The Future of Rare Earth Elements

Will these high-tech industry elements continue in short supply?

By Keith R. Long, Mineral Resource Analysts
Western Mineral and Environmental Resource Science Center
Tucson, AZ

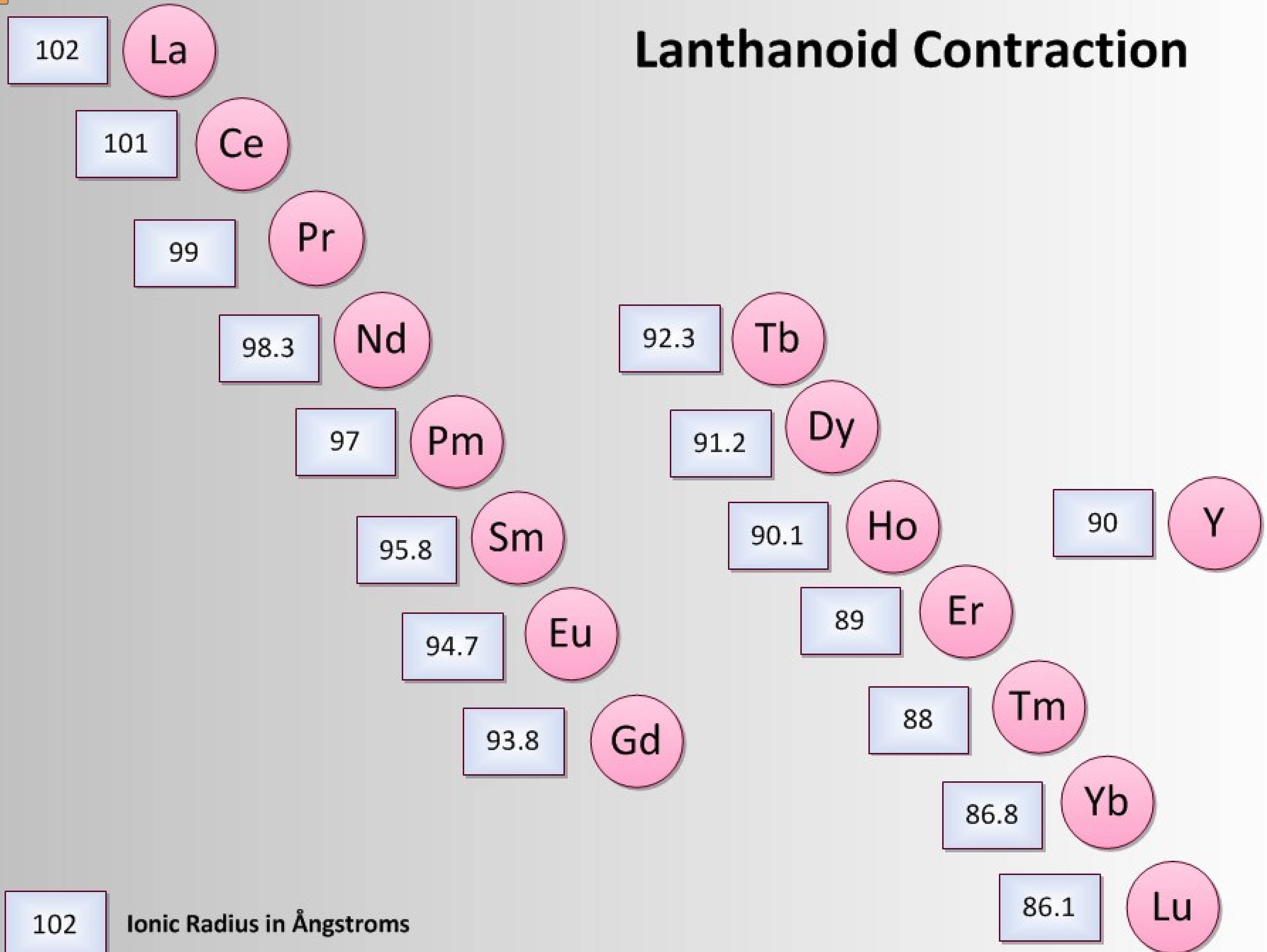
U.S. Department of the Interior
U.S. Geological Survey

PERIODIC TABLE OF THE ELEMENTS

1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magne-sium											13 Al Aluminum	14 Si Silicon	15 P Phos-phorus	16 S Sulphur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manga-nese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge German-ium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molyb-denum	43 Tc Techne-tium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	57-71 Lantha-nides see below	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	89-103 Actinides see below	104 Rf Rutherfor-dium	105 Db Dubnium	106 Sg Seabor-gium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Uum Unun-nilium								

Lanthanoids	57 La Lantha-num	58 Ce Cerium	59 Pr Praseo-dymium	60 Nd Neo-dymium	61 Pm Pro-methium	62 Sm Samarium	63 Eu Europium	64 Gd Gado-linium	65 Tb Terbium	66 Dy Dys-prosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
	89 Ac Actinium	90 Th Thorium	91 Pa Pro-tactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Califor-nium	99 Es Ein-steinium	100 Fm Fermium	101 Md Mende-levium	102 No Nobelium	103 Lr Lawren-cium

