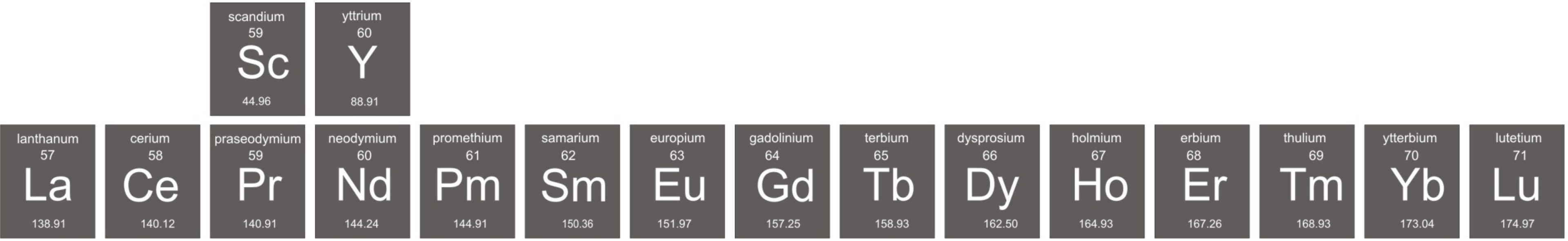
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Critical metals and rare earth elements



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Mines and Money 2010

Outline

- Critical raw materials
- Introduction to the rare earth elements
- Economic importance and applications
- Characteristics of the market:
  - Geological factors
  - Technical factors
  - Commercial factors
- Global production
- The impact of Chinese policy on supply
- Global response to the supply challenge
- The supply-demand balance
- Developing new capacity
- Hurdles to developing new capacity
- Outlook

REE mineral - gadolinite (Ce,La,Nd,Y) BGS © NERC

Critical raw materials

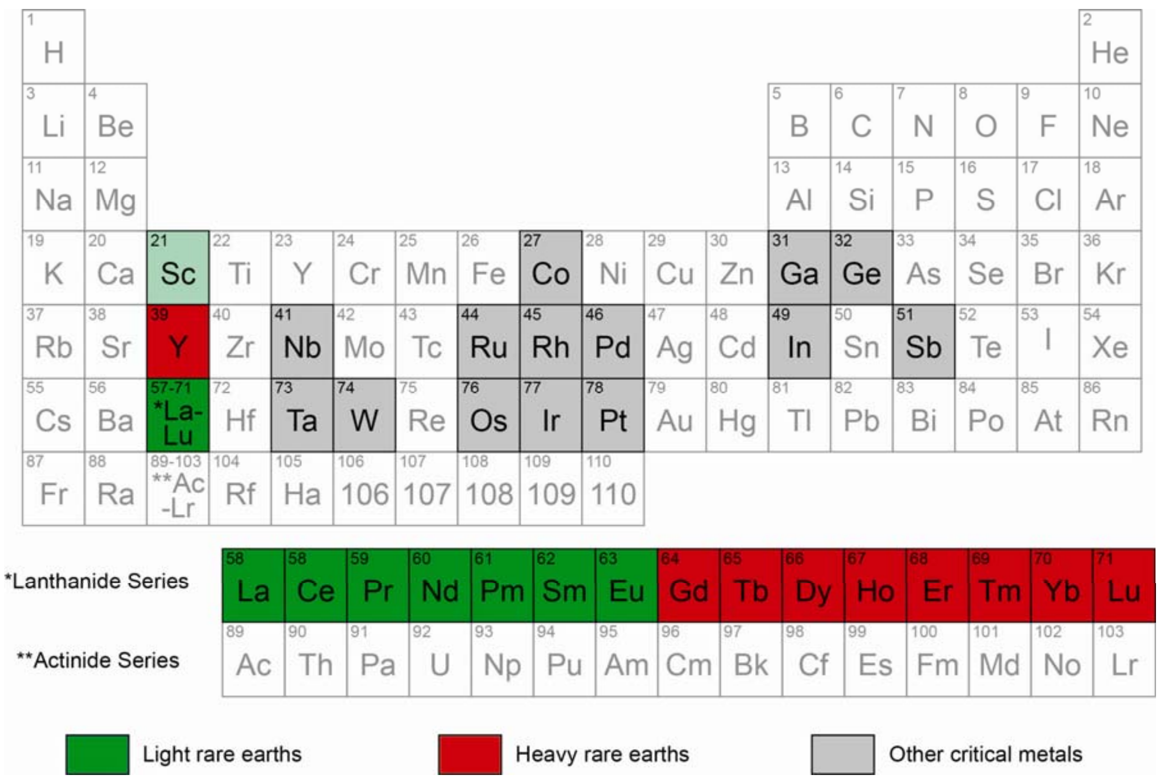
- Increasing vulnerability in the supply of specific minerals
- Definitions: critical (strategic) minerals, technology minerals, minerals for emerging technologies
- Critical minerals:
  - High supply risk (concentration production)
  - High impact of supply restriction (critical to the economy)
  - Compounded by low substitutability/recycling rates
- Geopolitical-economic framework

