palabora, South Africa
31 Richards Bay, South Africa
32 Kangankunde, Malawi
33 Congolone, Mozambique
34 Karonge, Burundi
35 Chavara, India
36 Amba Dongar, India
37 Orissa, India
38 Perak, Malaysia
39 Maoniuping/Dalucao, China
40 Bayan Obo, China
41 Weishan, China,
42 Xunwu/Longnan, China
43 Dong Pao, Vietnam
44 Eneabba, Australia
45 Jangardup, Australia
46 Mount Weld, Australia
47 Brockman, Australia
48 Nolans Bore, Australia
49 Mary Kathleen, Australia
50 Olympic Dam, Australia
51 WIM 150, Australia
52 Dubbo Zirconia, Australia
53 Fraser Island, Australia

Figure 1 Map showing the global distribution of REE deposits.

REE - Rare Earth Elements and their Uses

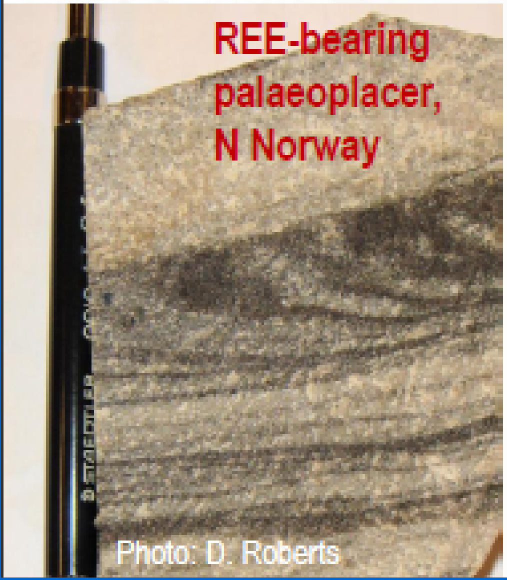
The demand for rare earth elements has grown rapidly, but their occurrence in minable deposits is limited.



Rare Earth Element Production: This chart shows a history of rare earth element production, in metric tons of rare earth oxide equivalent, between 1950 and 2016. It clearly shows the United States' entry into the market in the mid-1960s when color television exploded demand. When China began selling rare earths at very low prices in the late-1980s and early-1990s, mines in the United States were forced to close because they could no longer make a profit. When China cut exports in 2010, rare earth prices skyrocketed. That motivated new production in the United States, Australia, Russia, Thailand, Malaysia, and other countries. In 2016, rare earth production in the United States stopped as the only remaining mine was put on care and maintenance.


Salmon Bay, AK
Bokan Mtn, AK
Hall Mtn
MT
Placers
Diamond Creek
Lemhi Pass
ID
Bear Lodge Mtns
WY
NE
Elk Creek
IL
MO
Hicks Dome
Pea Ridge
CO
Iron Hill
Wet Mtns
CA
Mountain Pass
Petaca
Laughlin Peak
El Porvenir
NM
Music Valley
Lemitar Mtns
Chupadera Mtns
Gallinas Mtns
Capitan Mtns
Gold Hill
Red Hills
Wind Mtn
Mineville
NY
NC
Placers
SC
GA
Placers
FL
Land-pebble Phosphate Field
USGS SIR10-5220

Yttrium, erbium, terbium and ytterbium all have their names from Ytterby: also holmium, thulium and gadolinium were first discovered in minerals from Ytterby.



Rare Earth Elements

- **World production** was 123 000 t in 2010 (BGS, 2011)
- REE are not so rare (0,3 – 64 g/t in the crust), except Pm
- The ores contain several REE (usually also U and Th): processing is challenging
- **554** projects outside China, few in Europe outside Norden, NW Russia
- **Main uses**: Catalysts, magnets, metallurgical applications, phosphors ++ Several REE have properties which are uniquely important in a wide range of high-tech applications.

Potential in Europe includes:

- REE in alkaline intrusions, carbonatites, skarn, + related pegmatites, e.g. Norra Kärr (Sweden) – **60 Mt @ 0.54% TREO + 1.72% ZrO_2**
- REE in apatite (e.g. Kiruna (Sweden) – study in progress)
- Beach sands (e.g. Peramos (Greece) - **5.7 Mt @ 1.17 % REE**)
- New deposit types, e.g. palaeoplacers
- Lovozero (Kola Peninsula) (reserves **>200 Mt @ >1.2% REE**) is in ?sporadic production

Project	Owner	Asset Location	Listing	Market Cap (US$M)	Resources (REO)	Stage	Capacity (REO tpa)	Start Up
Kvanefjeld	Greenland Minerals & Energy	Greenland	ASX	$150	10.3Mt	Feasibility	44,000+	2016
Mountain Pass	Molycorp	CA, USA	NYSE	$1,100	1.8 Mt	Commissioning	37,000	2012
Mt Weld	Lynas Corp	WA, Australia	ASX	$1,200	1.8 Mt	Construction	21,000	2012
Nechalacho	Avalon Rare Metals	NT, Canada	TSX	$200	4.35 Mt	Feasibility	8,000	2016
Strange Lake	Quest	QC, Canada	TSX-V	$75	2.4 Mt	Exploration	12,500	2017+
Zandkopsdrift	Frontier	South Africa	TSX-V	$70	0.94 Mt	Feasibility		2017
Nolans	Arafura	NT, Australia	ASX	$60	1.7 Mt	Feasibility	10,000	2017?
Dubbo Zirconia	Alkane Resources	NSW, Australia	ASX	$290	0.5 Mt	Feasibility	2,600	2015
Steenkampskraal	Great Western Minerals Group	South Africa	TSX-V	$115	0.03Mt	Construction	2,700	2013?

http://www.australianrareearths.com/images/rees-by-company-country-ex-china.gif

Global Rare Earth Deposits

Deposit	Location	Owner	Status	In-situ	TREO	HREO	Ratio
Kangankunde	Malawi	LYC	Inf	2.5mt	107,019	759	0.7%
Steenkampskraal	Sth Africa	GWG	Hist	0.3mt	29,125	2,246	7.7%
Hoidas Lake	Canada	GWG	M+Ind+Inf	2.9mt	68,400	2,563	3.7%
Eco Ridge	Canada	GEM	Ind+Inf	47.4mt	66,402	5,218	7.9%
Sarfartoq	Greenland	HUD	Inf	14.1mt	216,946	5,623	2.6%
Mountain Pass	USA	MCP	M+Ind+Inf	31.6mt	2,066,525	9,466	0.5%
Bokan	Alaska	UCU	Inf	3.7mt	27,525	10,530	38.3%
Bear Lodge	USA	RES	Inf	21.2mt	795,000	20,691	2.6%
Kutessay II	Kyrgyzstan	HRE	Inf	18.0mt	46,800	25,000	53.4%
Nolans Bore	Aust	ARU	M+Ind+Inf	46.0mt	1,150,000	35,995	3.1%
Zeus (Kipawa)	Canada	MAT	Ind+Inf	24.5mt	101,957	36,551	35.8%
Hastings	**Aust**	**HAS**	**Ind+Inf**	**36.2mt**	**76,020**	**65,160**	**85.7%**
Zandkopsdrift	Sth Africa	FRO	Inf	43.7mt	944,568	69,968	7.4%
Mt Weld	Aust	LYC	M+Ind+Inf	23.9mt	1,888,100	88,578	4.7%
Eldor	Canada	CCE	Inf	117.3mt	2,041,716	104,433	5.1%
Dubbo	Aust	ALK	Ind+Inf	73.2mt	651,480	167,960	25.8%
Norra Karr	Sweden	TSM	Inf	60.5mt	332,750	175,450	52.7%
Nechalacho	Canada	AVL	Ind+Inf	315.0mt	4,284,000	660,206	15.4%
Strange Lake	Canada	QRM	Ind+Inf	229.8mt	2,091,180	853,860	40.8%
Kvanefjeld	Greenland	GGG	Ind+Inf	861.0mt	9,212,700	1,103,802	12.0%

Owner	Stock Exchange Ticker Code (ASX and TSX)
Status	M = Measures, Ind = Indicated, Inf = Inferred, Hist = Historical
In-situ	Ore Tonnes
TREO	Total Rare Earth Oxides (Contained)
HREO	Heavy Rare Earth Oxides (Contained)
Ratio	Ratio of HREO to TREO
	HREO Deposit (Ratio greater than 30%)

http://www.australianrareearths.com/known-rees-resources-reserves.html

Table 1. Percentage distribution of rare-earth elements by type of ore at major production sites in the United States and China.

[Data are percentage of total rare-earth elements in ore and are rounded to no more than three significant digits; may not add to totals shown. Rare-earth elements are listed in ascending order of atomic number]

Rare-earth element	Bastnäsite		Monazite
	Mountain Pass, Calif., United States[1]	Bayan Obo, Inner Mongolia, China[2]	Nangang, Guangdong, China[3]
Yttrium	0.10	trace	2.40
Lanthanum	33.20	23.00	23.00
Cerium	49.10	50.00	42.70
Praseodymium	4.34	6.20	4.10
Neodymium	12.00	18.50	17.00
Samarium	0.80	0.80	3.00
Europium	0.10	0.20	0.10
Gadolinium	0.20	0.70	2.00
Terbium	trace	0.10	0.70
Dysprosium	trace	0.10	0.80
Holmium	trace	trace	0.12
Erbium	trace	trace	0.30
Thulium	trace	trace	trace
Ytterbium	trace	trace	2.40
Lutetium	trace	trace	0.14
Total	100	100	100
	Xenotime	**Rare-earth laterite**	
	Southeast Guangdong, China[4]	Xunwu, Jiangxi Province, China[5]	Longnan, Jiangxi Province, China[5]
Yttrium	59.30	8.00	65.00
Lanthanum	1.20	43.40	1.82
Cerium	3.00	2.40	0.40
Praseodymium	0.60	9.00	0.70
Neodymium	3.50	31.70	3.00
Samarium	2.20	3.90	2.80
Europium	0.20	0.50	0.10

https://pubs.usgs.gov/of/2013/1072/OFR2013-1072.pdf

China's rare earth monopoly operates on 4 levels:

1. Mining: Basic Resource Production Monopoly

2. Value Chain: Integration Monopoly

3. Industry & IP Capture: Leverage & Control over All End-Users

4. Supplication & Resource Redirection

---

1. Mining: Basic Resource Production Monopoly

a. Mining REs without a supporting domestic value chain is pointless because RE concentrates & oxides are useless to technology & defense end-users

b. Consequently, these RE resource would need to pass through China which has the world's only fully integrated value chain and necessary capacity

c. Realistically, China will undercut western production costs, resulting in bankruptcies, as evidenced by Molycorp's bankruptcy and all other *'ongoing'* non-Chinese producers

2. Value Chain: Integration monopoly:

a. Free market actors cannot be expected to establish any part of the value chain through independent action because the capital required is significantly higher than what is required for resource production (mining), and is at risk of bankruptcy through Chinese manipulation at the value chain level and indirectly through the resource supply level.

b. China's value chain consists of over 400 companies that produce over 1000 ultra-high specification products spanning two cities, referred to by the Chinese government as *'rare earth cities',* with a combined population of 17 million people.

c. U.S. Corporations are exclusively motivated by short term profits. Relocating to China typically results in higher profits in the short-term.

    i. Short term profit incentives for publicly traded companies outweigh long term consequences. This fuels China's aggressive mercantilist strategy of knocking off non-Chinese producers through relocation and the incremental capture of their technologies and industries

d. China can bankrupt the value chain directly or bankrupt the resource supplier (the rare earth mine(s)): a two-tiered strategy.

3. Industry & IP Capture: Leverage & Control over End-Users

a. China is the only country that can guarantee an uninterruptable flow of value added rare earths.

b. China uses its monopoly control over rare earths to incrementally capture non-Chinese technologies and manufacturing: first by capturing the production of rare earth dependent components, then component sub-assemblies, then product lines, then entire industries.
   - China has already captured much of the world's RE dependent technology and RE end-users because most of the world's leading technologies, consumer goods, commercial goods, industrial goods and defense systems are rare earth dependent.

c. Now under China's control, China can use carrot-and-stick incentives to force these Chinese dependent companies to continue to use Chinese only value added rare earth products and prevent these companies from developing or supporting the emergence of alternative non-Chinese supply lines through the implied threat of supply disruption.
   - This threat is greatly compounded for defense contractors who may be utilizing Chinese materials without federally required 'waivers' to do so (a federal crime)

d. As time goes on, China's relative position in all of the above increases. Eventually all rare earth related technology, IP and manufacturing ends up in China
   - Japan is the only exception, but they are losing ground to China

e. Soon China's control over global technology, markets and economics will become unassailable as it continues to expand far outside the confines of rare earth related technologies, products and industries

Supplication & Resource Redirection:

a. China will eventually run out of rare earths, but before that happens,

b. China's next play will be to make the rest of the world its resource supplier

c. China will allow supplicant non-Chinese producers to feed China's rare earth value chain, but China will retain its monopoly at the value adding, metallurgy, component, system, product, industry and IP level.

- Molycorp was an example of resource supplication, as it became a supplier to China's metallurgical value chain.
- All new non-Chinese resource producers can be expected to follow the same strategy.