Lanthanoid Contraction



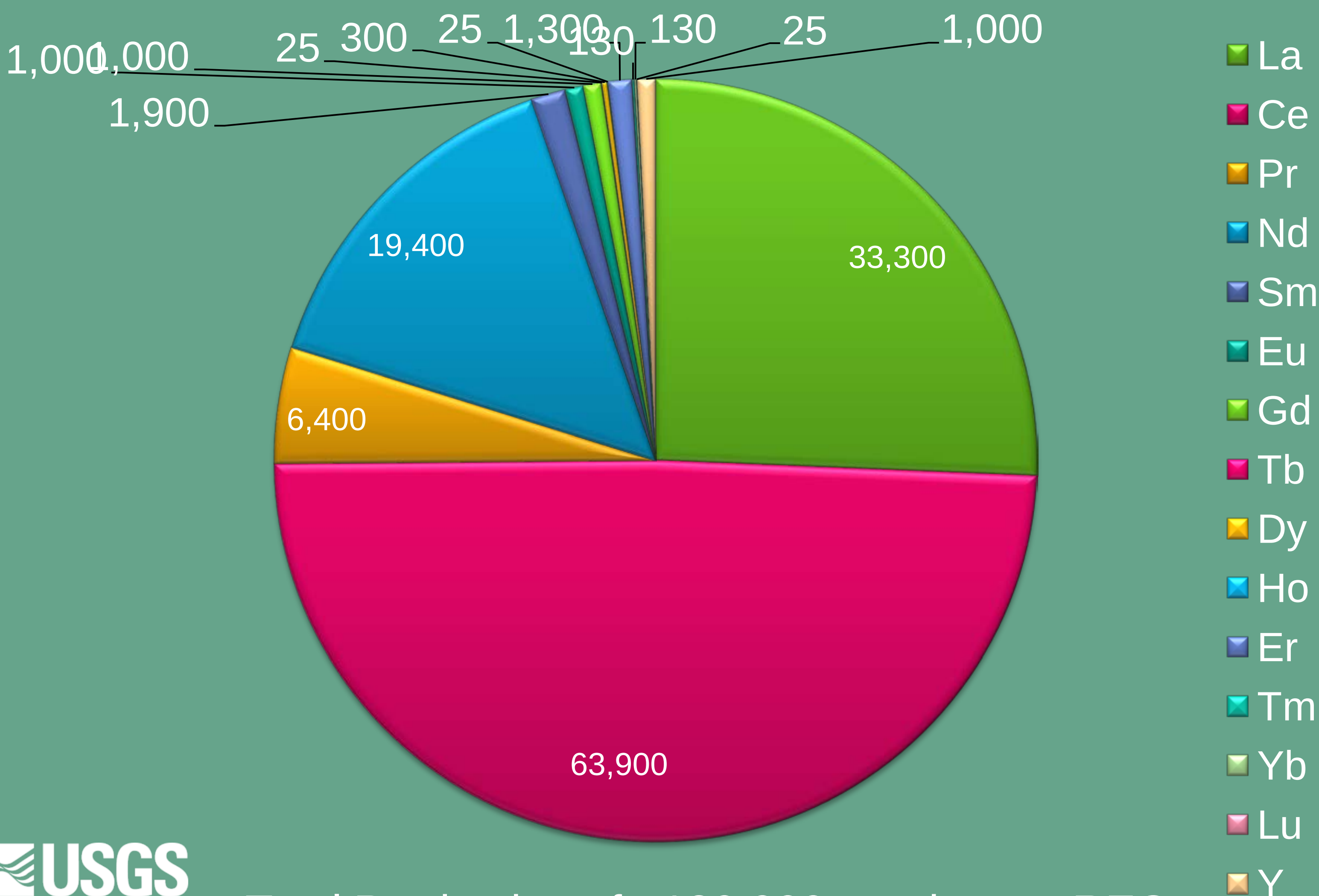
Lanthanoid Abundance

Crustal Abundance in ppm	Element	Price Pure REO USD/kg
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
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
30	Y	$50

$40 Price Pure REO USD/kg

32 Crustal Abundance in ppm

World Production of Rare Earths as Oxides 2009



USGS

Total Production of ~130,000 metric tons REO

Principal Use Categories for Rare Earths

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

CATALYSTS

Automotive Catalysts
6,000 tpy REO
Ce (90%) La (5%) Nd (3%) Pr (2%)
Oxygen storage, carbon removal

Fluid Cracking Catalysts
18,400 tpy REO
La (90%) Ce (10%)
Petroleum refining – cracking heavy molecules
Increases per barrel yield by 7 to 10%

USGS

MAGNETS

Rare earth magnets are stronger per unit weight and volume than any other magnet type. Used wherever weight and space are at a premium.

26,500 tpy REO
Nd (69%) Pr (23%)
Dy (5%) Tb (0.2%)
also Sm

METAL ALLOYS

NiMH Batteries use La Ni anode to protect against corrosion and increase battery life
La (50%) Ce (33%) Nd (10%) Pr Sm

Prius battery pack has 10-15 kg La

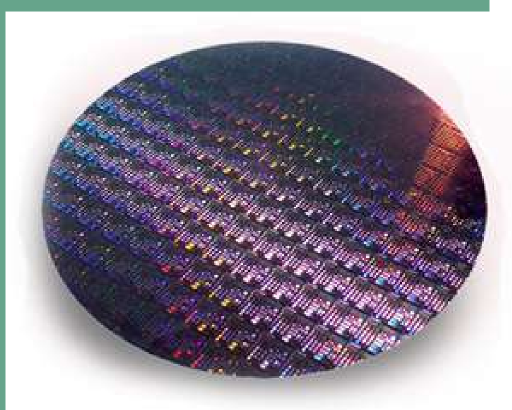
22,500 tpy REO

Mischmetal a La Ce alloy used to purify steel and for special alloys
Ce (52%) La (26%) Nd (17%) Pr (5%)

USGS

POLISHING

Cerium powders polish glass and silicon better than any other substance. Cerium oxide polishes by chemical reaction rather than abrasion.



15,000 tpy REO
Ce (65%) La (32%) Pr (3%)

USGS

GLASS

Lanthanum makes up as much as 50 percent of glass lenses for digital cameras, including cell phone cameras.

Cerium is added to optical lenses and other specialty glass to inhibit UV transmission.

12,500 tpy REO
Ce (66%) La (24%) Nd (3%)
Pr (1%)

USGS

PHOSPHORS

Y, Eu, and Tb phosphors are the RGB phosphors used in all types of light bulbs, display panels, and televisions.

9,000 tpy REO
Y (69%) Ce (11%) La (9%),
Eu (5%) Tb (5%) Gd (2%)