Antimony	Indium
Beryllium	Magnesium
Cobalt	Niobium
Fluorspar	PGMs (Platinum Group Metals)
Gallium	Rare earth elements
Germanium	Tantalum
Graphite	Tungsten

Source: EU Study, 2010

What are the rare earth elements (REE)

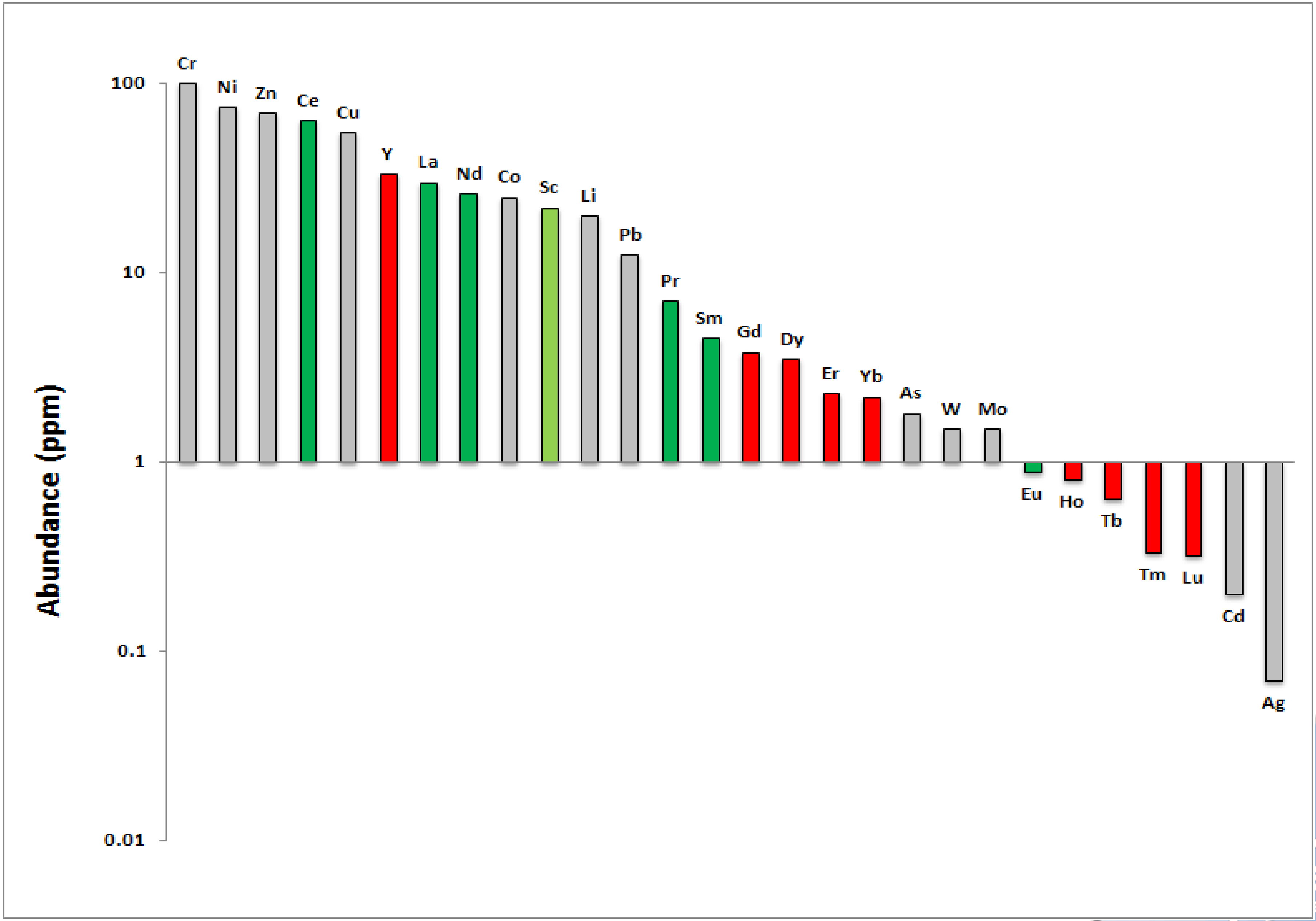
- 17 chemical elements on the periodic table: the 15 lanthanides, plus scandium (Sc) and yttrium (Y)
- Average concentration crust 150-220 ppm (Cu 55 ppm, Zn 70 ppm)



Light REE
La: Lanthanum
Ce: Cerium
Pr: Praseodymium
Nd: Neodymium
Pm: Promethium
Sm: Samarium
Eu: Europium