The potential viability of any other stand-alone RE projects is no different without China's sanction; as China *is the market and sets price*

Other issues

1. At the time Chinese rare earth industry publications disclosed that the Chinese mining industry maintained rare earth mining capacity equal to three-times global demand

   - Various Chinese publications, available on-line and in English, outlined China's internal production capacity and capabilities. Credible sources listed Chinese internal rare earth production capacity at three-times global demand (*much of this would later manifest as 'black market' production)
   - According to these same sources one-third of this capacity was decommissioned, beginning sometime in 2013*

2. Most of China's rare earth production was a byproduct of iron ore mining: having no direct mining cost

Circa 2010 – 2013: China's combined production capacity of rare earths exceeds three times global demand: Association of China Rare Earth Industry, Chinese Society of Rare Earths and other Chinese publications

Continued

3. Various commodities producers in the U.S. mining industry were already dumping the recoverable equivalent of at least 85% of global demand each year to avoid regulatory changes first implemented in 1980 (Part 75 of U.S. 10 CFR 40). These regulatory changes were ultimately responsible for transferring the rare earth industry to China in the first place
4. Raw rare earth resources and oxides had no high-value uses until they were converted into a useful form, such as metals, alloys, magnets, garnets, phosphors, etc.
5. China has the only fully integrated value chain with capacity to produce metals, alloys, magnets, garnets and other value added products from oxides
6. Japan has a limited value chain with no available capacity and Japanese industry continues to rely heavily on China to meet its internal / domestic needs

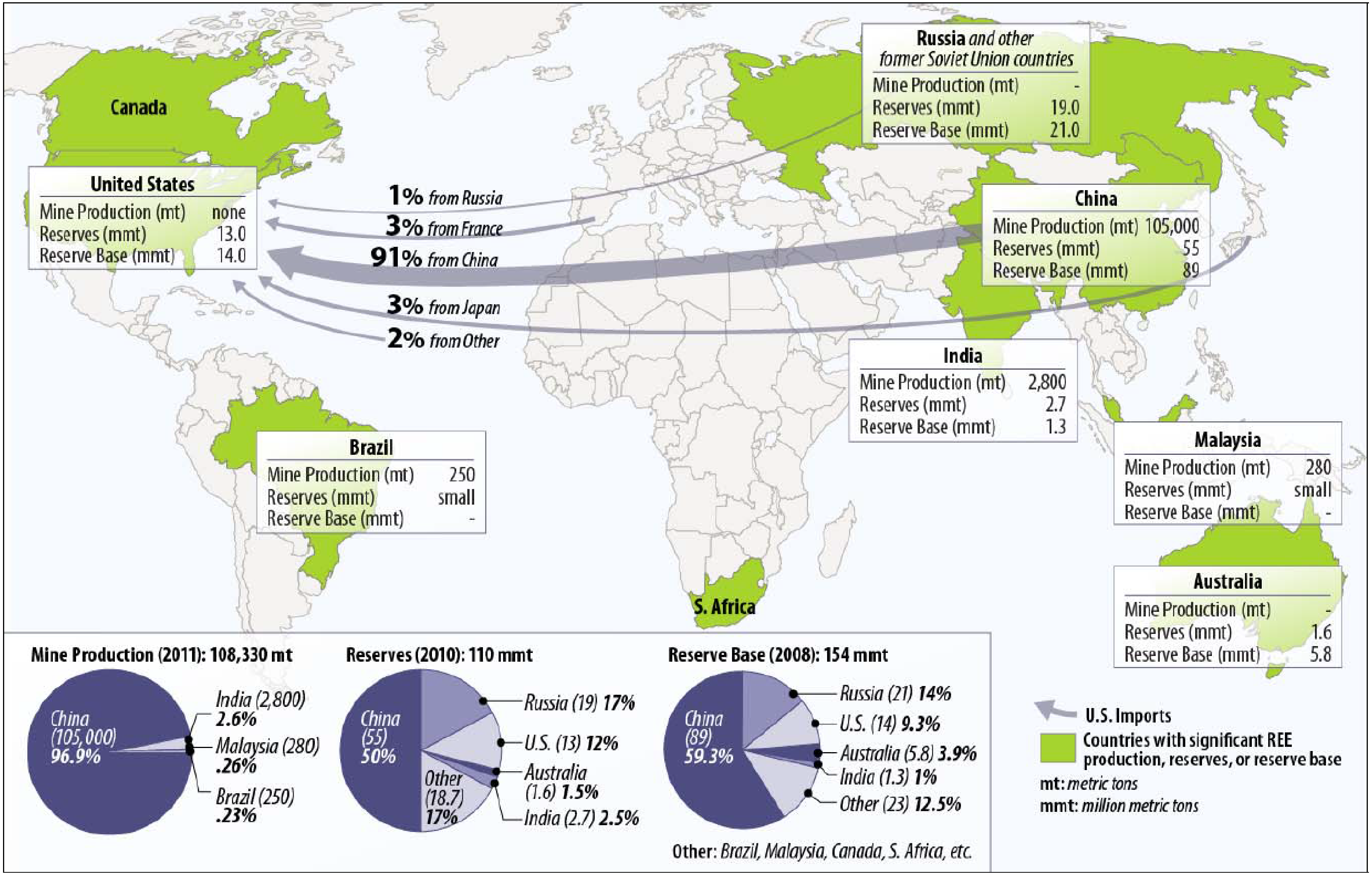
Continued

7. Japan was reluctant to expand internal rare earth value chain capabilities because Chinese pricing and control over the market for value added goods offered little or no profit and was ultimately subject to Chinese monopoly price and supply manipulation
8. The U.S. had no metallurgical or other value chain capabilities, because;

   a) China acquired, idled or bankrupt all U.S. value adding capabilities; as a consequence of the same-said regulations above

   b) U.S. corporations had no interest in investing or developing their own rare earth value chain capabilities because China provided these materials at reasonable prices and the cost of establishing their own value chains would greatly exceed any one company's projected demand of these materials over any time or return measure.

Figure 4. Rare Earth Elements: World Production, Reserves and U.S. Imports



Source: U.S. Geological Survey, Mineral Commodity Summaries, 2008-2013. (Figure created by CRS.)

https://fas.org/sgp/crs/natsec/R41347.pdf

Demand

Not all REE are equal

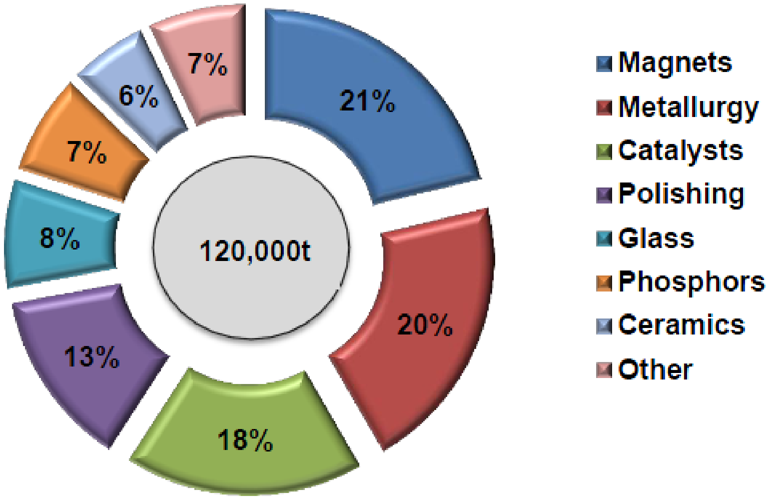
AND

Good substitutions for REE used in modern technology do not exist

Global demand for rare earths by end-use in 2012

- World 'official' production of REO ~110,000t in 2012, 85-90% in China
- World demand ~120,000t in 2012, 65-70% in China

World: Demand for rare earths by end-use, 2012 (%)



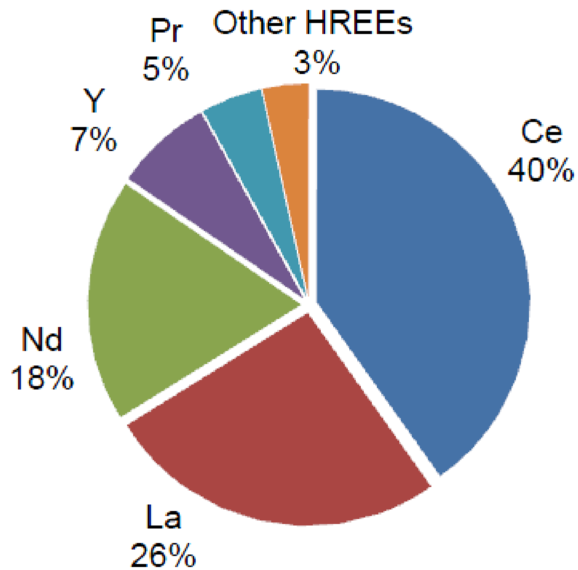
Source: Roskill estimates

Demand for rare earths by element in 2012

Other HREEs
magnets, lasers, phosphors, glass, metallurgy, other

Pr
magnets, phosphors, ceramics, metallurgy, polishing, other

Y
phosphors, ceramics, other



Ce
polishing, metallurgy, catalysts, glass, phosphors, ceramics, other

La
metallurgy, catalysts, glass, phosphors, ceramics, polishing, other

Nd
magnets, ceramics, metallurgy, glass, catalysts, phosphors, other

Source: Roskill estimates

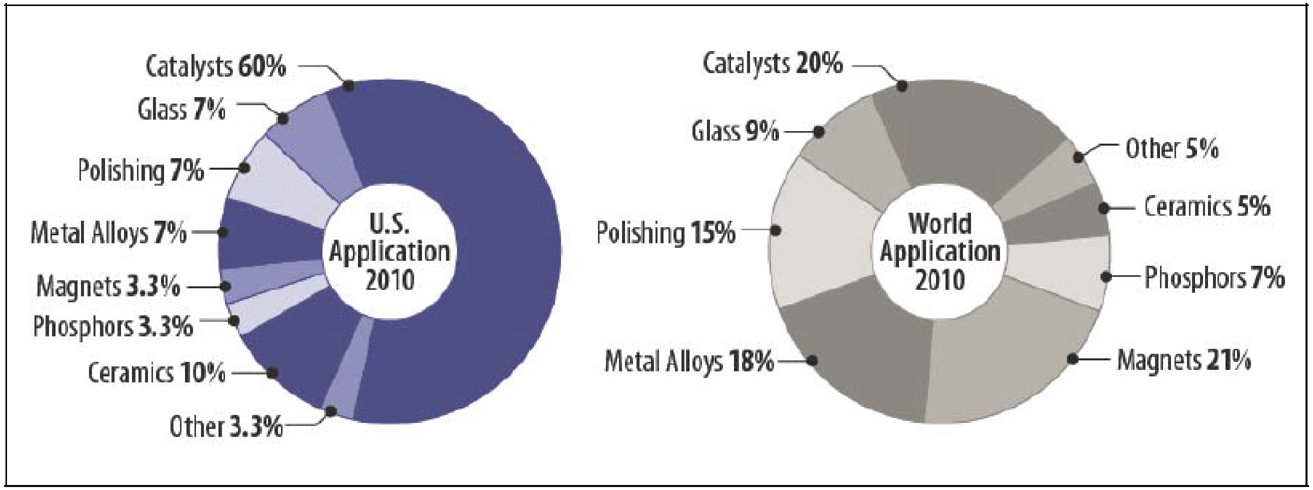
ARNOLD MAGNETIC TECHNOLOGIES

Roskill
Approachable. Independent. Expert.

Forecast Rates of Growth 2010-2020

Forecast Rare Earths Sector Rates of Growth 2010-2020			
Application	**Growth 2010-2015**	**Growth 2015-2020**	**Comments**
Catalysts	3-5%pa	3-5%pa	Growth rate unchanged through the decade.
Glass	Negligible	Negligible	Negligible growth rate as use in television and computer screens falling off rapidly.
Polishing	7-10%pa	8-12%pa	Until recently growth was forecast at 4-8%pa, but with increasing use in nano-particulate polishing powders for the electronic industry growth has been strong.
Metal Alloys	8-12%pa	4-8%	From 2010 to 2015 growth will be driven by the use of NiMH batteries in hybrid vehicles. IMCOA is of the view that meaningful substitution of hybrids by electric vehicles driven by Li-ion batteries will not occur before 2015/16.
Magnets	10-15%pa	10-15%pa	The real driver of demand in the next decade; price and availability a constraint. Could be greater than the indicated forecast if more of the rare earths used in permanent magnets were to become available.
Phosphors	6-10%pa	3-6%pa	New lighting devices under development use less rare earths, even though television and computer screens are getting bigger and being replaced more often.
Ceramics	6-8%pa	4-8%pa	Steady growth rates at historic rates.
Other	6-8%pa	4-8%pa	Barring the development of a new application with a high demand; steady growth rates at historic rates. Use of gadolinium for refrigeration is included.

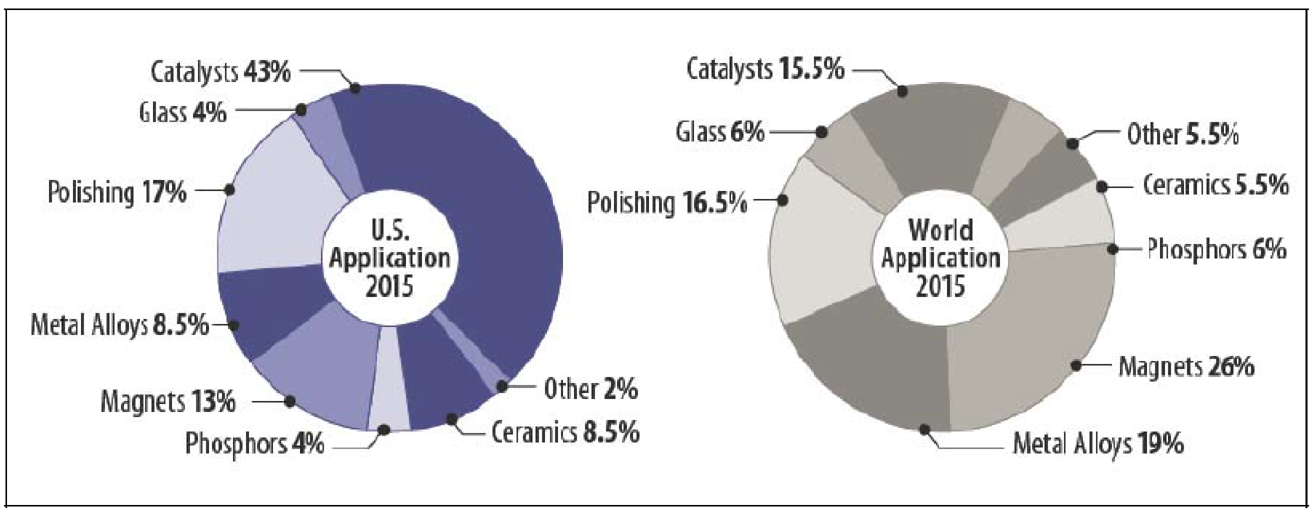
Figure 1. Rare Earth Demand by Application-U.S. and World, 2010



Source: IMCOA, 2011

Note: Figure created by CRS.