USGS

OTHER

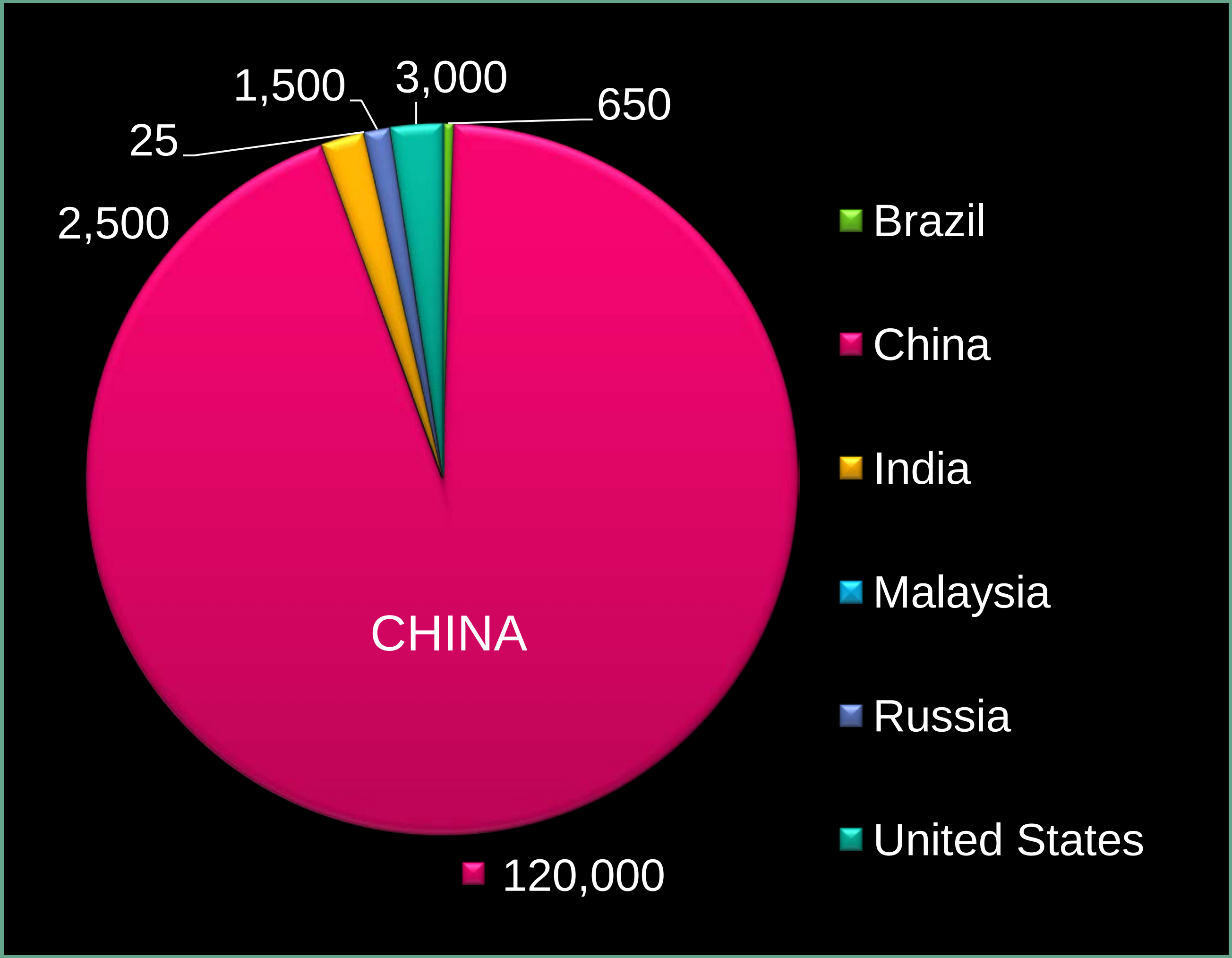
La and Nd are used to stabilize current in ceramic capacitors. Y and Ce are used to stabilize zirconia ceramics, such as those used in solid oxide fuel cells.

7,000 tpy REO
Y (53%) La (17%) Ce (12%) Nd (12%) Pr (6%)

REE-bearing fertilizer is used in China. Rare earths have no known biological function.
8,500 tpy REO – Ce La Y Nd Pr Sm Gd

USGS

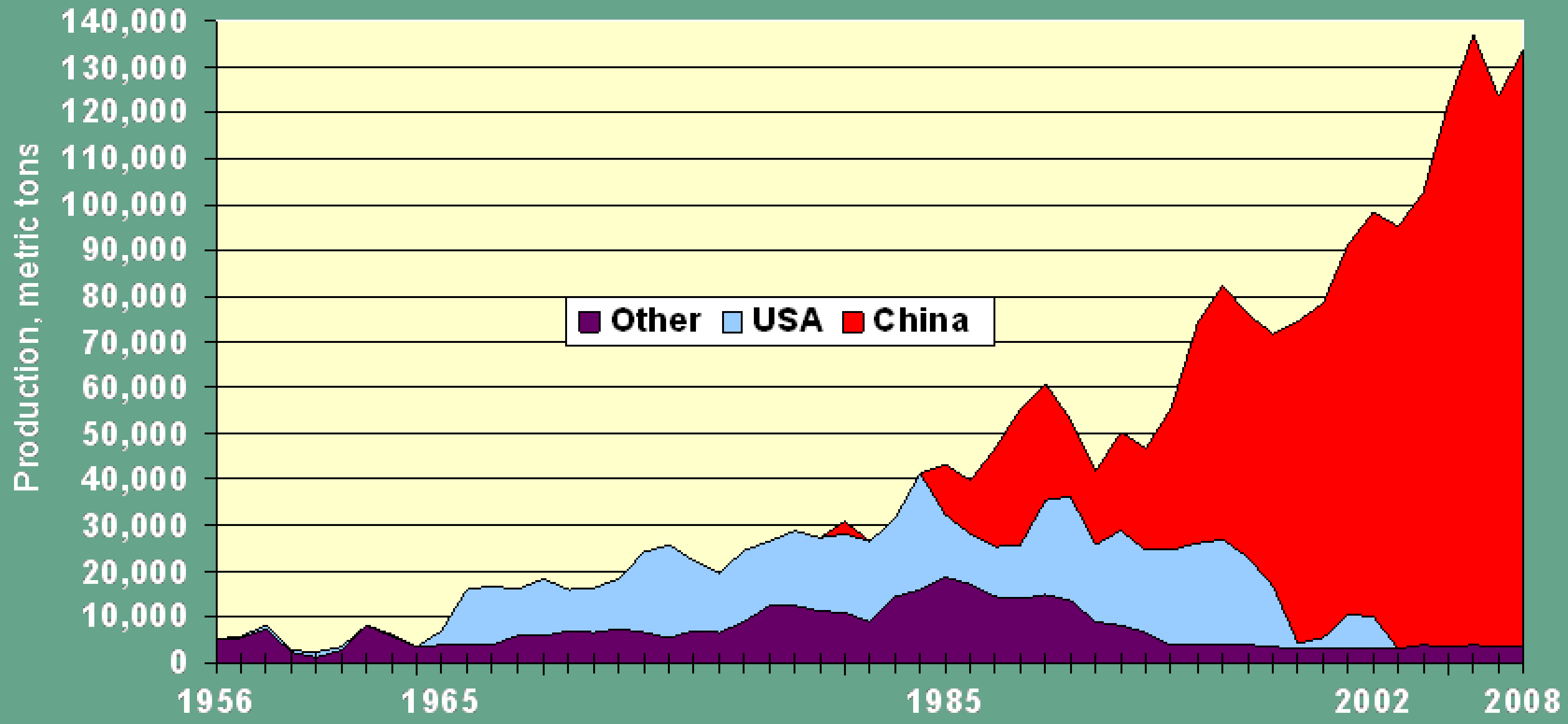
World Production by Country



Production in metric tons REO (rare earth oxides)