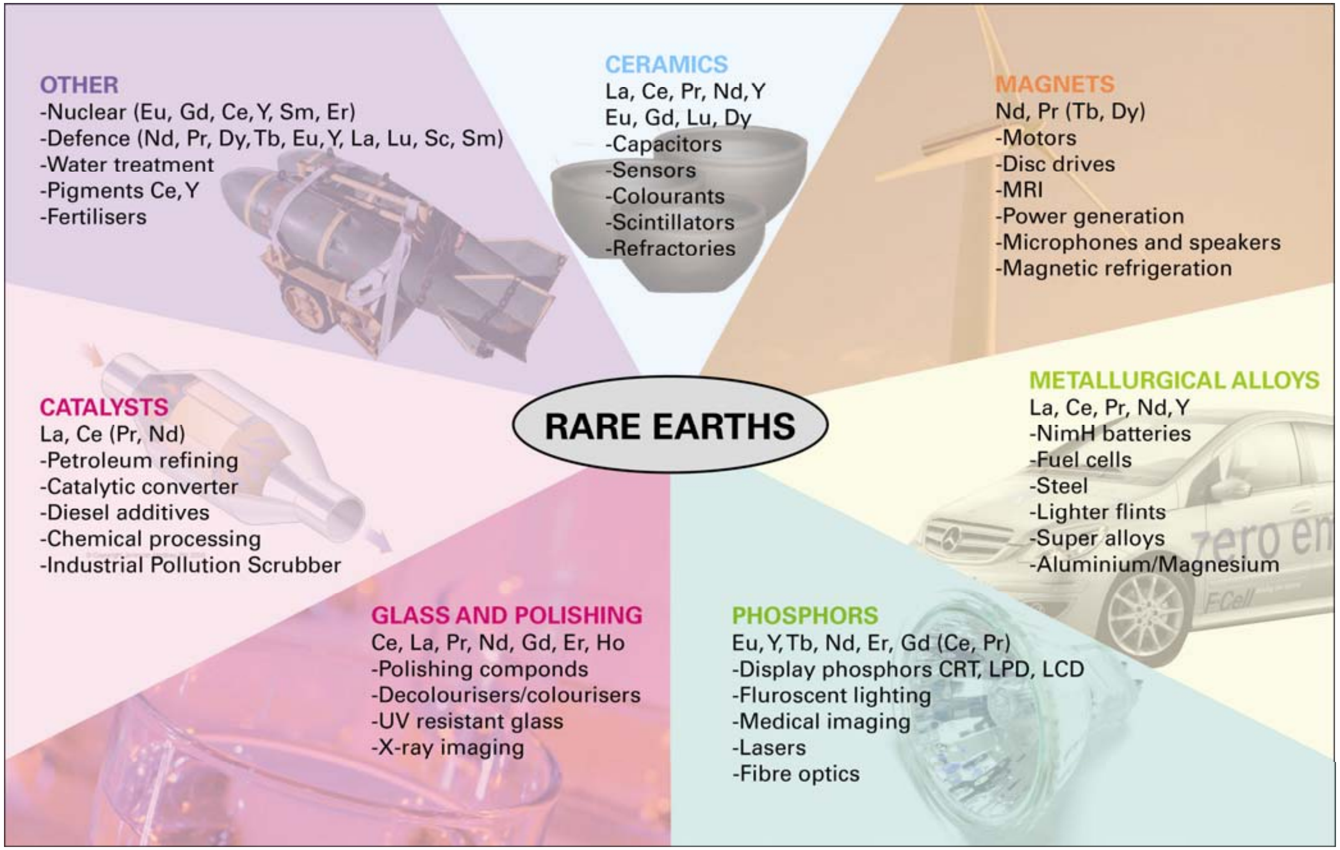
Heavy REE

Gd: Gadolinium
Tb: Terbium
Dy: Dysprosium
Ho: Holmium
Er: Erbium
Tm: Thulium
Yb: Ytterbium
Lu: Lutetium


Abundance (ppm)
100
10
1
0.1
0.01
Cr
Ni
Zn
Ce
Cu
Y
La
Nd
Co
Sc
Li
Pb
Pr
Sm
Gd
Dy
Er
Yb
As
W
Mo
Eu
Ho
Tb
Tm
Lu
Cd
Ag

Economic importance

- 17 elements = hundreds of applications
- Unique properties
- Not currently substitutable in many applications