Figure 2. Rare Earth Demand by Application-U.S. and World, 2015



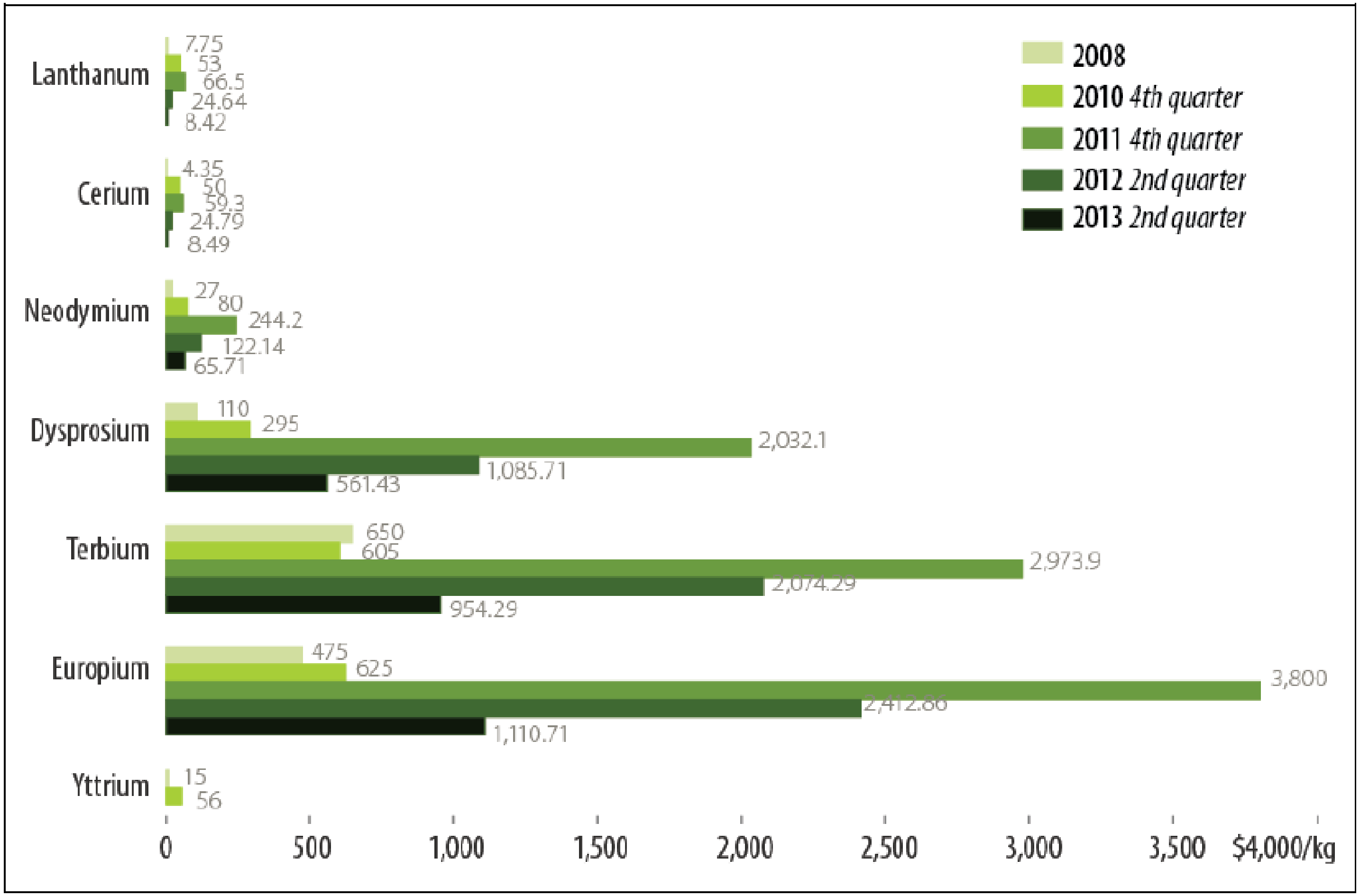
Source: IMCOA, 2011

Note: Figure created by CRS.

https://fas.org/sgp/crs/natsec/R41347.pdf

Figure 3. Selected Rare Earth Oxide Prices, 2008-2013

(US $/kg)



Source: IMCOA, 2011, 2013 and METI, 2011.

Notes: According to the Ministry of Economy Trade and Industry (METI) of Japan, prices for dysprosium and neodymium metals rose dramatically. The price for dysprosium metal rose from $250/kg in April 2010 to $2,840/kg by July 2011, while the price for neodymium metal rose from $42/kg in April 2010 to $334/kg in July 2011. 2011 prices taken from CRS Report R42510, *China's Rare Earth Industry and Export Regime: Economic and Trade Implications for the United States*, by Wayne M. Morrison and Rachel Y. Tang. Prices for 2012 (Q-2) and 2013 (Q-2) were obtained from the Lynas Corp. Ltd., Quarterly Report, June 2013.

https://fas.org/sgp/crs/natsec/R41347.pdf

FORECAST DEMAND FOR RARE EARTHS APPLICATIONS*

Application of separated Rare Earths products	2014 Demand Tonnes REO
Neodymium Rare Earths magnets	49,600
Nickel Metal Hydride battery alloy	32,500
Metallurgy applications excluding NiMH	12,700
Automotive catalytic convertors	12,200
Fluid Cracking Catalyst in oil refining	24,900
Glass polishing powder	20,600
Glass additives	7,800
Phosphors for lighting	10,800
Others	6,100
Total	**177,200**

* Forecasts are based on Lynas' current expectations and they are not guarantees of future events.

http://www.lynascorp.com/SiteCollectionDocuments/Fact%20Sheets/Rare_Earth_Applications.pdf

Key demand drivers and growth outlook

Sector	Segment	Sub Segments	Growth rate over GDP	Rare Earths used
Conventional Energy	Fuel Cracking Emissions control Nuclear	FCC Catalysts Material	+ 2%	La Ce Gd
Renewable Energy	Storage Wind turbines	NiMH Batteries Magnets	+10-15% +25-30%	La, Nd NdPr
Auto / Transportation	Emissions Control e-Mobility	Autocat Oxygen Sensors Magnets Batteries	+6-8% 0% +20-25% +20-25%	Ce Y NdPr, Dy La, Nd
Lighting	TC Lamps LEDs	Phosphors	+5%	Eu, Tb, Y, Ce, La
Metallurgy	Special Alloys	RE Silicides	+10-15%	CeLa
Electronics	GHD Cameras Displays Capacitors & chips	Polishing Materials Phosphors	+2-5% +5-10% 0% 0%	CeLa La Eu, Tb, Y, Ce, La Dy, Nd, Ce
Medical	MRI PET Scans Medicines	Magnets Crystals Material	+5-10% +10-15% +10-15%	Gd, NdPr Lu La
Miscellaneous	Defense Decorative Ceramics Agriculture	Niches		NdPr, Dy, La Ce, Pr Ce

Looming crisis - Rare Earths supply will be outstripped by demand; 115kt REO in 2010

CHINESE SUPPLY SOURCES (2010 CAPACITY, REO)	
Baotou	**55,000t**
▪ By product of iron ore mine	
▪ Moving to higher grade iron, with lower impurities and Rare Earths	
▪ Tailing facilities near capacity	
Sichuan	**10,000t**
▪ Jiangxi Copper to invest ¥1.2Bn	
▪ Target to increase value added	
▪ Capacity expected to increase	
Ionic clay regions	**35,000t**
▪ Reportedly 14 yrs of resource	
▪ Large amount of illegal mining	
▪ Government action taking effect	
Recycling	**3,300t**
Total	**103,300t**

NON CHINESE SUPPLY SOURCES (2010 CAPACITY, REO)	
India	**3,000t**
▪ Subsidiary of Indian AEA	
▪ Toyota Tsusho bought trading firm with Japanese distribution	
Russia	**4,000t**
▪ Limited expansion capacity	
▪ By product of Mg production	
Recycling	**1,500t**
▪ Magnet swarf	
▪ Batteries – future potential	
USA – Mountain Pass	**3,000t**
▪ Reprocessing stockpiles	
▪ Requires approx. US$530 million rebuild	
Total	**11,500t**

Source: Industry resources and Lynas research

Lynas CORPORATION LTD

Our assumptions show global supply at 170kt by 2014, compared to demand of 190kt

2014 FORECAST SUPPLY ASSUMPTIONS

SUPPLY SOURCES

• Baotou	60,000t
• Sichuan	20,000t
• Ionic Clay Regions	30,000t
• Recycling in China	4,000t
China Total	**114,000t**
• Mount Weld	22,000t
• Mountain Pass	20,000t
• Others (India & Russia)	12,000t
• Recycling outside China	1,800t
Outside China Total	**55,800t**
Grand Total	**169,800t**

KEY UNDERLYING ASSUMPTIONS

- Baotou – 10% production increase 2010 / 2014
- Sichuan – full production quota to be utilised
- Iconic Clay – 2010 reduced from 2008 reported levels due to news reports. 2014 reduced to double current production quota (conservative estimate, could be lower)
- Mountain Pass – full production (20,000tpa) achieved
- Recycling – 20% Nd, Pr & Dy recycled from previous year's magnet production (~30% SWARF losses)

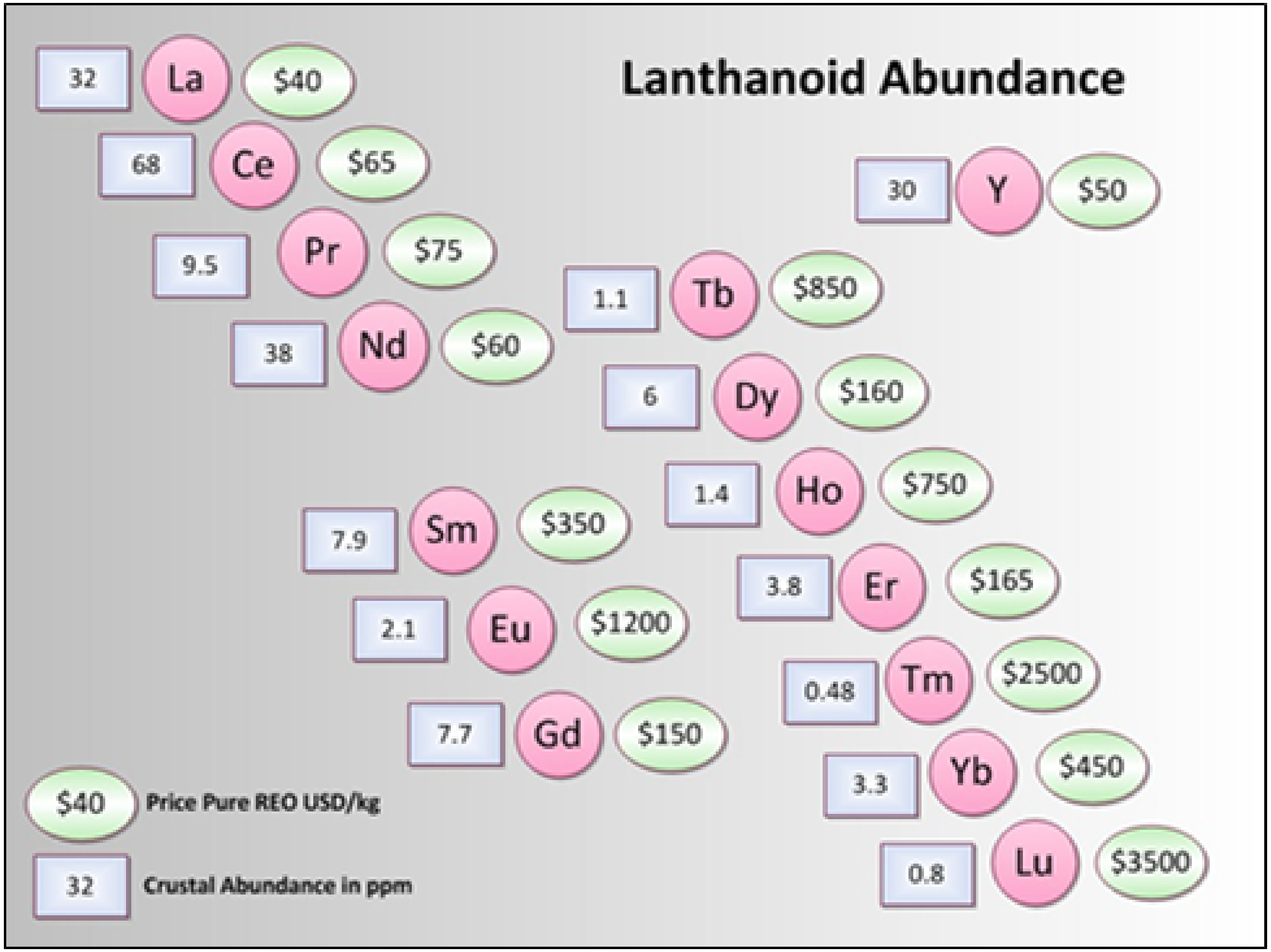
Table 1.2: Range of projected surpluses / deficits for select REOs

	2010e	2011p	2012p	2013p	2014p	2015p	2016p	2017p
La_2O_3	O	O	O	✔	✔ ✔	✔ ✔	✔ ✔ ✔	✔ ✔ ✔
CeO_2	O	O	O	✔	✔ ✔	✔ ✔ ✔	✔ ✔ ✔	✔ ✔ ✔
Nd_2O_3	✘	✘	✘	O	O	✔	✔ ✔	✔ ✔ ✔
Eu_2O_3	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘	O	✔ ✔	✔ ✔
Tb_4O_7	✘	✘	✘	✘	✘	O	✔ ✔	✔ ✔ ✔
Dy_2O_3	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘ ✘	O	✔
Y_2O_3	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘ ✘	✘	✔	✔ ✔
CREO	✘	✘	✘	✘	✘	✔	✔ ✔	✔ ✔ ✔

Supply as % demand: ✘ ✘ = 50-74% : ✘ = 75-94% : O = 95-105% : ✔ = 106-125% : ✔ ✔ = 126-150% : ✔ ✔ ✔ ≥ 151%

CREO = oxides of Nd, Eu, Tb, Dy & Y

Source: TMR estimates / projections



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.