USGS

REO Production Trends



Monazite-placer era | **Mountain Pass era** | **Chinese era ⟶ ?**

USGS

Sources: USGS Fact Sheet 087-02 updated with recent USGS Minerals Yearbook

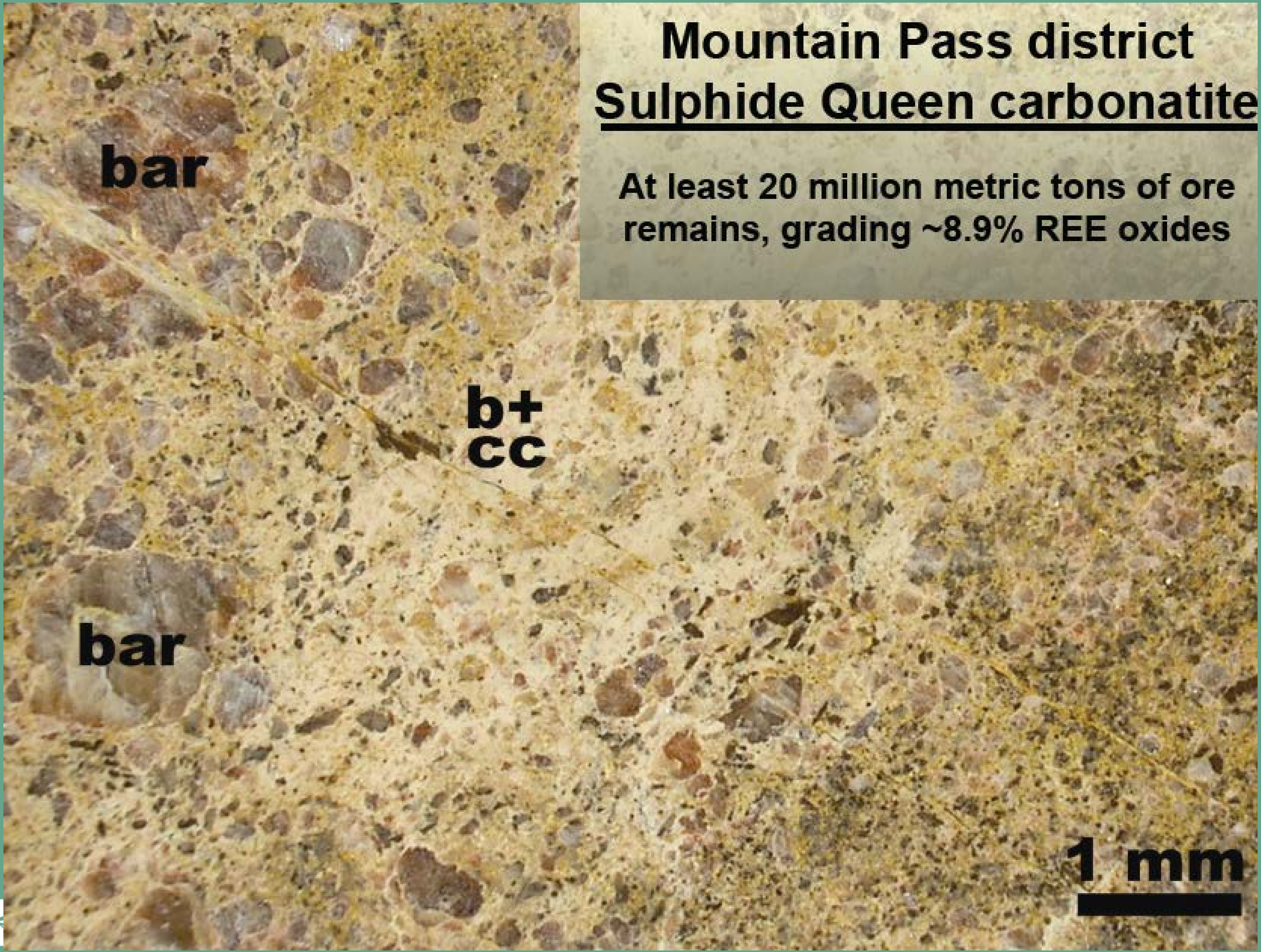
Types of Rare Earth Deposits

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

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

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

USGS



Bradley Van Gosen, U.S. Geological Survey

Bokan Mountain U-REE Vein Deposit, Alaska
Bradley Van Gosen, U.S. Geological Survey

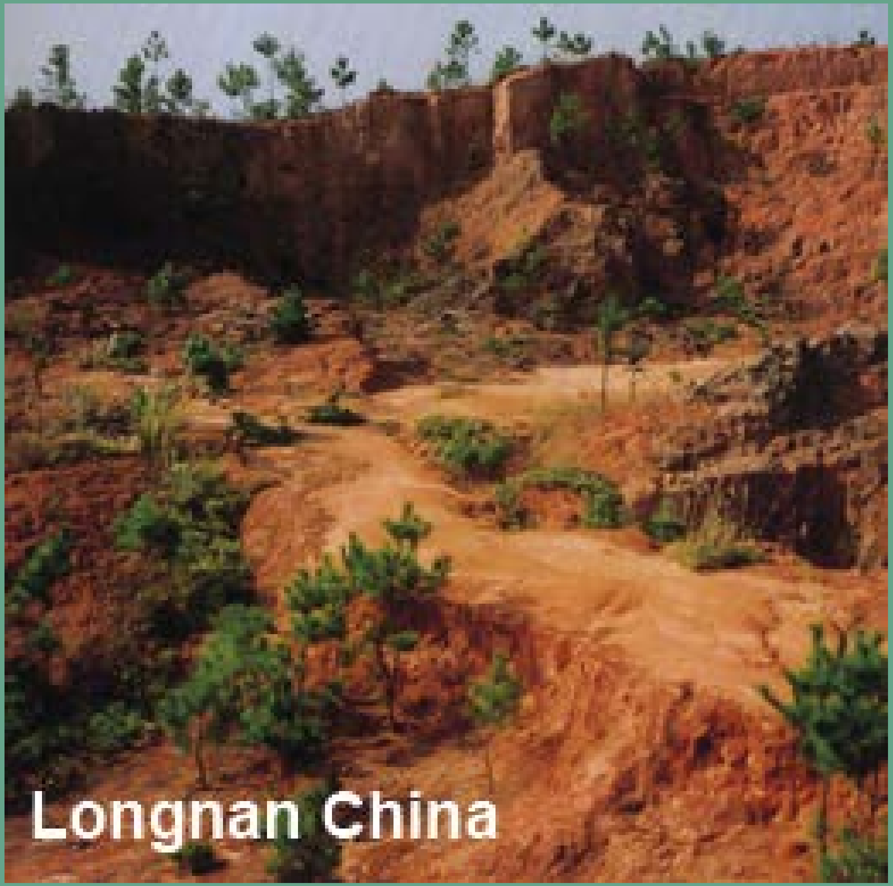
Australia

Heavy Mineral Sand Deposits

Small quantities of monazite-(Ce) are sometimes recovered as a by-product

USGS

Ionic Clay Deposits



T. Tagaki, Geological Survey of Japan

About 0.5 percent TREO in a readily leached form in laterite formed on “tin” granites in southern China.