Chemicals
-Unique electron configuration

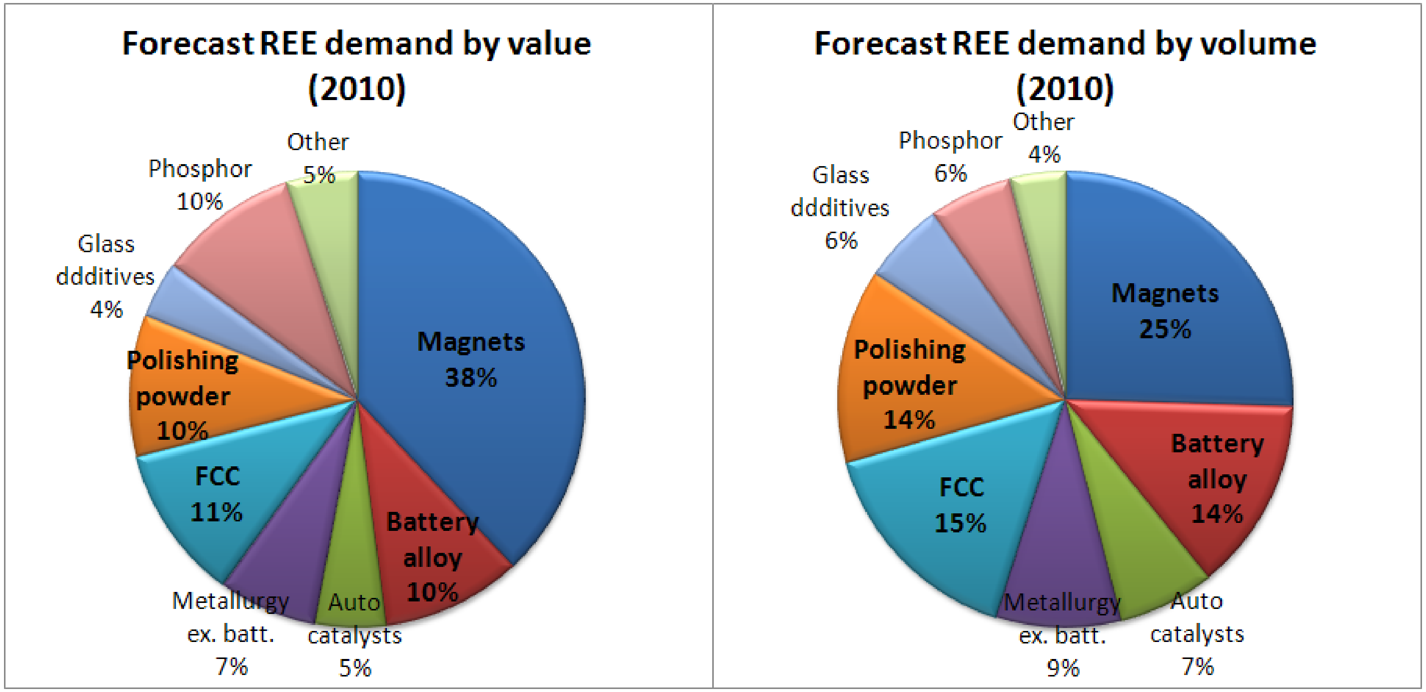
Catalytic
-Oxygen storage and release

Magnetic
-High magnetic anisotropy and large magnetic moment

Optical
-Fluorescence, high refractive index

Electrical
- High conductivity

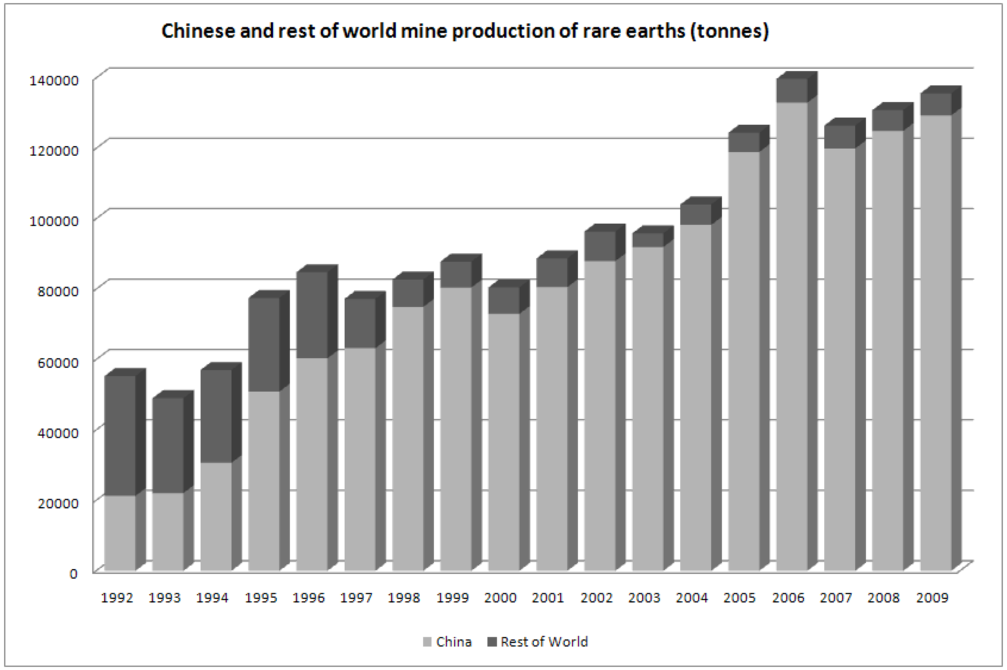
Metallurgical
- Efficient hydrogen storage in REE alloys



Source: Lynas Corporation Ltd, 2010

Scale of the market

- Production REO 2009: 126,230 tonnes[1]
- Value of the REO market: ~US$1.25 billion (before downstream processing)
- Significant potential for market growth (linked to technological change)



[1]USGS, 2010

Source: British Geological Survey

REE market – geological factors

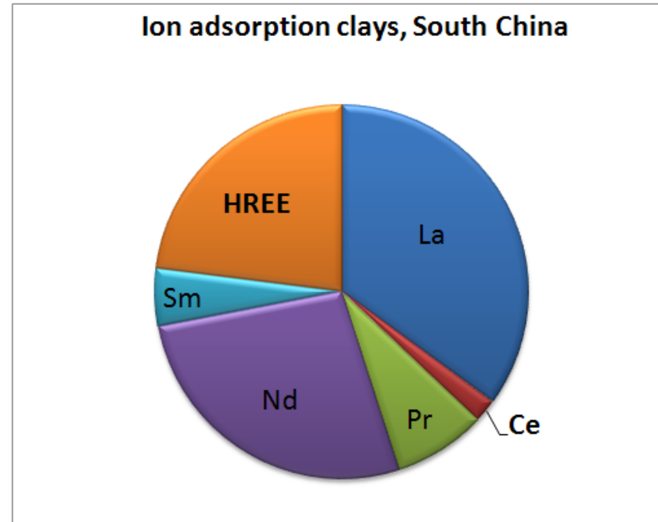
- Geology strongly influences supply and prices
- Rare earths relatively abundant but rarely concentrated
- Naturally occur together
- Relative abundance of REE within and among deposits is highly variable