USGS
OF2011-1189

ECONOMICS REE

RARE EARTH ELEMENTS—MINERALOGY

- 270 minerals
- Bastnaesite $LnFCO_3$
- Apatite > 5400 ppm total REE $Ca_5(PO_4)_3(OH,F,Cl)$
- monazite 500,000 ppm total REE $(Ln,Th)PO_4$
- manganese nodules 99,000 ppm total REE

TABLE 2

RARE EARTH CONTENTS OF SELECTED SOURCE MINERALS[1, 2]

(Percent of total rare-earth oxide)

Rare earth	Bastnäsite: Mountain Pass, CA, United States[3]	Bastnäsite: Bayan Obo, Nei Mongol, China[4]	Monazite: Mount Weld, Australia[5]	Monazite: Nangang, Guangdong, China[6]
Yttrium	0.10	trace	trace	2.40
Lanthanum	33.20	23.00	26.00	23.00
Cerium	49.10	50.00	51.00	42.70
Praseodymium	4.34	6.20	4.00	4.10
Neodymium	12.00	18.50	15.00	17.00
Samarium	0.80	0.80	1.80	3.00
Europium	0.10	0.20	0.40	0.10
Gadolinium	0.20	0.70	1.00	2.00
Terbium	trace	0.10	0.10	0.70
Dysprosium	trace	0.10	0.20	0.80
Holmium	trace	trace	0.10	0.12
Erbium	trace	trace	0.20	0.30
Thulium	trace	trace	trace	trace
Ytterbium	trace	trace	0.10	2.40
Lutetium	trace	trace	trace	0.14
Total	100	100	100	100

Rare earth	Loparite: Revda, Murmansk Oblast, Russia[7]	Rare earth laterite: Xunwu, Jiangxi Province, China[2]	Rare earth laterite: Longnan, Jiangxi Province, China[2]	Xenotime: Southeast Guangdong, China[2]
Yttrium	1.30	8.00	65.00	59.30
Lanthanum	25.00	43.40	1.82	1.20
Cerium	50.50	2.40	0.40	3.00
Praseodymium	5.00	9.00	0.70	0.60
Neodymium	15.00	31.70	3.00	3.50
Samarium	0.70	3.90	2.80	2.20
Europium	0.09	0.50	0.10	0.20
Gadolinium	0.60	3.00	6.90	5.00
Terbium	trace	trace	1.30	1.20
Dysprosium	0.60	trace	6.70	9.10
Holmium	0.70	trace	1.60	2.60
Erbium	0.80	trace	4.90	5.60
Thulium	0.10	trace	0.70	1.30
Ytterbium	0.20	0.30	2.50	6.00
Lutetium	0.15	0.10	0.40	1.80
Total	100	100	100	100

[1]Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Rare earths are listed in order of atomic number.

http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2012-raree.pdf

Rare Earth Element Minerals & Deposit Types

Group-Mineral	Formula	Carbonatite	Alkaline Intrusion-Related	Placer	Phosphorite
Oxides					
Aeschynite	$(Ln,Ca,Fe)(Ti,Nb)_2(O,OH)_6$		X		
Euxenite	$(Y,Ln,Ca)(Nb,Ta,Ti)_2(O,OH)_6$		X	X	
Fergusonite	$YNbO_4$		X		
Carbonates					
Bastnäsite	$(Ln,Y)CO_3F$	X	X		
Parisite	$Ca(Ln)_2(CO_3)_3F_2$	X	X		
Synchisite	$Ca(Ln,Y)(CO_3)_2F$	X	X		
Tengerite	$Y_2(CO_3)_3 \bullet n(H_2O)$		X		
Phosphates					
Apatite	$(Ca,Ln)_5(PO_4)_3(OH,F,Cl)$	X	X		X
Monazite	$(Ln,Th)PO_4$	X	X	X	
Xenotime	YPO_4		X	X	
Silicates					
Allanite	$(Ln,Y,Ca)_2(Al,Fe^{3+})_2(SiO_4)_3(OH)$		X		
Eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$		X		
Thalenite	$Y_2Si_2O_7$		X		
Zircon	$(Zr,Ln)SiO_4$		X	X	

USGS science for a changing world

Ln: Lanthanide (a.k.a. REE)

REE ORES

- REE ores contain all rare earth elements except Pm
- There is no shortage of REE ores

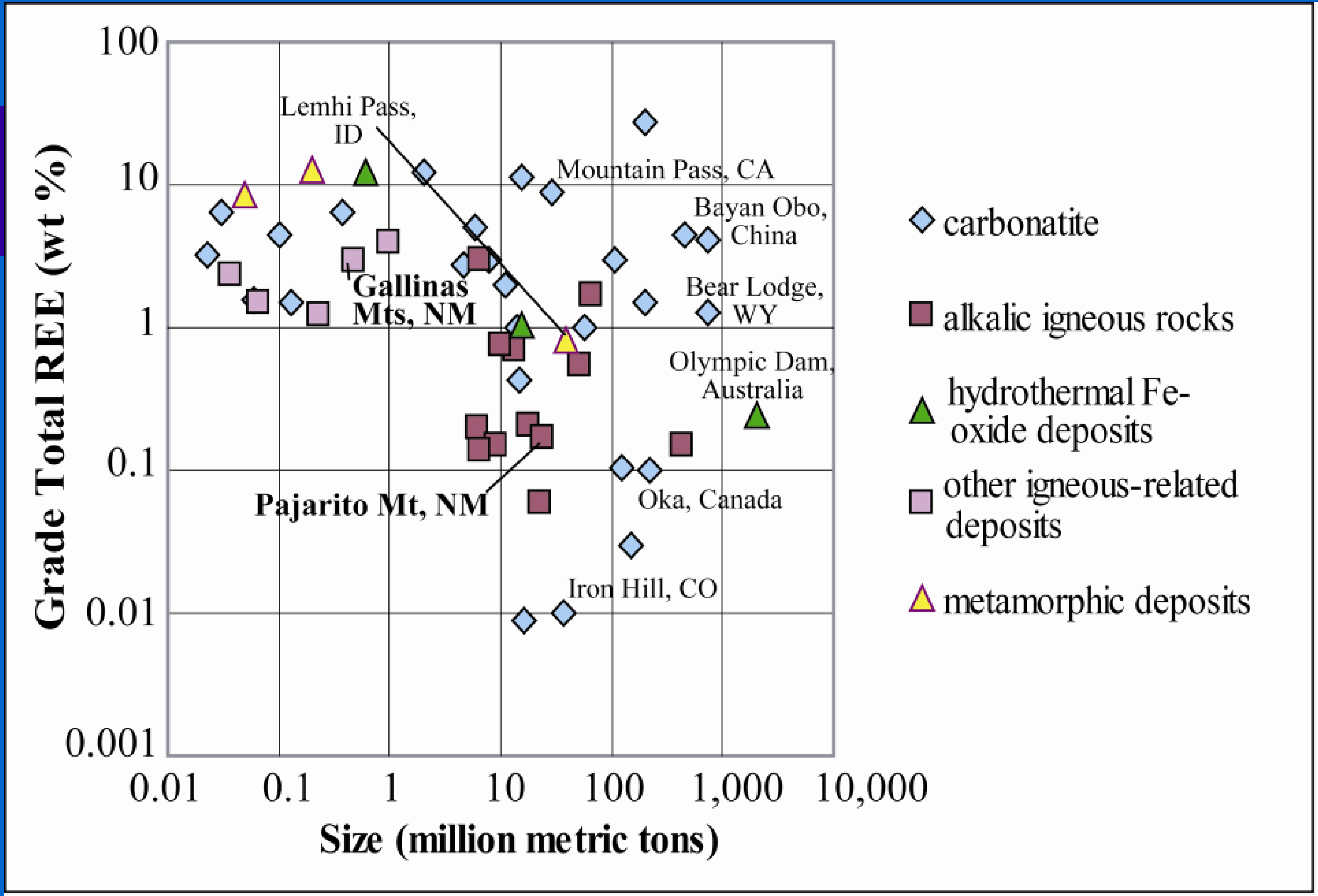
  Most rare earths are not rare
- Most ores are rich in Ce, La, Nd and Pr
- The rare earths are chemically very similar
- Producers try to balance supply and demand

  And are *rarely* successful!

Commodity	US production 2009 mt	World production 2009 mt	consumption 2009 mt	Price 2009	World reserves 2009 mt
Cu	1,190,000	15,800,000	1,660,000	$2.3/lb	540,000,000
Au	210	2,350	170	$950/oz	47,000
REO	0	124,000	7,410	varies	99,000,000
Be	120	140	140	$120/lb	15900+
Sb	0	187,000	22,400	$2.3/lb	2,100,000
As	385	52,500	3,600	$0.92/lb	1,070,000
Bi	100	7,300	1,020	$7.4/lb	320,000
Ga	0	78	20	$480/kg	1,000,000
Ge	5	14	5	$950/kg	450+
Te	W		W	$145/kg	22,000
cement	71,800,000	2,800,000,000	73,800,000	$100/mton	

Deposit	Location	Size (tons REE)	Grade % REE	Type of deposit
Bayan Obo	Inner Mongolia	48,000,000	6	Carbonatite and/or Fe oxide-Cu-Au
Mountain Pass	California	1,800,000	8.9	Carbonatite
Mount Weld	Australia	1,700,000	11.2	Carbonatite laterite
Dubbo	Australia	700,000	0.86	trachyte
Thor Lake	NW Territories, Canada	1,547,000	0.41	Alkaline rock
Strange Lake	Laborador, Quebec	440,000	0.85	Alkaline rock

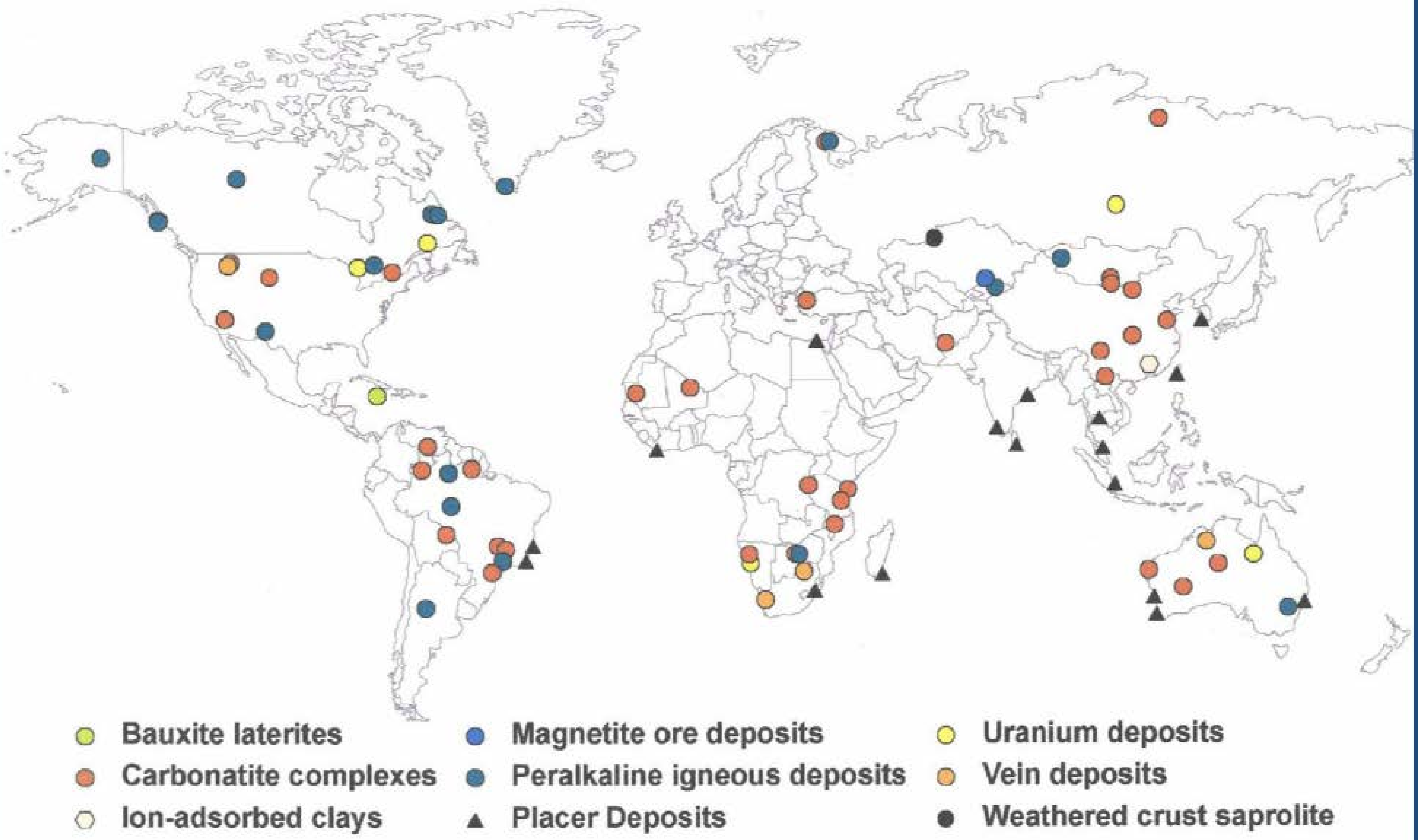
Deposit		Tonnage (metric tons)	Grade (percent TREO)	Contained TREO (metric tons)	Source
Reserves—Proven and probable					
Mountain Pass,	California	13,588,000	8.24	1,120,000	Molycorp, Inc. (2010).
Resources—Inferred					
Bear Lodge,	Wyoming	10,678,000	3.60	384,000	Noble and others (2009).
Resources—Unclassified					
Bald Mountain,	Wyoming	18,000,000	0.08	14,400	Osterwald and others (1966).
Bokan Mountain,	Alaska	34,100,000	0.48	164,000	Keyser and Kennedy (2007).
Diamond Creek,	Idaho	5,800,000	1.22	70,800	Staatz and others (1979).
Elk Creek,	Nebraska	39,400,000			Molycorp, Inc. (1986).
Gallinas Mtns.,	New Mexico	46,000	2.95	1,400	Jackson and Christiansen (1993).
Hall Mountain,	Idaho	100,000	0.05	50	Staatz and others (1979).
Hick's Dome,	Illinois	14,700,000	0.42	62,000	Jackson and Christiansen (1993).
Iron Hill,	Colorado	2,424,000,000	0.40	9,696,000	Staatz and others (1979).
Lemhi Pass,	Idaho	500,000	0.33	1,650	Staatz and others (1979).
Mineville,	New York	9,000,000	0.9	80,000	McKeown and Klemic (1956).
Music Valley,	California	50,000	8.6	4,300	Jackson and Christiansen (1993).
Pajarito,	New Mexico	2,400,000	0.18	4,000	Jackson and Christiansen (1993).
Pea Ridge,	Missouri	600,000	12	72,000	Grauch and others (2010).
Scrub Oaks,	New Jersey	10,000,000	0.38	38,000	Klemic and other (1959).
Wet Mountains,	Colorado	13,957,000	0.42	59,000	Jackson and Christiansen (1993).



Grade and size (tonnage) of selected REE Deposits, using data from Oris and Grauch (2002) and resources data from Schreiner (1993) and Jackson and Christiansen (1993) for the Gallinas Mountains. Deposits in bold are located in New Mexico.

TYPES OF REE DEPOSITS

- **Alkaline/peralkaline Igneous Rocks**
- **Carbonatites**
- **Pegmatites**
- **Iron oxide Cu-Au (REE)**
  - **Magnetite ore bodies**
- **Porphyry Mo**
- **Metamorphic/ metasomatic**
- **Paleoplacer/placer/ beach sands**
- **Colluvial REE**
- **Residual**
  - **Stratiform phosphate residual**
  - **Ion adsorption clays/laterite/bauxite**
- **REE-Th-U Hydrothermal Veins**
- **Unconformity uranium deposits**
- **Quartz-pebble conglomerate deposits**
- **Collapse breccia pipes**
- **Sea floor muds**
- **Other REE-Bearing Deposits**



http://www.adimb.com.br/simexmin2012/wp-content/themes/simexmin/palestras/06terras/VII_1_Mariano.pdf

Recycling

Ce in automotive catalytic converters

- Recovering PGMs
- 19,000 metric tons Ce
- No technologies at the present time

http://pubs.usgs.gov/of/2013/1037/OFR2013-1037.pdf

Figure 1. Stockpiled catalytic converters (CATCONs) that have been removed from vehicles before the CATCONs were dismantled and recycled for platinum-group metals. Photograph courtesy of Ashok Kumar, Director, A–1 Specialized Services & Supplies, Inc. Used with permission.

New process recycles valuable rare earth metals from old electronics

Feb 27, 2015

"Recycling rare-earth metals out of consumer waste is problematic, and there are multiple obstacles in the entire chain from manufacturing to collection infrastructure to sorting and processing," said CMI scientist Ryan Ott. "We're looking at ways to make the processing part of that chain—removing the rare-earths from scrap magnet material—better."