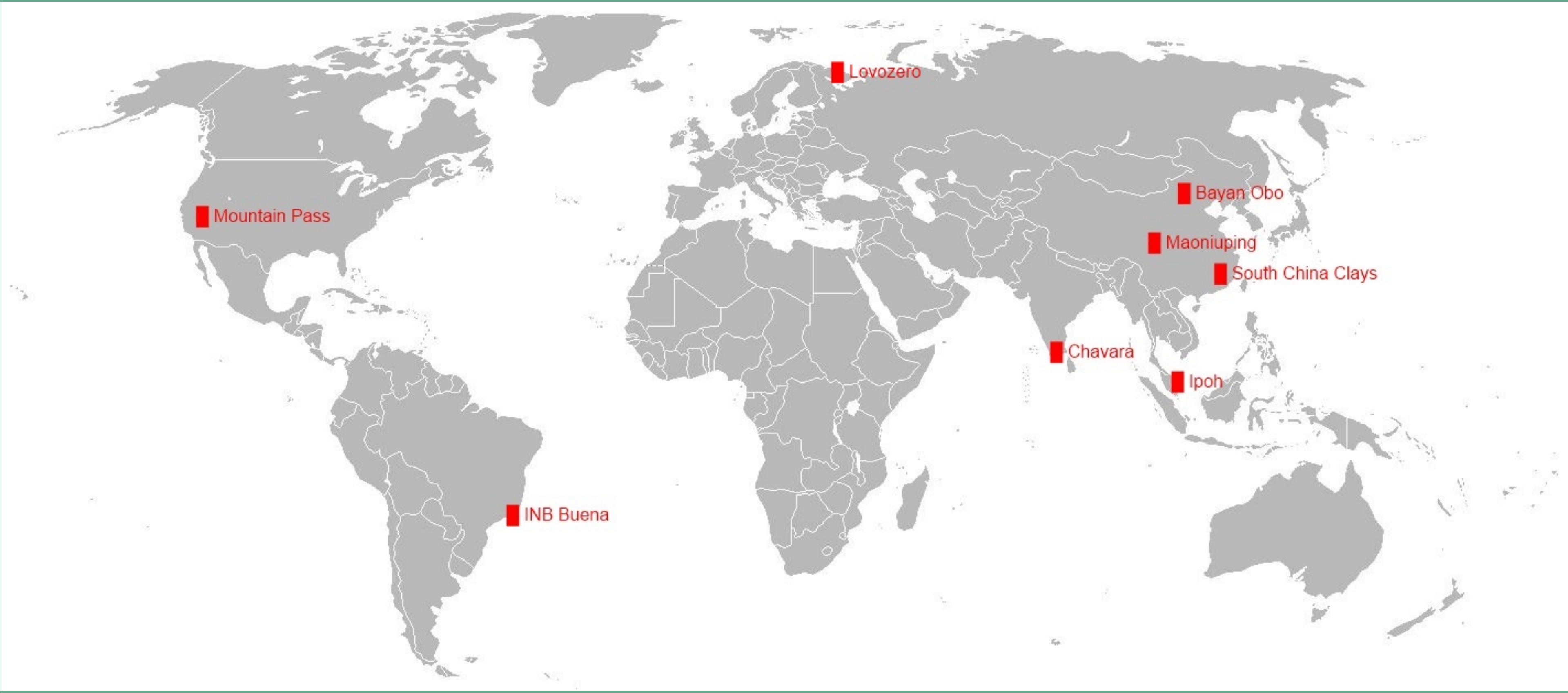
Many of these deposits are enriched in HREE.

A significant source of REE, especially HREE, but resources are rapidly being depleted.

Mining of these deposits in South China by undercapitalized small operators is environmentally problematic.