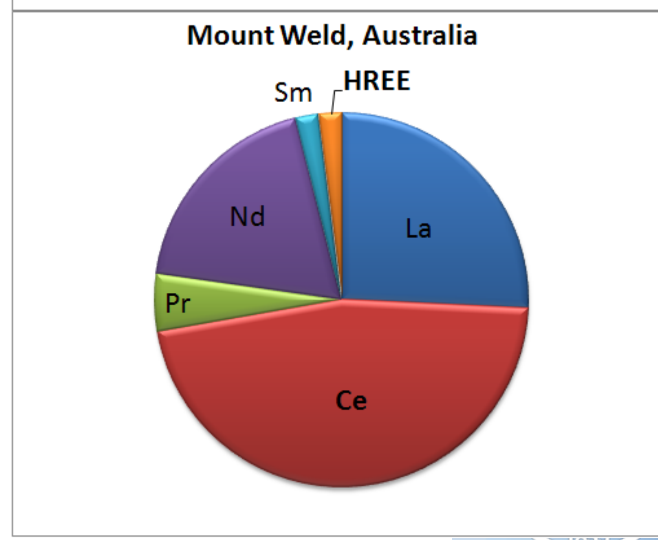
  - LREE typically 80-99% most deposits
- Many REE minerals – few commercially important:

  - **bastnäsite** (76% REO – Ce, La, Y)

  - **monazite** (71% REO – Ce, La, Nd)

  - **xenotime** (61% REO – Y, HREE)





Source: Oakdene Hollins, 2009

Diverse range of minerals deposit types

Primary deposits:

- Carbonatite-associated
- Alkaline igneous rock-associated
- Iron REE deposits (Fe-Ox-Cu-Au)
- Hydrothermal deposits

Secondary deposits:

- Marine placers
- Alluvial placers
- Paleoplacers
- Lateritic deposits
- Ion-adsorption clays

REE market – technical factors

- REE ores are mineralogically complex
- Must be recovered as a group → separated (chemically similar therefore expensive)
- Dirty ores for clean technologies – ores commonly contain radioactive minerals (environmental approvals challenging)
- Deposits vary significantly in composition (processing route – project specific)
- Deposits complex to evaluate – pilot studies required
- Coupled production - frequently produced as by-products e.g. Bayan Obo (Fe), loparite, Russia (Ti), Canada (U)

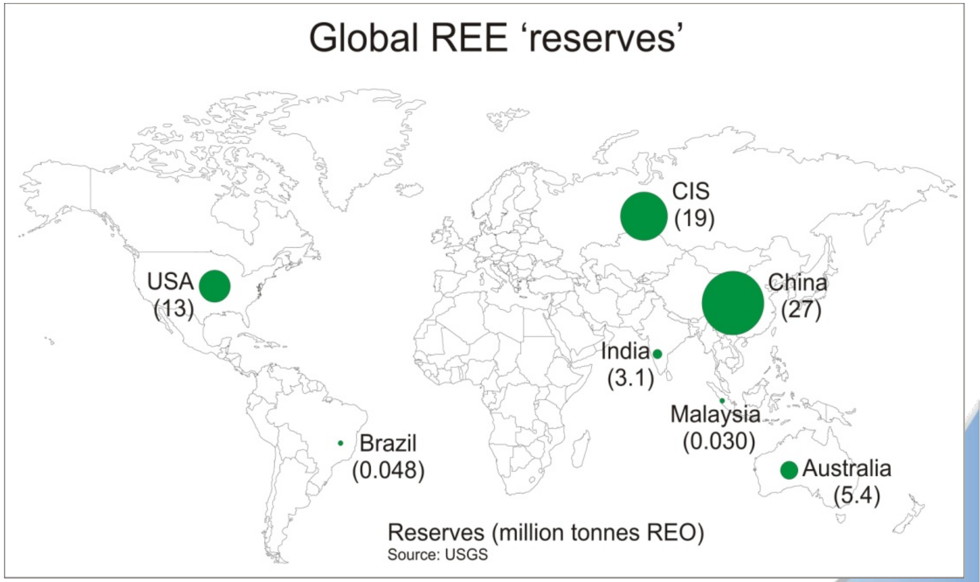
REE market – commercial factors

- Not a single commodity - 17 elements with unique properties and specific applications
- Matching geological ratios to demand is a challenge
  - Potential oversupply of LREE
  - Variable pricing: HREE more expensive
- Non-exchange traded (analogies to industrial minerals):
  - Specialist REE trading companies
  - Reliability of price information
  - Chemicals not conventional commodities (varying purity, customer specific)
- Used in small quantities – demand is inelastic