Construction begins 2016 for

In the liquid extraction method CMI has developed, scrap metals are melted with magnesium. The lighter atomic weight rare earths like neodymium bind with the magnesium and leave the iron scrap and other materials behind. Then the rare earths are recovered from the magnesium through vacuum distillation.

In the second step, another material is used to bind with and extract the heavier atomic weight rare earths, like dysprosium.

http://phys.org/news/2015-02-recycles-valuable-rare-earth-metals.html

Economic risks

- Less than 1 in 10,000 deposits become mines
- Estimated 1 in 2,000 or 3,000 prospects become mines
- Ore processing is very deposit specific because of the mineralogy

Table 2 Current producers out of China

No.	Company	Location	Country	Current capacity (tpy REO)	Target capacity after 2015 (tpy REO)
1	Molycorp Minerals	Mountain Pass, CA	USA	3 000	40 000
2	Lovozersky Mining Company	Kamasurt Mine, Kola Peninsula	Russia	3 000–4 400	15 000
3	Solikamsk Magnesium Works	Solikamsk Processing Plant,Urals	Russia		
4	Indian Rare Earths	Orissa,Tamil Nadu and Kerala	India	100	10 000
5	Toyota/Sojitz/Gov.of Vietnam		Vietnam	1 800–2 000	>2 000
6	Neo		Thailand		
7	Lynas/Malaysia	Gebeng, Malaysia	Malaysia		
8	Indústrias Nucleares do Brasil S/A (INB)	Buena Norte	Brazil	1 500	>1 500
Total				9 500–11 000	>68 500

Table 3 Under preparation producers

No.	Company	Location	Countries	2011-2013 Capacity (tpy REO)	Target capacity after 2010 (tpy REO)
1	Lynas Corp	Mount Weld, Western Australia, and a processing plant in Gebeng, Malaysia	Australia	10 500	21 000
2	Rareco/Great Western Minerals Group	Steenkramskaal, South Africa	South Africa/Canada	3 000	5 000
3	Sumitomo/Kazatomprom/ SARECO JV	Kazakhstan	Kazakhstan/ Japan	3 000	15 000
4	Toyota/Sojitz/Govt. of Vietnam	Dong Pao,Vietnam	Vietnam/Japan	300	5 000
5	Toyota/Indian Rare Earths jv	Orissa, India	India/Japan	5 000	10 000
6	Mitsubishi/Neo Material Technologies	Pitinga, Brazil	Japan/USA/Canada/Brazil	500	1 000
7	Alkane Resources	Dubbo, NSW, Australia	Australia	2 600	6 000
Total				24 900	63 000

Table 4 Exploration-candidate supplier

No.	Company	Location	Countries	2011-2013 Capacity (tpy REO)	Target capacity (tpy REO) in 2015
16	Avalon Rare Metals Inc	Nechalacho deposit rich in HREEs in NWT, Canada	Canada	0	5 000
17	Quest Rare Metals	Strange Lake and others in Quebec/ Labrador, Canada	Canada	0	0
18	Ucore	Bokan-Dotson Ridge project, Alaska	USA	0	0
19	Matamec	Kipawa deposit in Quebec, Canada	Canada	0	0
20	Arafura	Nolan's project, Australia	Australia	10 000	20 000
21	Great Western Minerals Group	Hoidas Lake, Canada	Canada	3 000	5 000
22	Rare Element Resources	Bear Lodge, Wyoming, USA	USA	0	0
23	Stans Energy Corp	Kutessay ll Mine, Orlovka Kyrgyz Republic	Kyrgyz Republic	0	0
24	Greenland Minerals and Energy	Kvanefjeld-Greenland	GreenLand	0	10 000
25	Japan-Mongolia JV	Mongolia	Mongolia	0	0
Total				13 000	40 000

Property	Proven & Probable Reserves	Measured & Indicated Resources	Inferred Resources	Total
Mountain Pass	48,375			48,375
Mount Weld	2,040	12,200	5,294	19,534
Steenkampskraal			250	250
Dubbo Zirconia		37,500	35,700	73,200
Nolan's Bore		17,400	12,800	30,200
Bear Lodge			15,876	15,876
Montviel			133,636	133,636
Nechalacho	12,001	88,130	226,880	327,011
Kvanefjeld		365,000	92,000	457,000
Strange Lake			114,823	114,823

Project	Tonnage (000)	Grade (%)	Mineral Type	HREE (%)	Stage	Start Up?
Mountain Pass	48,375	7.0	Carbonatite	0.4	Construction	2012
Mount Weld	19,534	8.8	Carbonatite	3.0	Construction	2012
Steenkampskraal	250	11.7	Monazite	7.7	Feasibility	2013
Dubbo Zirconia	73,200	0.9	Peralkaline syenite	23.0	Feasibility	2014
Nolan's Bore	30,200	2.8	Pegmatite	4.0	Feasibility	2014
Bear Lodge	15,876	3.5	Carbonatite	3.3	Pre-feasibility	2015
Montviel	133,636	1.3	Carbonatite	2.0	Scoping	2015
Nechalacho	327,011	1.3	Peralkaline syenite	26.0	Feasibiity	2016
Kvanefjeld	457,000	1.0	Peralkaline syenite	14.0	Pre-feasibility	2016
Strange Lake	114,823	1.0	Peralkaline syenite	47.0	Pre-feasibility	2016

Project	TREO Basket Value (mid 2011)	Annual TREO Production	Infra-structure	Necessary Capital Expenditure (US$ million)
Mountain Pass	127	40,000		781
Mount Weld	150	22,000		512
Steenkampskraal	161	5,000	Good	70
Dubbo Zirconia	207	6,500	Good	178
Nolan's Bore	161	20,000	Poor	1,014
Bear Lodge	222	10,000	Good	88
Montviel	208		Good	300 (?)
Nechalacho	301	10,000	Poor	863
Kvanefjeld	218	43,729	Poor	2,310
Strange Lake	313	12,100	Poor	563

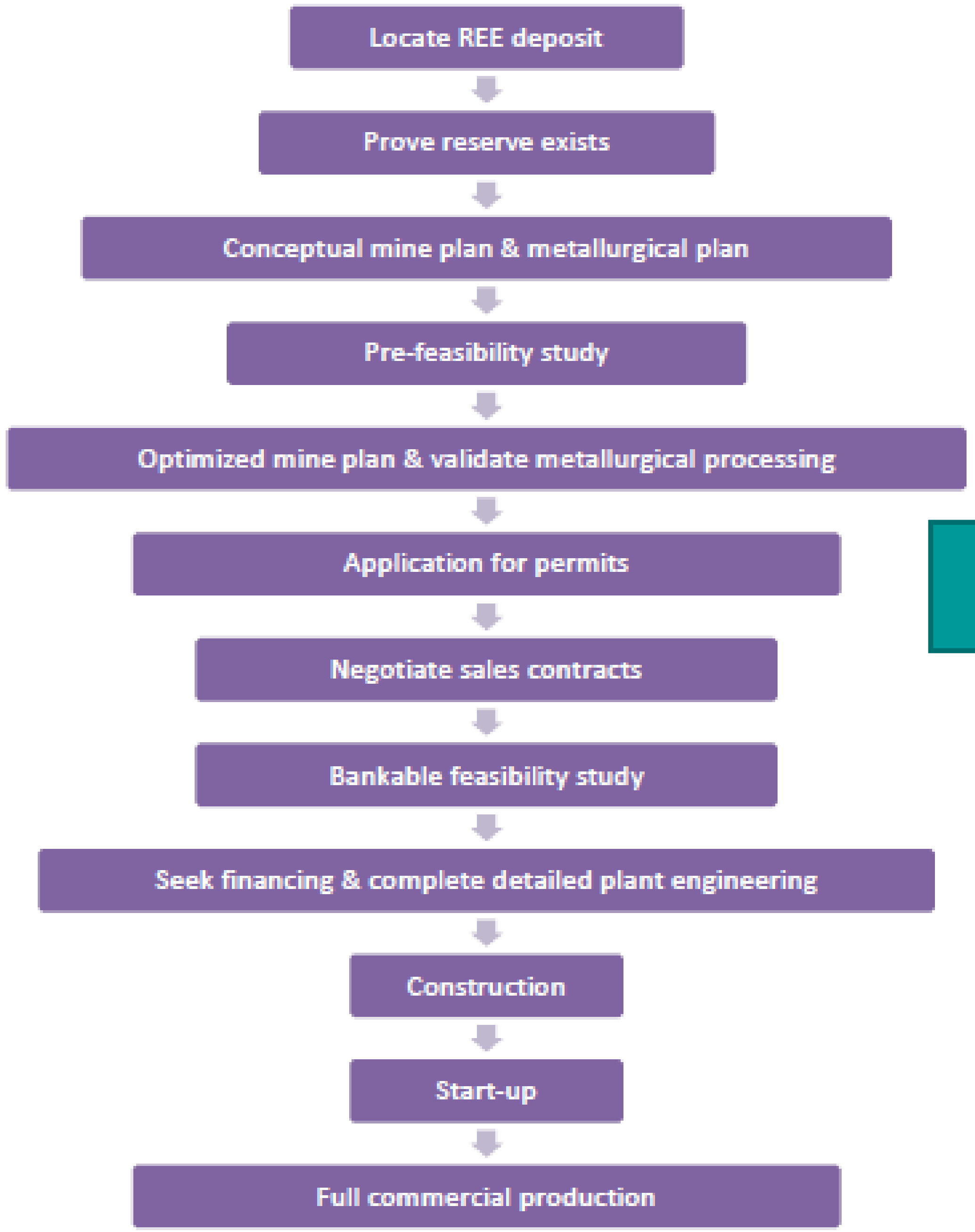
RE-oxide prices, FOB China (US$/kg)

Oxide 99% min purity	2007	2008	2009	2010	31 March 2011	30 June 2011	18 Oct 2011
Cerium	3.65	4.25	4.15	61.00	121.00	149.00	71.00
Dysprosium	93.00	94.50	116.50	295.00	640.00	1510.00	2240.00
Europium	350.00	480.00	480.00	630.00	940.00	3190.00	3790.00
Gadolinium	10.45	7.75	6.75	44.50	147.50	202.50	142.50
Lanthanum	4.70	7.75	5.55	60.00	120.50	148.00	64.00
Neodymium	29.25	14.24	22.75	87.00	201.50	317.50	154.69
Praseodymium	29.75	14.25	22.25	86.50	196.00	238.50	218.50
Samarium	4.05	4.50	4.50	34.50	106.50	128.50	101.50
Terbium	610.00	410.00	350.00	605.00	990.00	2910.00	3010.00
Yttrium	11.40	15.25	10.25	72.50	142.50	169.50	142.50

Source: metal-pages.com

Mine life cycle

Figure 16: Major Steps Taken In Developing A Rare Earth Elements Mine



Closure

The Kingsnorth 8: steps in developing rare-earths projects

1. Resource: grade, REO distribution
2. Mineralogy : which minerals; liberation not too fine; beneficiate to > 30% REO
3. Scoping study
4. Pilot plant (beneficiation, extraction, separation)
   - Demonstrate technical viability/flexibility

Source: Kingsnorth 2011

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

The Kingsnorth 8 (cont'd)

5. Environmental approval: government, social
6. Marketing plan: recognizing the 'balance' issue
7. Definitive feasibility study and financing
8. Construction & start-up

Source: Kingsnorth 2011

Exploration methods

Exploration methods

- Radiometric
  - Most occur with U and Th
- Gravimetric
  - Many are surrounded by mafic alkaline rocks (gravity high) or sedimentary rocks (gravity low)
- Geochemical
- Drilling, trenching

Mining

Mine Design Sequence

Iterative Evaluation Process

- Geologic Analysis & Sampling
  - Resource Characterization
  - Geomechanics
  - Metallurgy
- Reserve Estimation & Cutoff Grade Assessment
- Mine Size & Mining Rate
- Closure, Reclamation & Post Mining Uses
- Mining Method & Systems
- Equipment, Infrastructure, Mine Layout, Labor Estimates
- Sequencing & Production Optimization
- Cost Estimation (Operating and Capital Costs)
- Financial Analysis
- Corporate Evaluation

Mining Method Selection

- Traditional Approach: Use designs and systems that have successfully work at mines with similar geologic and operating characteristics.
- Very conservative approach usually mandated by regulatory process and external financing, often is employed at the expense of technical innovations and improved labor practices.
- Mitigates risk: Mining history littered with examples of mines heavily reliant on new technology failing because of over estimated performance.
- Any Mining Method Considers Ore to Waste Ratios !

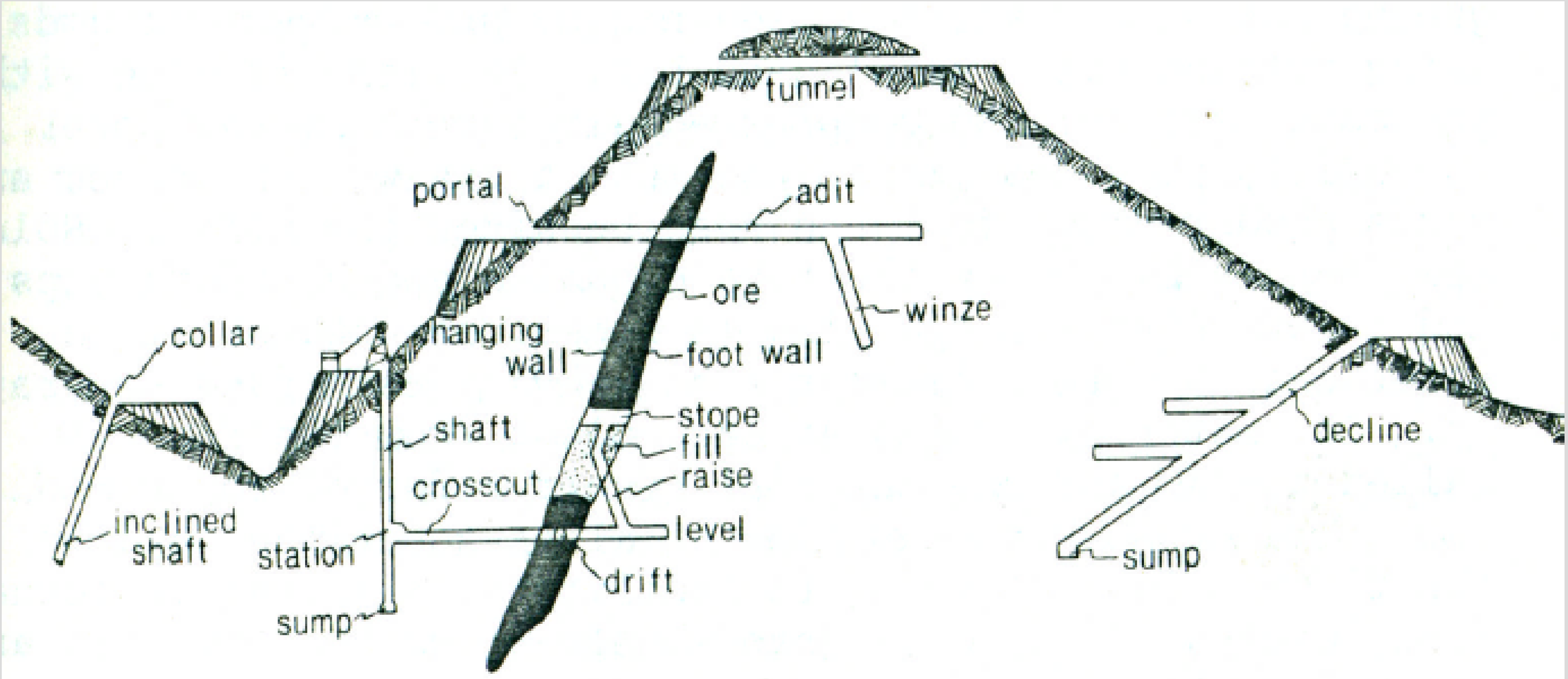
Open Pit Factors – Strip Ratio :: Underground Factors – Dilution Factor