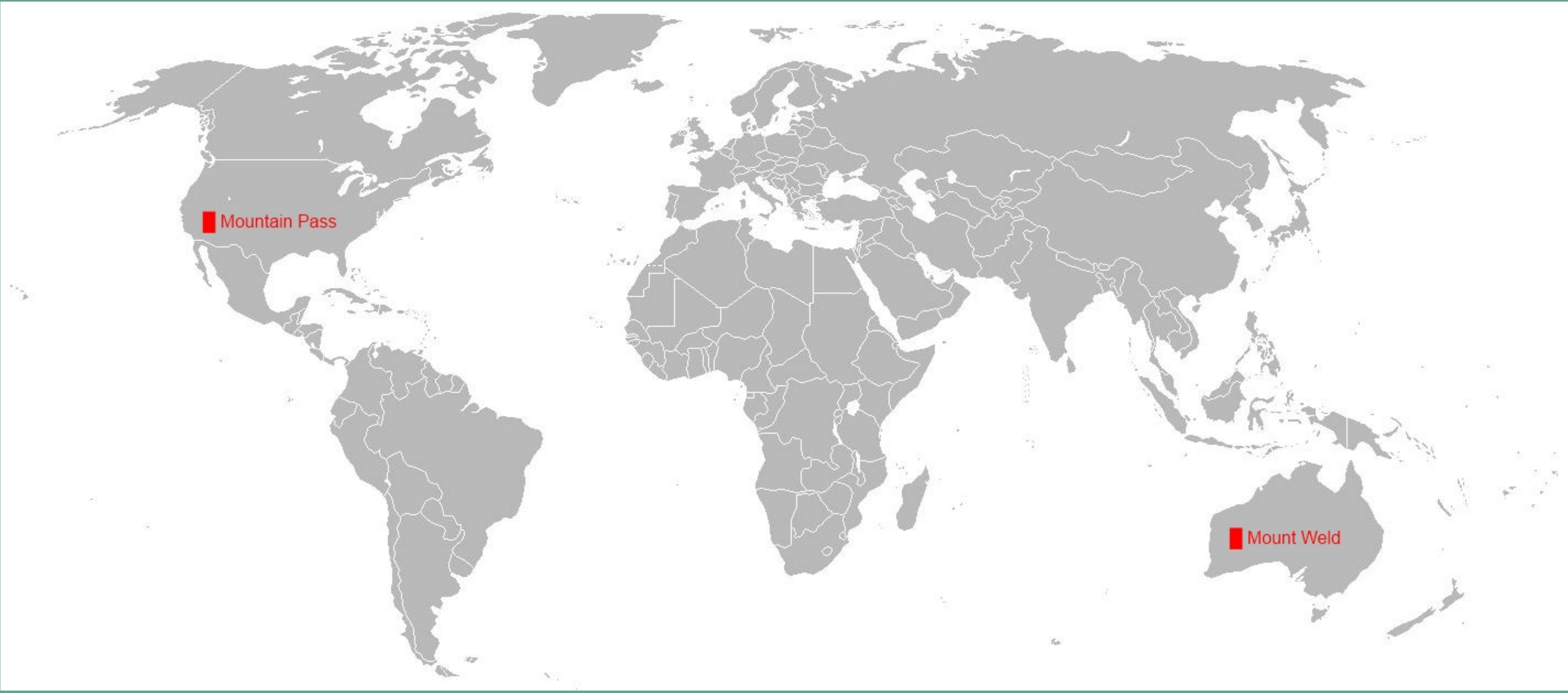
USGS

Operating REE Mines



USGS

REE Mine Development Projects



USGS

Advanced REE Mine Projects

USGS

Reserves and Resources

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

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

USGS

Mining

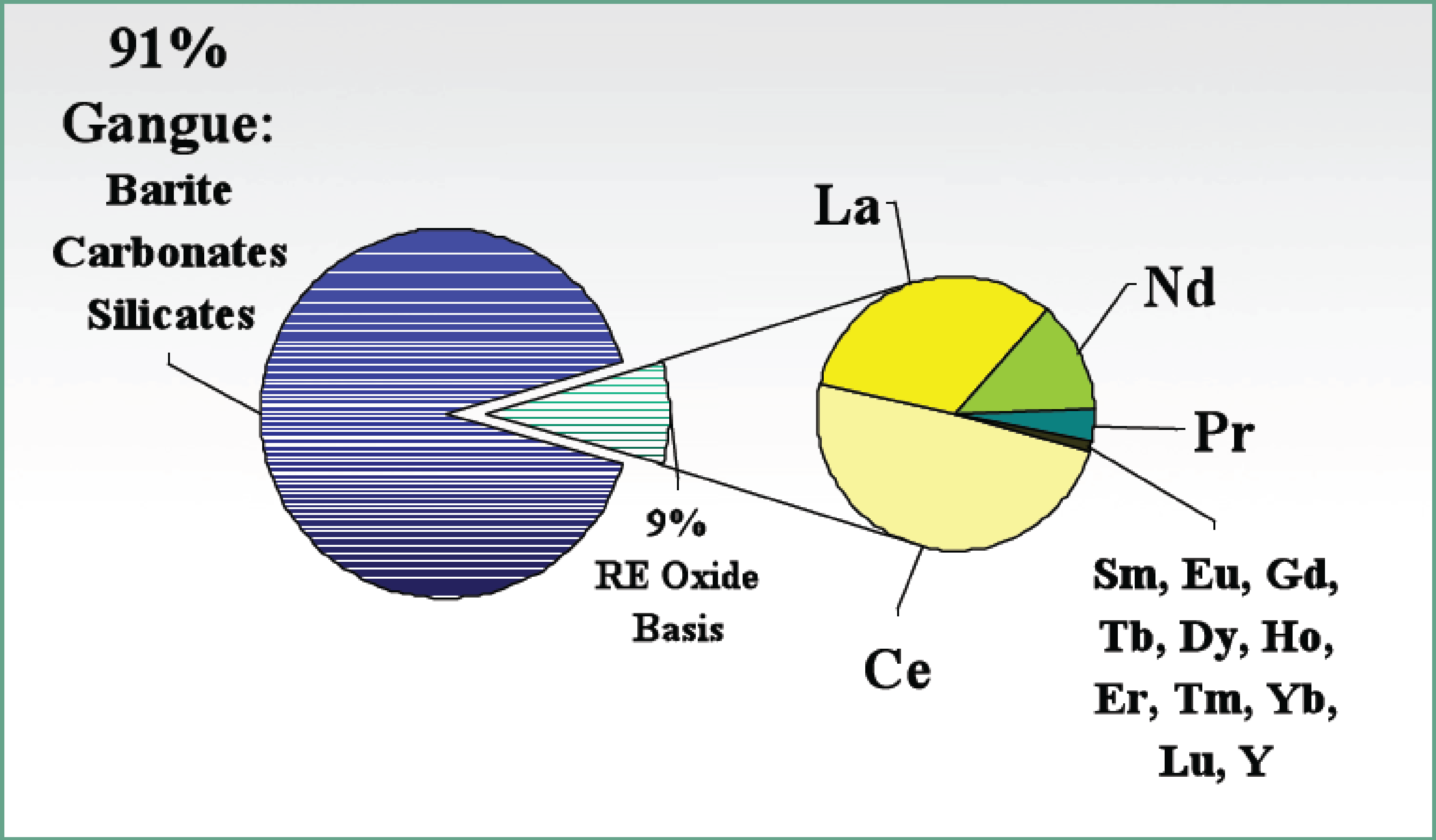
Mountain Pass, CA

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

Pea Ridge, MO

USGS

Mineral Processing