China dominates REE production

- China's – 95% global REE production, 30% 'reserves'*
- Limited reliable production data for individual countries and elements
- Geographic concentration of 'reserves' is characteristic of critical metals

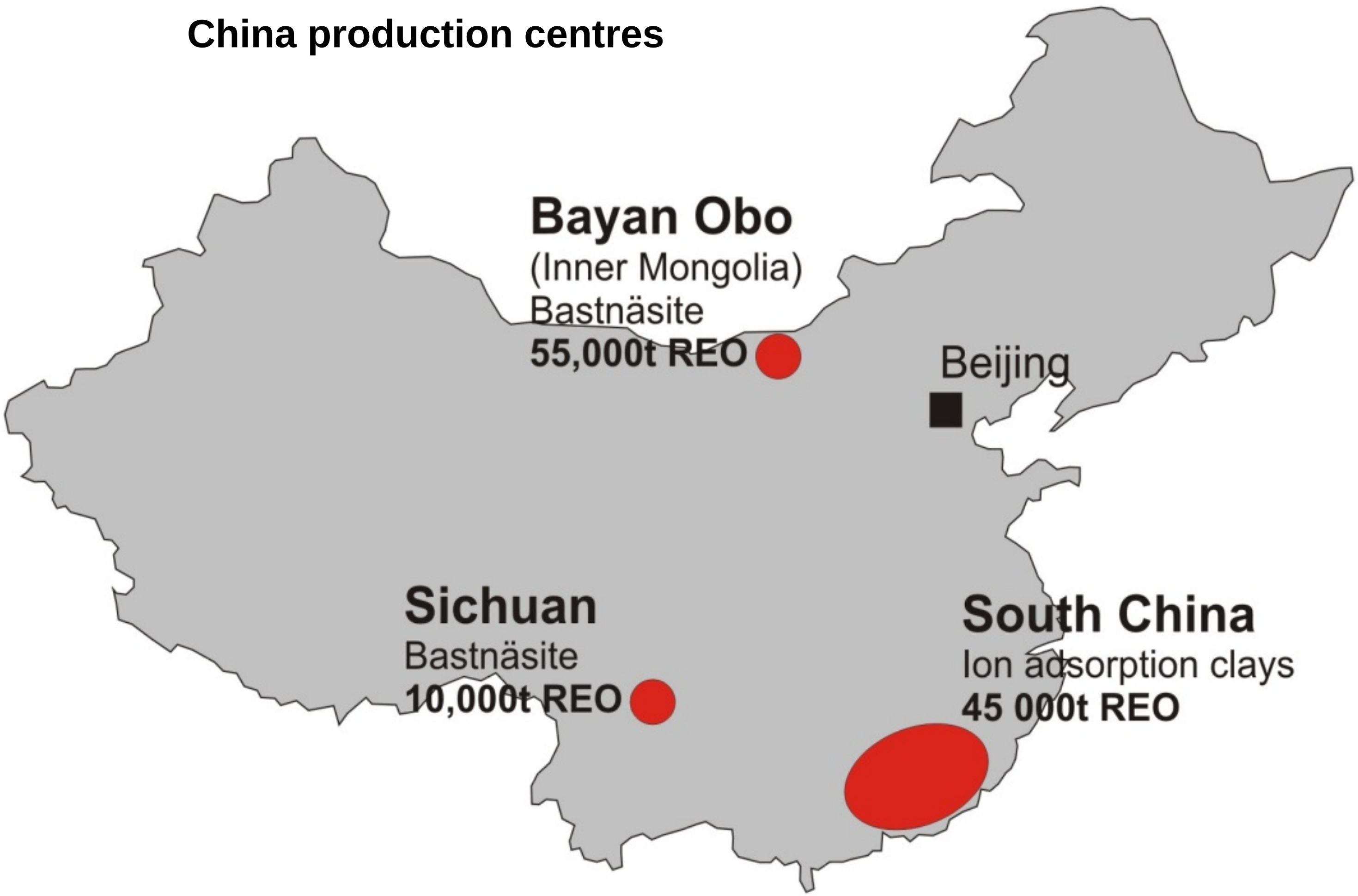
	Production 2009		**'Reserves'***	
	REO (tonnes)	*World %*	*REO*	*World %*
Country				
Australia	0	0	5 400 000	5
Brazil	650	0.5	48 000	0.05
China	**120 000[1]**	**95**	**27 000 000[3]**	**30****
CIS	2500	2.0	19 000 000	19
India	2700	2.0	3 100 000	3
Malaysia	380	0.3	30 000	0.03
USA	-[2]	0	13 000 000	13
Other	0	0	22 000 000	22
Total	**126 230**		**90 000 000**	



Source: USGS Mineral Commodity Summaries
[1]Ore output: 129 400 tonnes
[2]USA produces 3000 tonnes REO - reprocessing stockpiles Mountain Pass
[3]Chinese deposits declined to 27 000 000 million tonnes at the end 2009 or 30% World total, from 43 million in 1996 (Ministry Foreign Trade)