Surface Mining Methods & Systems

- Open Pit Mining – Massive & Disseminated Deposits
- Strip Mining – Bedded & Flat Laying Deposits
- Quarry/Aggregate Mining – Common to Place-Value Mineral Commodities
- Placer Mine – Minerals in Alluvium

Underground Mining Terms

(U.S. Forest Service, Anatomy of a Mine, Pg. 75)



PROCESSING

Mineral Processing

- The processes focused on physically separating the grains of valuable minerals from the gangue minerals to produce an enriched portion, or concentrate, and a discard portion, or tailings.
- Two major functions
  - Liberation
  - Separation

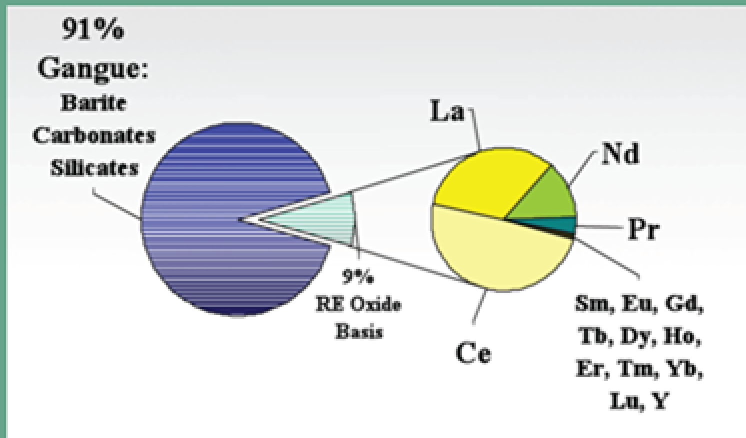
Comminution **is from the Latin word** ***comminuere*** **meaning to make small and is needed to achieve** **<u>Liberation</u>.**

Crushing and grinding of the ore to a particle size such that the product is a mixture of relatively free particles of valuable mineral and gangue.

Do not want to grind beyond the liberation size (wastes energy) or minimum size that unit operations do not function well at (reduces recovery and/or grade).

Mineral Processing

Source: Molycorp, Inc.

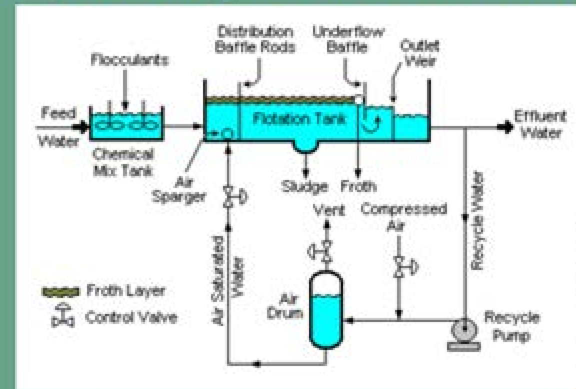


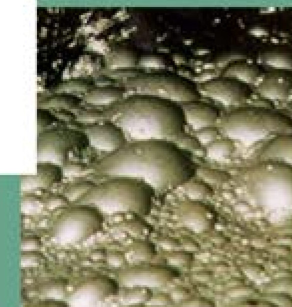
Mountain Pass, CA

Requires two steps: (1) separate REE minerals from other minerals; (2) separate individual REE.

USGS

Separating Rare Earth Minerals





Froth flotation is the most common method for separation of rare earth minerals from other minerals in ore.

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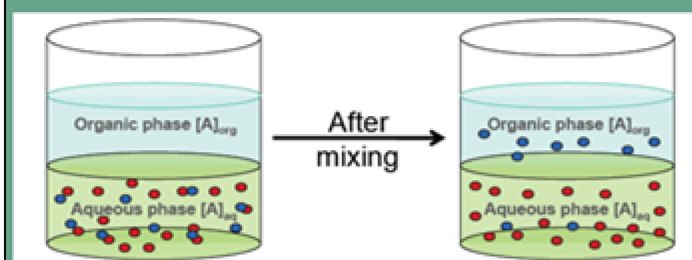
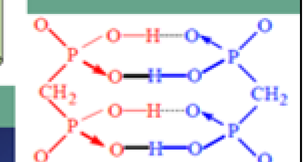
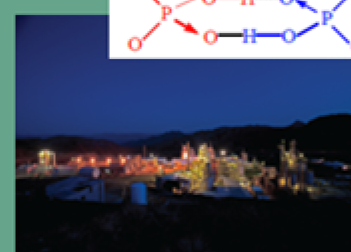
Separating Individual REE





Solvent extraction uses small differences in solubility between individual REE. REE minerals are leached with an acid or base, then mixed with an organic chemical that strips a selected REE.



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Separation

- Gravity
- Magnetic
- Flotation
- Electrostatic Separation

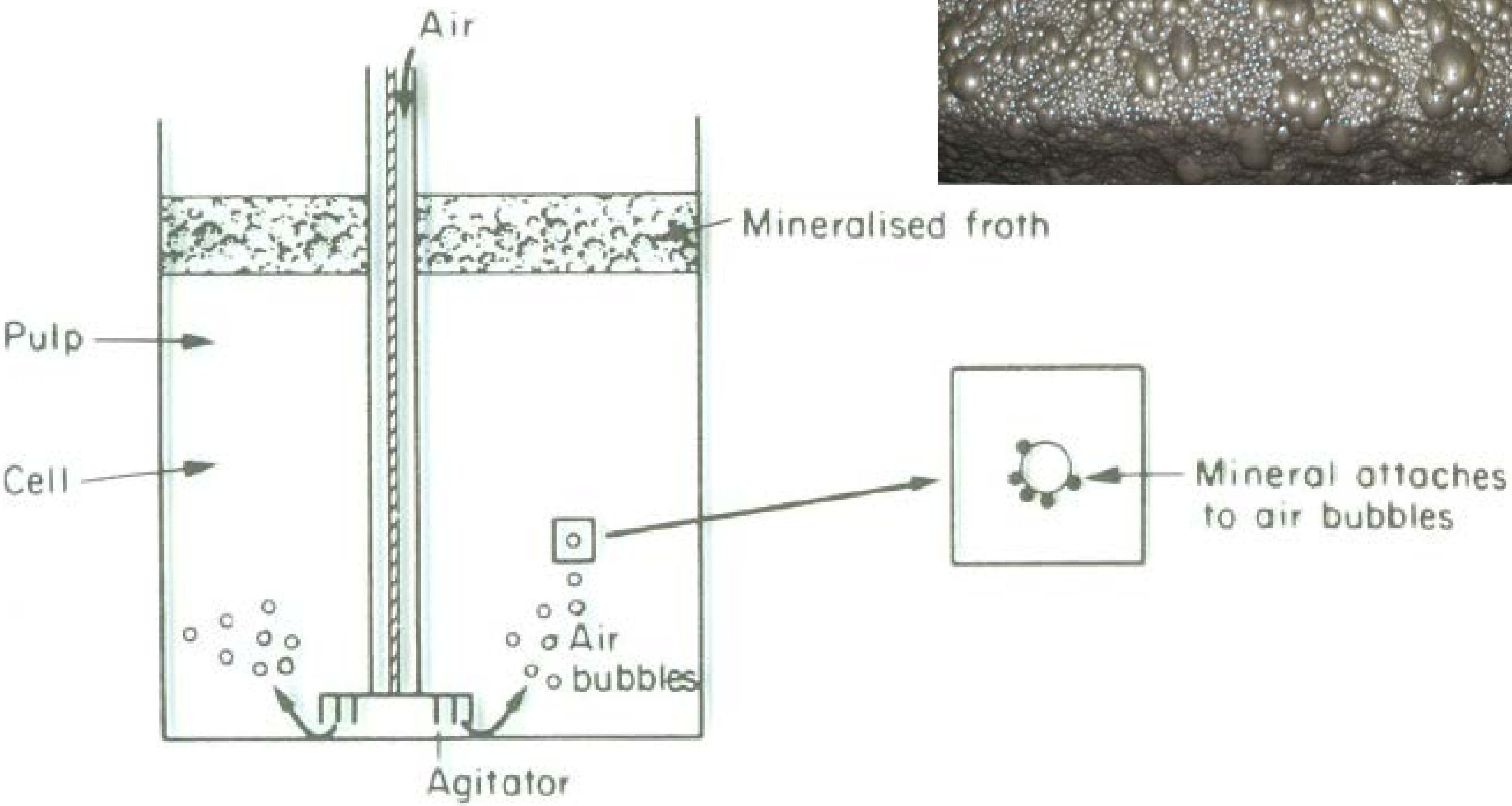


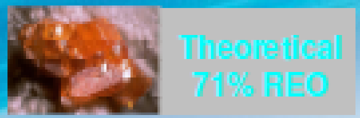
FIG. 12.1. Principle of froth flotation.

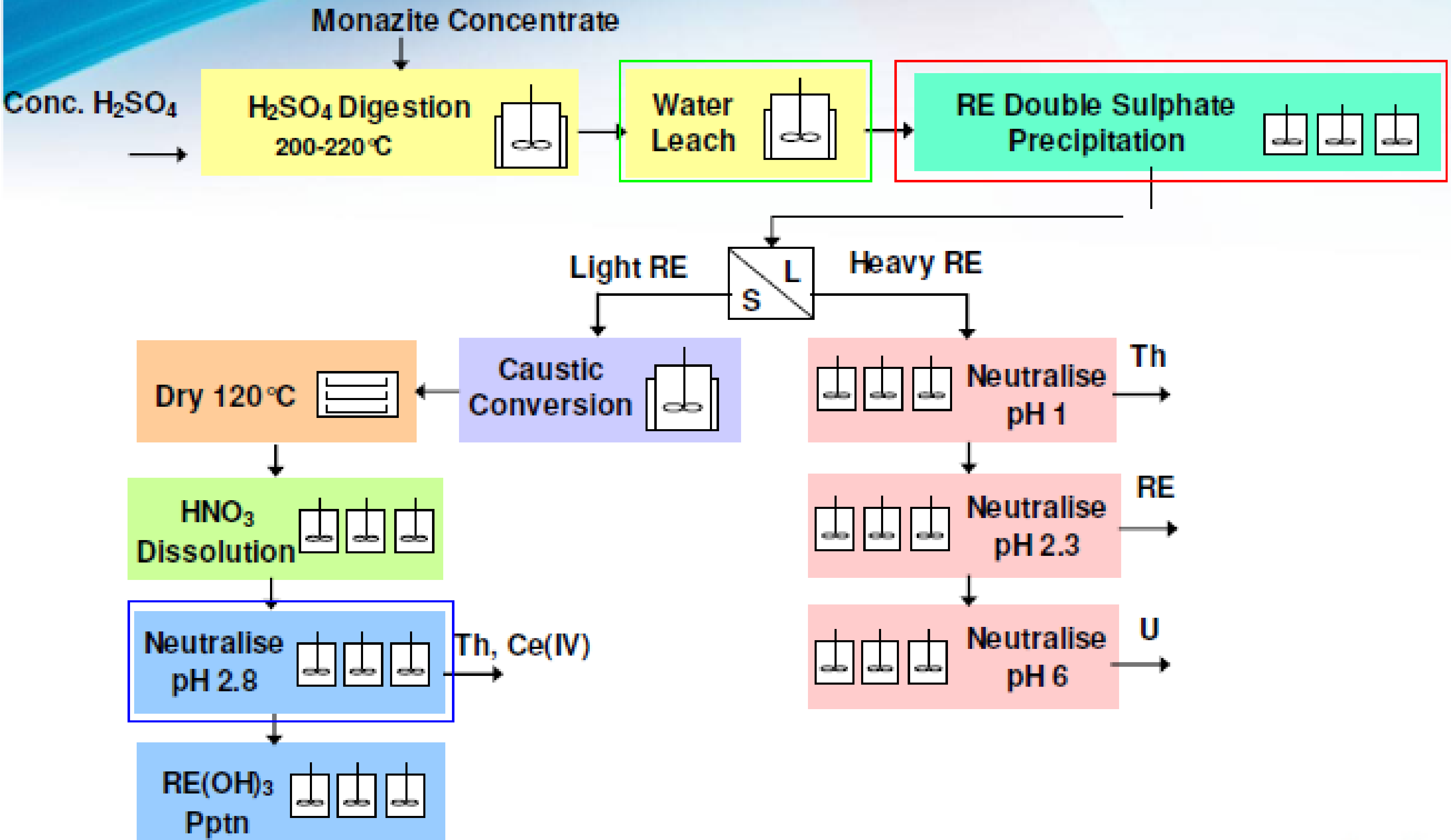
Monazite Ore Processing

- The ore undergoes grinding, spiraling, or other similar operations for the initial coarse upgrading of the ore.
- Magnetic separation removes the magnetic ore constituents which can be processed separately or discarded as waste.
- The refined ore is then digested with sulfuric acid at 200-220°C.
- Rare earth sulfates and thorium sulfates are then dissolved and removed from the waste monazite solids by filtration.
- Rare earth elements are then precipitated as oxalates or sulfates.
- These precipitates undergo separations to form rare earth oxides.