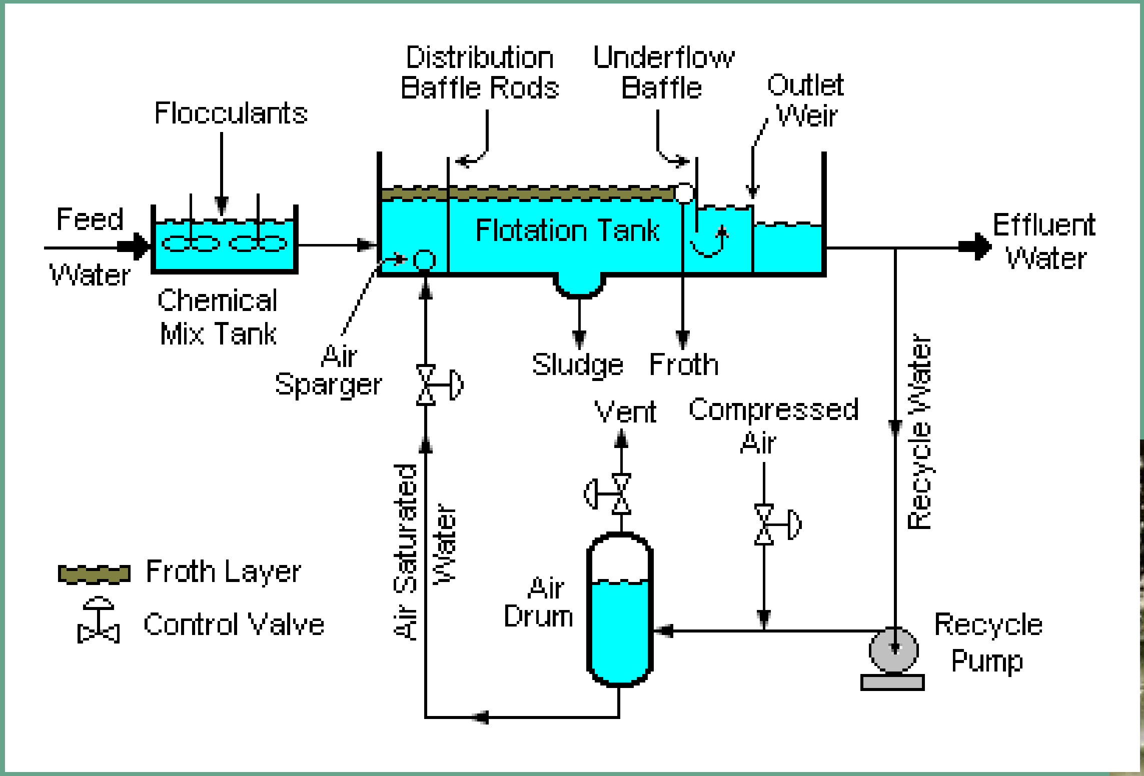


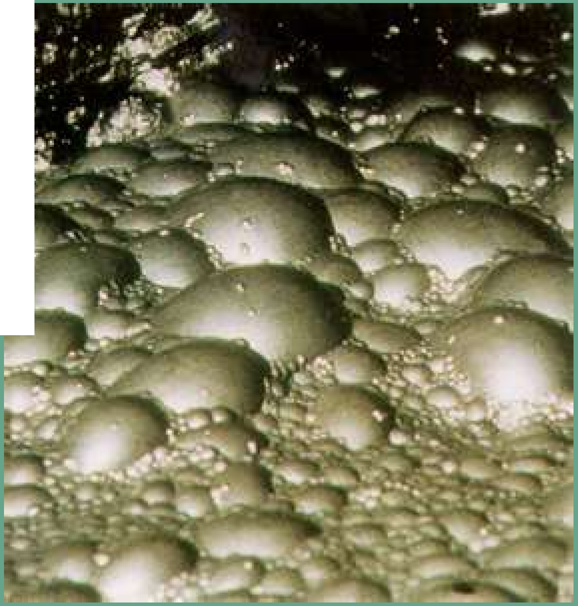
Source: Molycorp, Inc.

Mountain Pass, CA

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

Separating Rare Earth Minerals

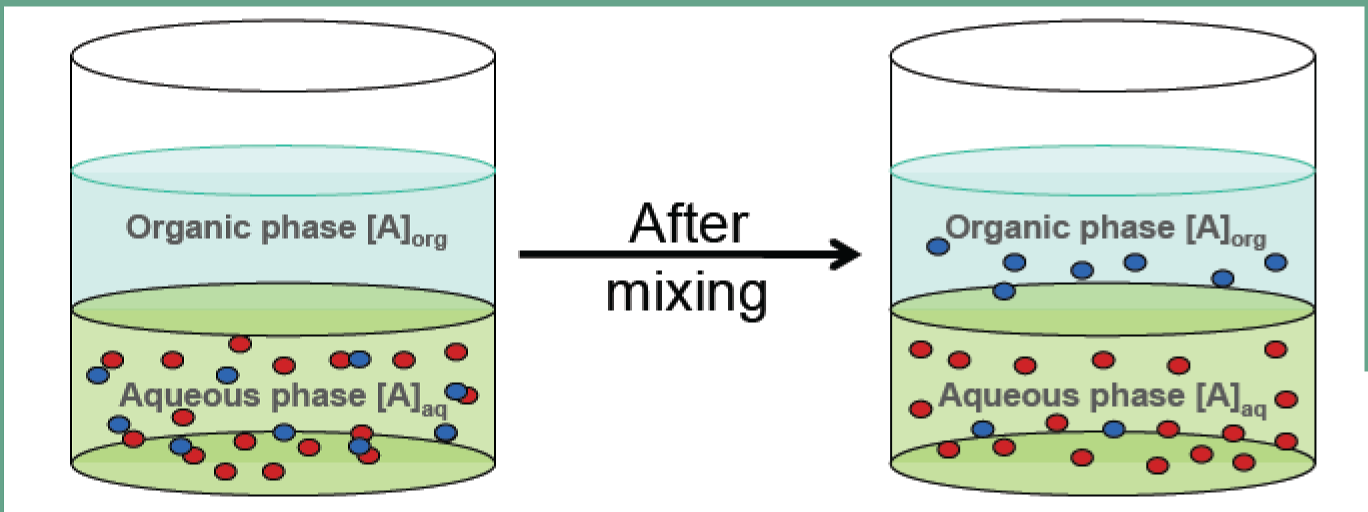


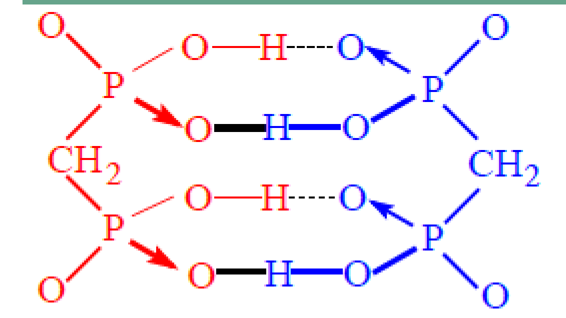


Froth flotation is the most common method for separation of rare earth minerals from other minerals in ore.

USGS

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.