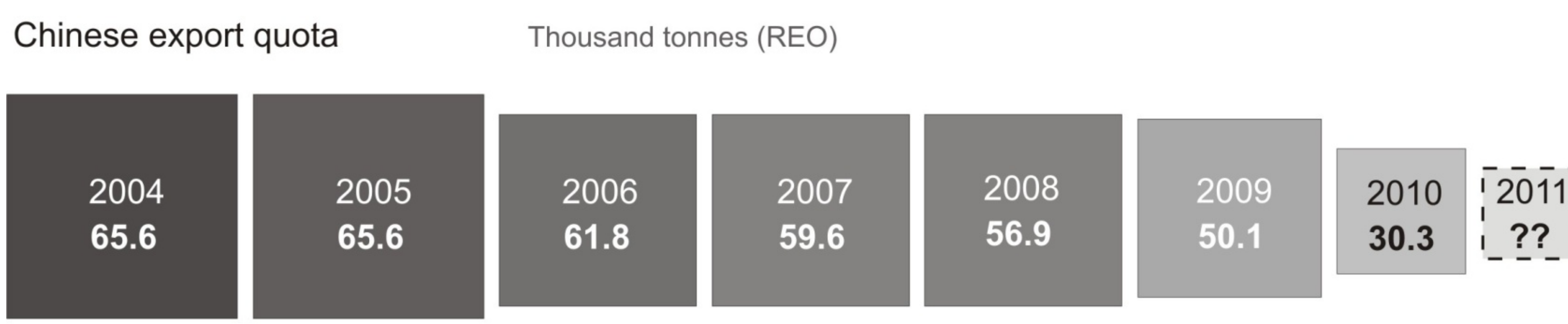
***Reserves - that part of the reserve base which could be economically extracted or produced at the time of determination** (USGS, 2010)

China production centres



Impact Chinese policy on REE supply

- “The Middle East has oil, and China has rare earths” *Deng Xiaoping*
- Key issues and motivation:
  - No incentive to support overseas supply chains
  - Attracting downstream industry (employment creation)
  - Maximise benefit to the Chinese economy – continue to drive Chinese policies to limit REE production and exports
- Policy objectives - improve resource management & conservation, exploitation efficiency, environmental protection:
  - Production quotas
  - Export quotas
  - Export taxes



Source: Chinese Ministry of Commerce

Developments Chinese REE industry

- Increased regulation and rationalisation of the sector:

  - Restructuring and consolidation

  - Crackdown on informal production & environmental protection

  - Creation of a unified pricing scheme for LREE

  - Stockpiling resources

- Future policy is unclear:

  - “China to reduce rare earth export quotas” *China Daily, 18 Oct. 2010*

  - “China will not significantly cut rare earth exports in 2011”, *China Daily, 03 Nov. 2010*

- Interest in acquisition of overseas REE resources
  - e.g. Arafura Resources

- Opportunities for western companies in China:

  - Processing joint ventures

  - Special REE research funds

Global response to the supply challenge

- Supply is volatile and demand is set to rise
- Policies and programmes e.g.:

- US: Rare Earth Materials in the Defense Supply Chain, *Government Accountability Office (2010)*
- Rare Earth Elements: The Global Supply Chain, *Congressional Research Service (2010)*
- Various Acts including - Rare Earths and Critical Materials Revitalization Act (Sept, *2010)*

- Japan: Guidelines for securing national resources *(2008)*
- Ministry of Economy, Trade and Industry release a new REE policy *(October, 2010)*
- Agreements with Mongolia to develop REE projects
- US-Japan roundtable on rare earth elements *(Nov. 2019)*

- South Korea: reducing dependence Chinese REE supplies, revising policy

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- UK: Lanthanide Resources and Alternatives, *Oakdene Hollins (2009)*
- Inquiry strategically important metals *Science & Technology Committee (Nov. 2010)*

- EU: Critical Raw Materials for the EU, *European Commission (2010)*

- Challenge export policies?
- Establishing stockpiles?
- Joint ventures – miners/industrial consumers

Supply-demand balance

- 2010 global demand forecast:136,100 tonnes REO[1] (2009 production 126,230 tonnes)
- 2015 - variable demand balance across the REE: cerium, lanthanum, neodymium, europium, terbium, dysprosium[2]