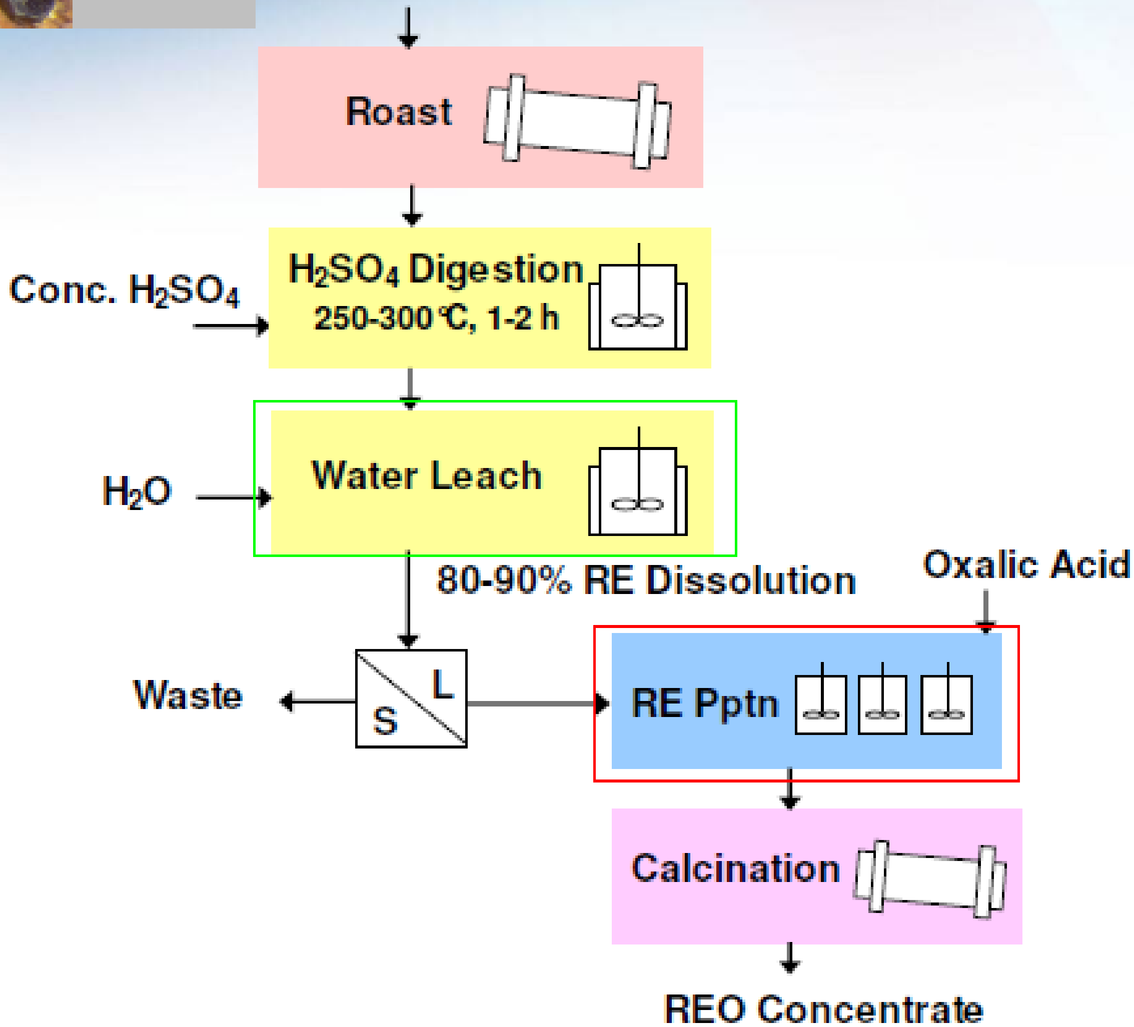
Conventional Processing

Monazite - Acid Digestion





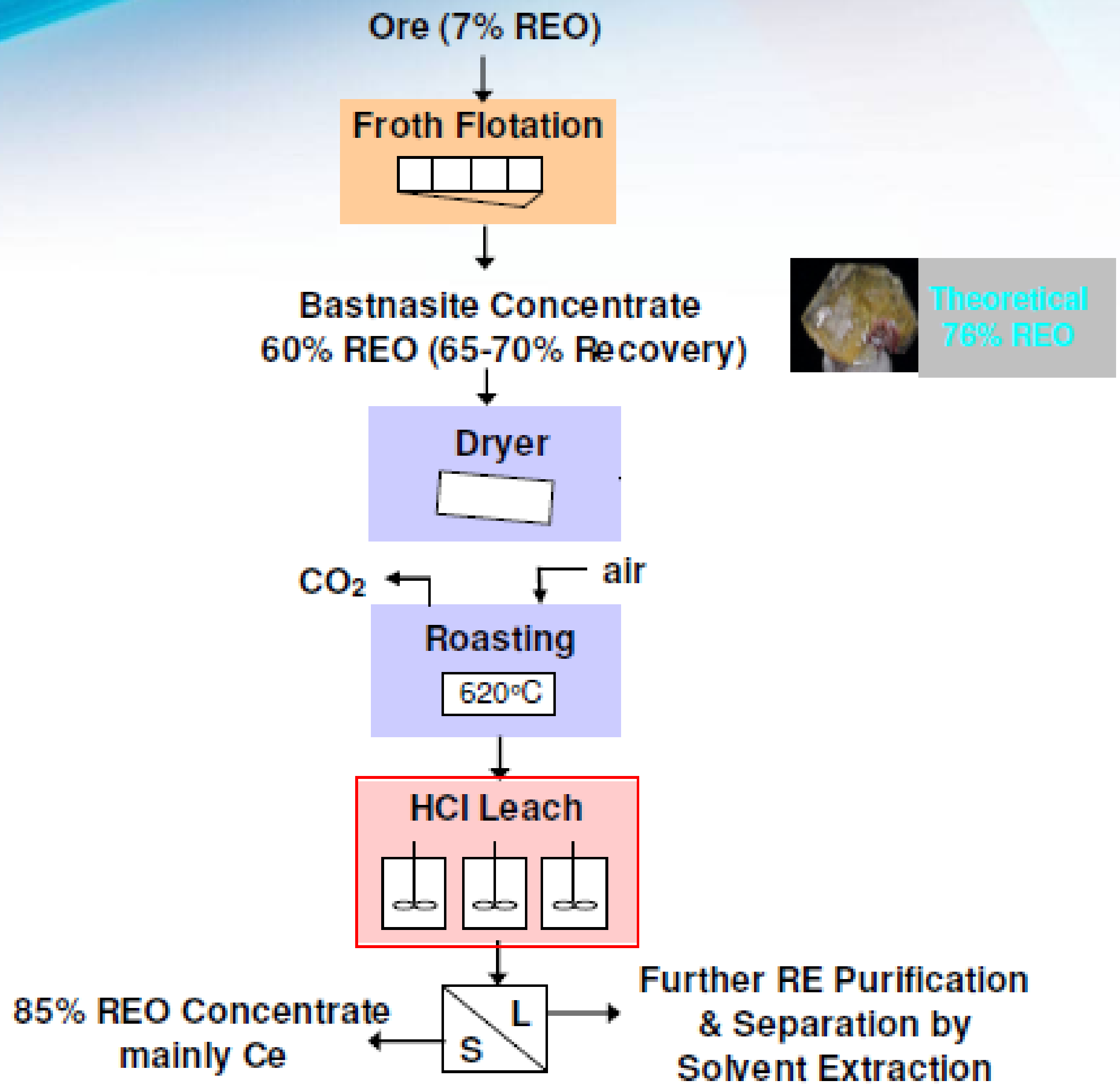
Conventional Processing
Xenotime - Acid Digestion



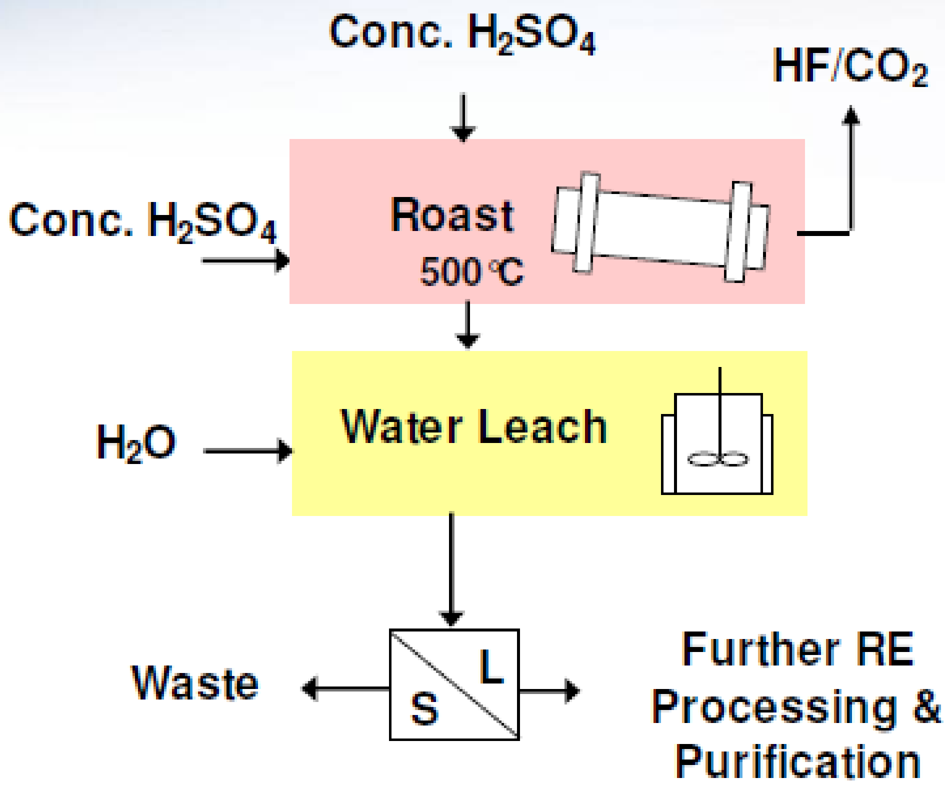
BASTNASITE ORE PROCESSING

- Bastnasite mining near Mountain Pass in southeastern California will be a the major source of rare earth metals in the U.S. again.
- The previous recovery process of the rare earths from this ore is shown.
- The ore was initially crushed, ground, classified, and concentrated by flotation to increase the rare earth concentrations from about 5% to about 60% (REO).
- The concentrated bastnasite undergoes an acid (HCl) digestion to produce several rare earth chlorides.
- The resulting slurry is filtered, with sodium hydroxide to produce rare earth hydroxides.
- This rare earth hydroxide cake is chlorinated, converting the hydroxides to chlorides.
- Final filtration and evaporation yields the solid rare earth chloride products.

Conventional Processing
Bastnasite - HCl Acid Leach



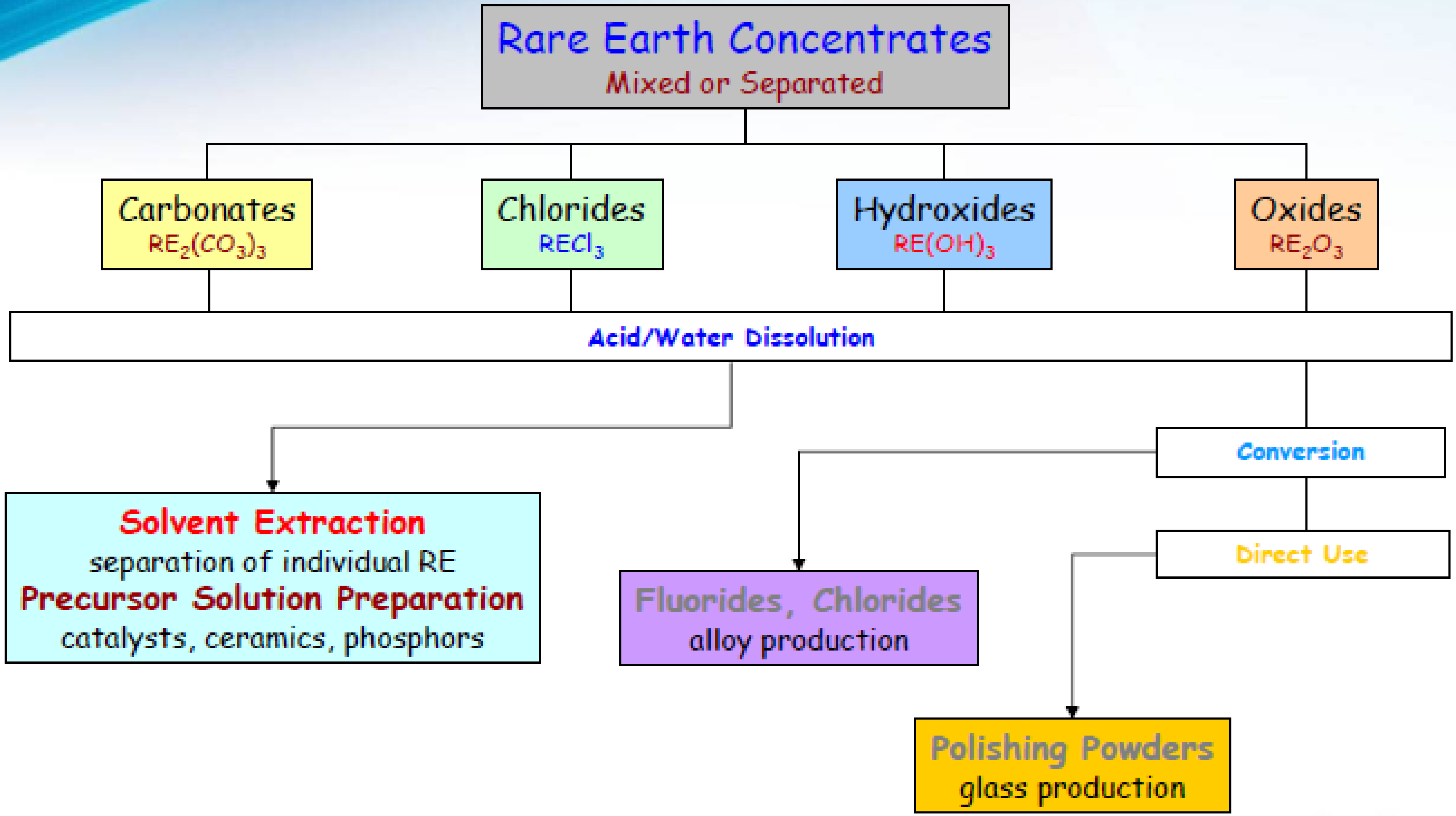
Conventional Processing
Bastnasite - H_2SO_4 Roast-Leach



Processing of the Products

- The rare earth hydroxides and chlorines which are recovered from monazite and bastnasite are, respectively, typically would undergo further processing to produce and recover individual rare earth metal compounds for a variety of applications.
- Several processes are used to produce rare earth fluorides, nitrates, carbonates, oxides, and pure metals.
- Processes used include fractional crystallization, fractional precipitation, solvent extraction, ion exchange, and reduction.