USGS

Cost to Produce REO

Reported Operating Costs at Full Production

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

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

USGS

Principal Operating Costs

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

USGS

Cost to Develop a New REO Mine

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

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

USGS

Time to Develop a New Mine United States

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

Time to Develop a New Mine Elsewhere

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

USGS

Scenario Analysis Future REO Capacity

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

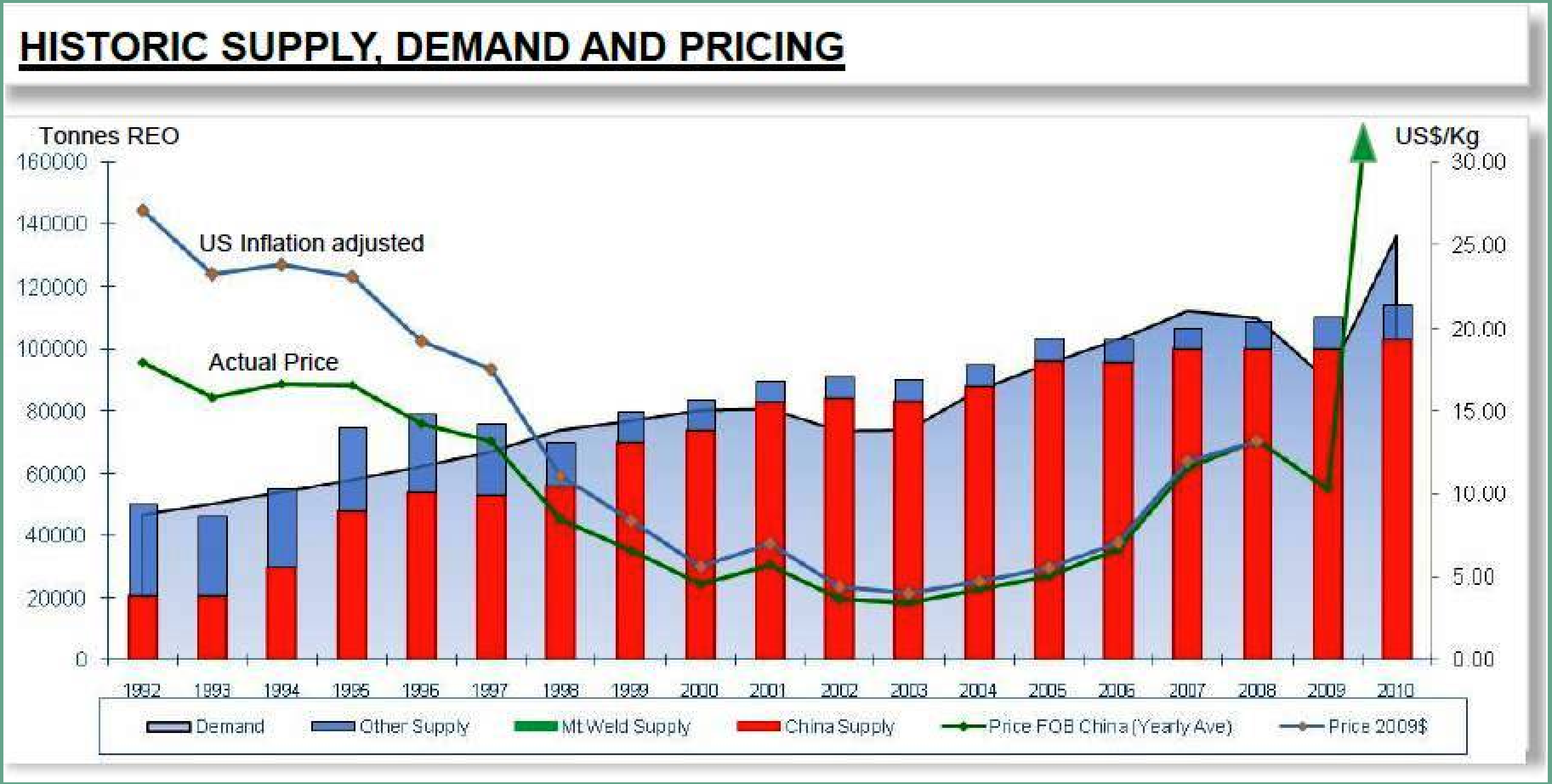
Scenario Analysis REO Supply

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

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

USGS

Historic REO Price Trends



Source: Lynas Corp

USGS

Worst Case Scenario

Ravensthorpe integrated nickel mine and refinery, Western Australia
Closed 1/2009 Sold 12/2009
Cost AUD 2 billion – 700 million more than projected
Never achieved commercial production

The worst case scenario is that either or both Mount Weld or Mountain Pass are unable to achieve commercial production due to technical problems.

USGS

Conclusions

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

USGS

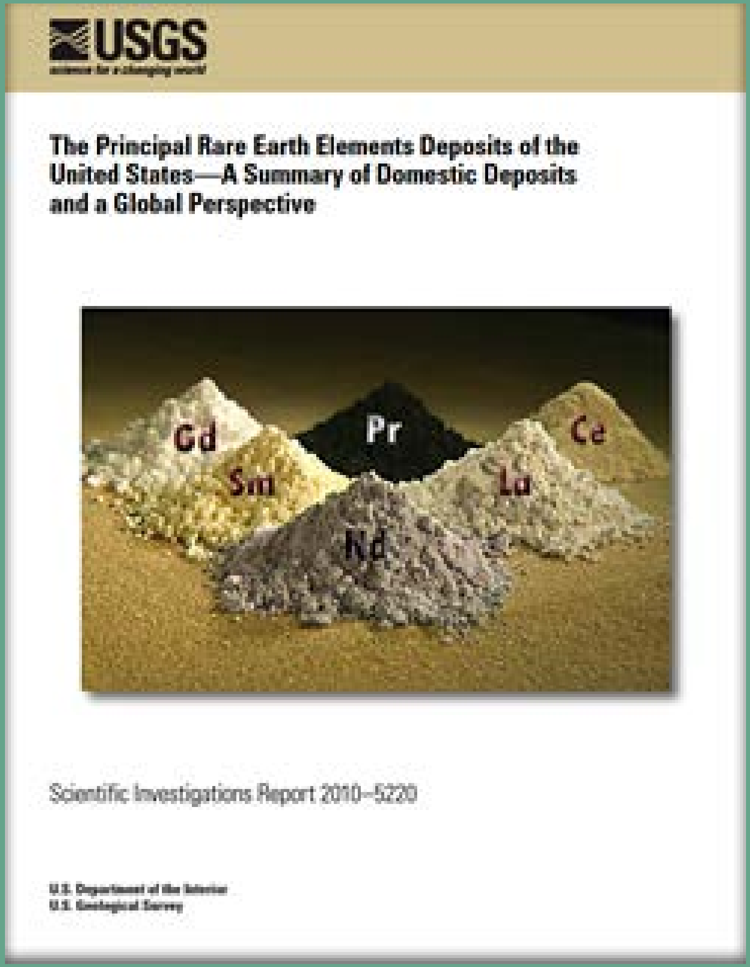
Salmon Bay, AK
Bokan Mtn, AK
Hall Mtn
MT
Placers
Diamond Creek
Lemhi Pass
ID
Bear Lodge Mtns
WY
NE
Elk Creek
CO
Iron Hill
Wet Mtns
CA
Mountain Pass
Music Valley
Petaca
Laughlin Peak
El Porvenir
NM
Lemitar Mtns
Chupadera Mtns
Gallinas Mtns
Capitan Mtns
Gold Hill
Red Hills
Wind Mtn
MO
Pea Ridge
IL
Hicks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

USGS REE Resources & Activities

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

USGS

USGS REE Publications



The Principal Rare Earth Elements Deposits of the United States

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

USGS