RE Products/Concentrates



Australian Government | ansto

Rare Earth Processing

Key Points

1. Processing of conventional RE sources is well established but processing of other sources is NOT;
2. The mineralogy of RE is complex and 'a specific process is needed for a specific ore';
3. Multiple unit processes are required to reject the elemental and radioactive impurities associated with the RE;
4. There is an exponential increase in the complexity where the RE are trying to be recovered as a by-product and multiple processing options need to be explored.

ansto MINERALS

Politics

Politics

- Government reports are abundant
- China’s policy is unknown and ever changing
- Afghanistan has potential REE deposits
- Some countries will subsidize the development of their deposits

Environmental issues

- Limited case studies
- Knowedge is limited
- Environmental risks likely vary among deposit types
- U, Th issues
- Other trace elements (Cd, Ni, Se????)
- Acid drainage is probably low, but monitor it
  - Few sulfide minerals
  - Abundant carbonates

Rare Earth Element Minerals & Chemistry

Group-Mineral	Formula	REO Wt%	ThO_2 Wt%	UO_2 Wt%
Oxides				
Aeschynite	$(Ln,Ca,Fe)(Ti,Nb)_2(O,OH)_6$			
Euxenite	$(Y,Ln,Ca)(Nb,Ta,Ti)_2(O,OH)_6$			
Fergusonite	$YNbO_4$			
Carbonates				
Bastnäsite	$(Ln,Y)CO_3F$	70 - 74	0 - 0.3	0.09
Parisite	$Ca(Ln)_2(CO_3)_3F_2$	59	0 – 0.5	0 – 0.3
Synchisite	$Ca(Ln,Y)(CO_3)_2F$	49 – 52	1.6	
Tengerite	$Y_2(CO_3)_3 \bullet n(H_2O)$			
Phosphates				
Apatite	$(Ca,Ln)_5(PO_4)_3(OH,F,Cl)$	0 -20		
Monazite	$(Ln,Th)PO_4$	35 - 71	0 - 20	0 - 16
Xenotime	YPO_4	52 – 67	0 - 3	0 -5
Silicates				
Allanite	$(Ln,Y,Ca)_2(Al,Fe^{3+})_3(SiO_4)_3(OH)$	3 – 51	0 -3	
Eudialyte	$Na_4(Ca,Ce)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$	1 - 10		
Thalenite	$Y_2Si_2O_7$			
Zircon	$(Zr,Ln)SiO_4$	0 – 0.7	0.1 – 0.8	

USGS science for a changing world

Ln: Lanthanide (a.k.a. REE)

Scarred landscape from small REE mines in China and pipeline spill

3)

Every ton of REE produced generates

approximately 8.5 kg (18.7 lb) of F and 13 kg (28.7lb) of dust. Using concentrated sulfuric acid high temperature calcination techniques to produce approximately 1 ton of calcined REE ore generates 9,600 to 12,000 m3 of waste gas containing dust concentrate, hydrofluoric acid, sulfur dioxide and sulfuric acid,

approximately 75 m3 of acidic wastewater, and about 1 ton of radioactive waste residue (containing water). (Chinese Society of Rare Earths)

1 ton of REES creates 2,000 tons of mine tailings

Rare Earth Element Minerals & Chemistry

Group-Mineral	Formula	REO Wt%	ThO_2 Wt%	UO_2 Wt%
Oxides				
Aeschynite	$(Ln,Ca,Fe)(Ti,Nb)_2(O,OH)_6$			
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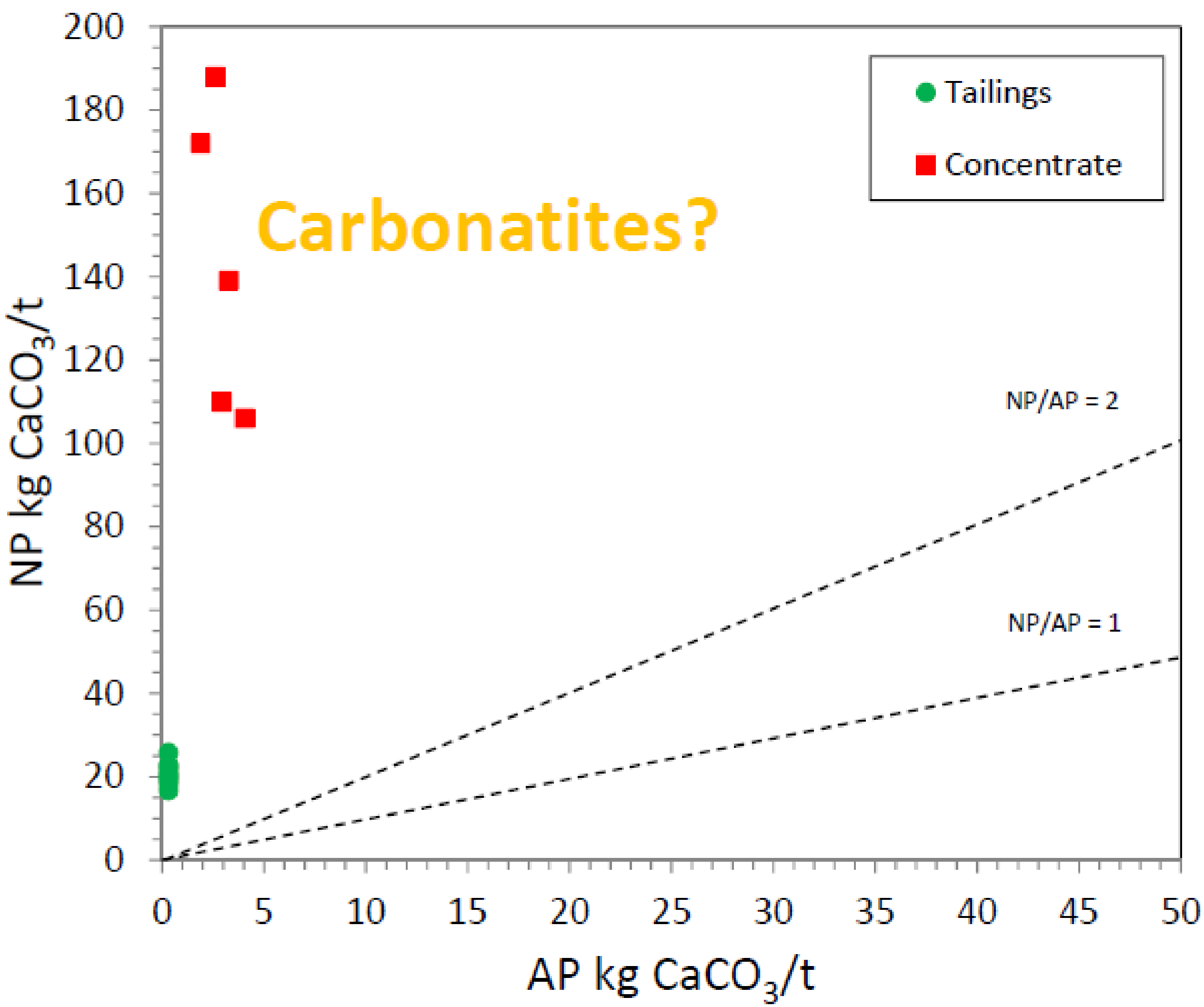
USGS science for a changing world

Ln: Lanthanide (a.k.a. REE)

Molycorp Mountain Pass

- Th and Ra contamination of waste water spills in 1990s closed the mine
- Desert tortoise
- Evaporating ponds
- Water use
- Th, Ra in waste materials

Acid-Generating Potential - Thor Lake, NWT, Canada



- Despite lack of data, carbonatite-hosted REE deposits would be expected to be strongly net alkaline.

Thor Lake data: http://www.reviewboard.ca/registry/project.php?project_id=87

Rare Earth Elements: Surface Water Guidelines

		Yellow River, Baotou, China Bayan Obo Industrial Complex			Valzinco, VA		Thor Lake, NWT, Canada
	MPC* µg/L	Main Channel	Site F	Site G	VLZN-10	VLZN-3	Tailings HCT
pH		7.6 - 8.2		3.7 - 6.9	1.1	3.3	7.5
Y µg/L	6.4				370	2.0	0.183
La µg/L	10.1	0.103	140	988	340	4.6	
Ce µg/L	22.1	0.22	152	1149	870	9.5	
Pr µg/L	9.1	0.0304	16.08	294	150	1.2	
Nd µg/L	1.8	0.095	52.01	1193	650	4.7	
Sm µg/L	8.2	0.023	6.91	62.35	180	0.9	
Gd µg/L	7.1	0.028	7.22	67.33	140	0.7	
Dy µg/L	9.3	0.082	3.8	9.08	93	0.4	

*From: Maximum Permissible Concerntration; Sneller et al. (2000)
Thor Lake data: http://www.reviewboard.ca/registry/project.php?project_id=87

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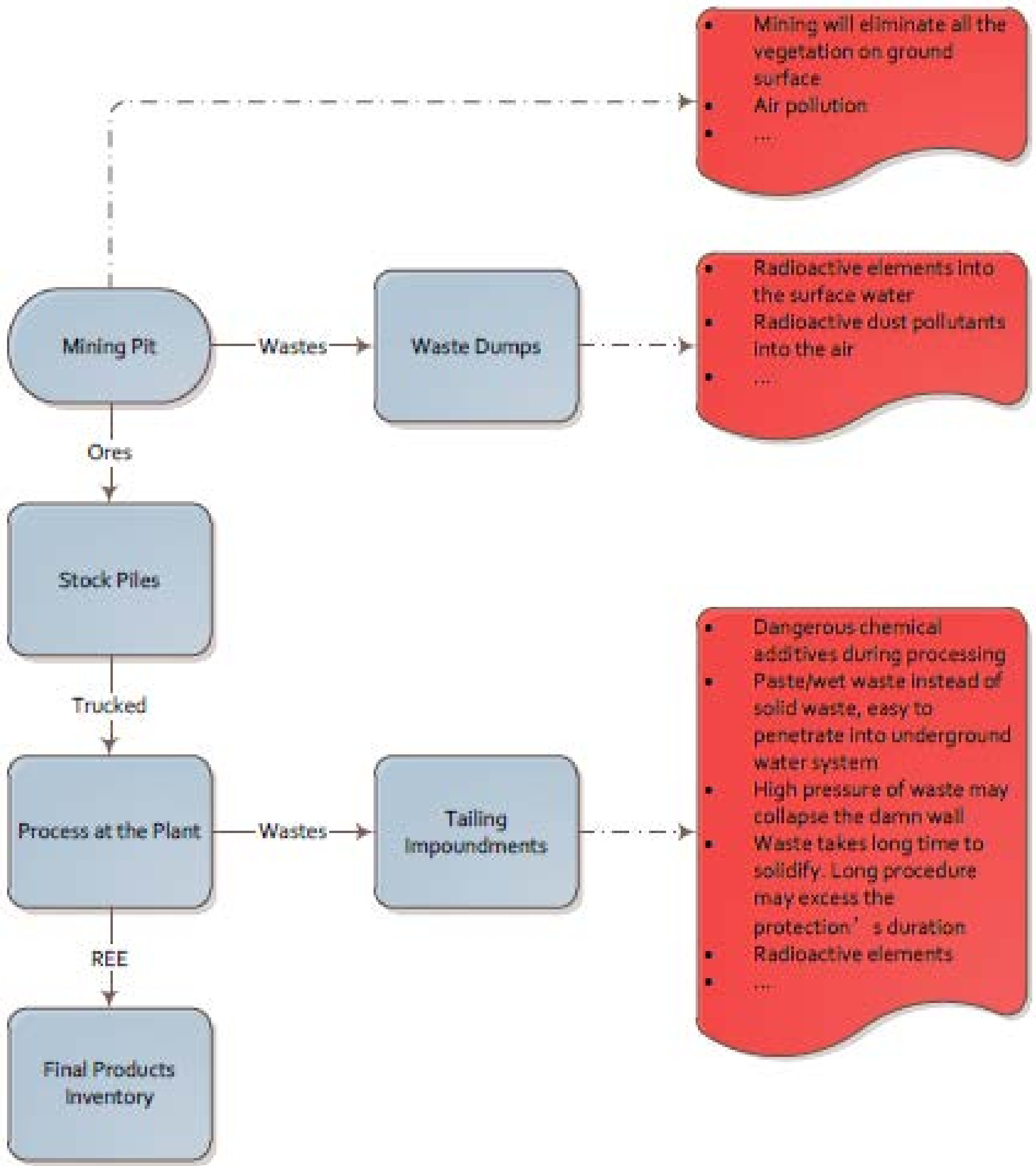
Appendix 15: Environmental Risks from REE Production



Challenges

KEY ISSUES FOR REE

- Finite resources
- Chinese market dominance
- Long lead times for mine development
- Resource nationalism/country risk
- High project development cost
- Relentless demand for high tech consumer products
- Ongoing material use research
- Low substitutability
- Environmental issues
- Low recycling rates
- Lack of intellectual knowledge and operational expertise in the west

Table 12. Time required to obtain permits, construct, and commission recently opened metal mines in the United States.

[NYA, not yet achieved, production not yet begun or commercial operations not achieved; PGE, platinum group elements. Yes, long permitting and development delays because of litigation by government agencies and nongovernmental organizations]

Mine		Commodity	Permitting began	Permitting completed	Production began	Commercial operations began	Litigation reported
Alta Mesa,	Texas	U	1999	2004	10/2005	1/2006	
Arizona 1,	Arizona	U	mid-2007	2009	NYA	NYA	Yes.
Ashdown,	Nevada	Mo Au	2/2004	11/2006	12/2006	NYA	
Buckhorn,	Washington	Au	1992	9/2006	10/2008	11/2008	Yes.
Carlota,	Arizona	Cu	2/1992	6/2007	12/2008	1/2009	Yes.
Eagle,	Michigan	Ni Cu Co PGE	4/2004	1/2010	NYA	NYA	Yes.
East Boulder,	Montana	PGE	1995	1998	6/2001	1/2002	
Kensington,	Alaska	Au	3/1988	6/2005	9/2010	NYA	Yes.
Leeville,	Nevada	Au	7/1997	8/2002	10/2006	4th quarter 2006	
Lisbon Valley,	Utah	Cu	2/1996	7/2004	1st quarter 2006	NYA	Yes.
Pend Oreille,	Washington	Zn	1992	9/2000	1/2004	8/2004	
Phoenix,	Nevada	Au	1/1999	1/2004	10/2006	4th quarter 2006	
Pogo,	Alaska	Au	12/1997	4/2004	2/2006	4/2007	
Rock Creek,	Alaska	Au	2003	8/2006	9/2008	NYA	Yes.
Rossi (Storm),	Nevada	Au	1990	3Q/2006	3/2007	12/2007	
Safford,	Arizona	Cu	4/1998	7/2006	4th quarter 2007	2nd half 2008	Yes.
Turquoise Ridge,	Nevada	Au	9/1995	5/2003	2004	NYA	

(Long et al., 2010)

ADDITIONAL CHALLENGES

- How much REE do we need?
- Are there enough REE in the pipeline to meet the demand for these technologies and other uses?
- Can REE be recycled?
- Are there substitutions that can be used?
- What are the reclamation challenges?
  - REE are nearly always associated with U and Th and the wastes from mining REE will have to accommodate radioactivity and radon

ADDITIONAL CHALLENGES

- Will there be enough scientists engineers to develop the mine?
- Substitutions

CONCLUSIONS

- REE are important for green technologies as well as our entire lifestyle and new uses will be found because of their unique properties
- REE are found in specific locations based on favorable geology and there is sufficient supply for the near future
- Need for understanding the mineralogy and distribution of these minerals in known ore deposits