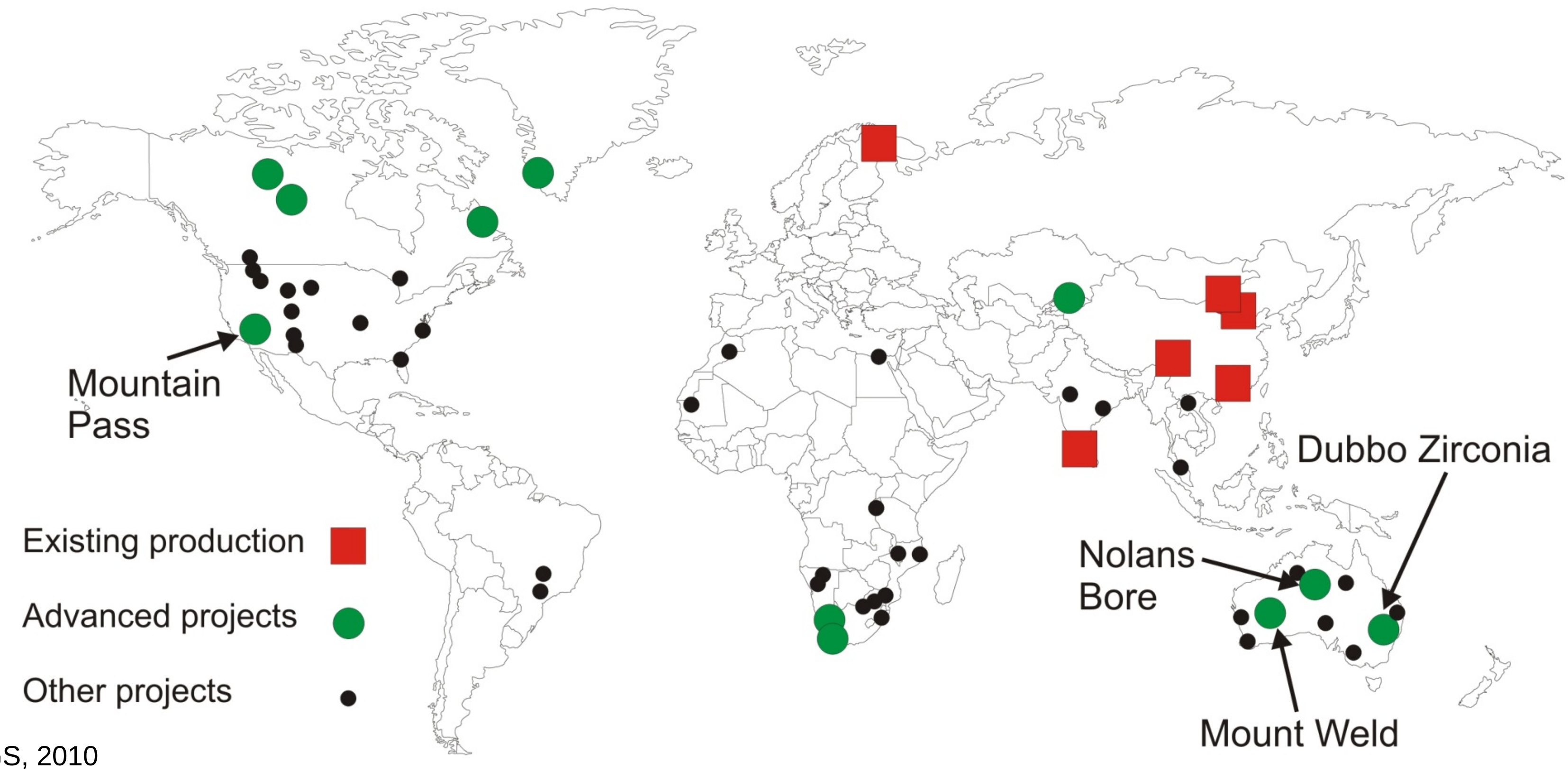
Global rare earth element demand (tonnes per annum) ±15%			
Application	**Consumption REO**		**Increase 2008-2015 (%)**
	2008[2]	**2015[2]***	**2015***
Catalysts	25 000	30-34 000	20
Glass	12 000	13 000	8.3
Polishing	15 000	20-22 000	33.3
Metal alloys	22 250	50-55 000	124.7
Magnets	26 250	45-50 000	71.4
Phosphors and pigments	9000	12-14 000	33.3
Ceramics	7000	8-10 000	14.2
Other	7500	10-12 000	33.3
Totals	**124 000**	**190-210 000***	**53.2**

[1]Lynas Corporation Ltd, 2010
[2]Industrial Minerals Company of Australia Pty Ltd, 2010

* Forecast

The race to develop non-Chinese rare earth resources

- No shortage of global 'reserves'(~90 million tonnes REO)[1] → issue bringing new production online in time
- Many projects but few mines (251 REE projects,165 companies, 24 countries)[2]



[1]USGS, 2010
[2]www.techmetalsresearch.com

Hurdles to developing new capacity

- Urgency for new producers:
  - Long start-up times (>7years[1])
  - "...rebuilding a U.S. rare earth supply chain may take up to 15 years"[2]
- Limited technical knowledge to develop projects
- REE ore mix – LREE vs. HREE-dominant projects
- High production costs
- Restricted opportunities for market entry – offtake agreements
- Project financing:
  - Capitally intensive (>US$40/kg annual capacity[3])
  - Access to debt market (early stage, unfamiliarity to investors)
  - Potential future market size?
  - Potential REE bubble?
  - Evaluation and valuing REE deposits

[1]USGS, 2010
[2]GAO-10-617R Rare Earth Materials in the Defense Supply Chain
[3]Industrial Minerals Company of Australia Pty Ltd, 2010

REE outlook

- China will remain the **dominant REE supplier** short-medium term
- Future **supply will be tight**, particularly for the **HREE**
- Projects outside China need to be developed rapidly to **reduce supply risk**:
  - New projects will come on stream over the next 5 years
- **Caught out by REE** – need to predict future supply problems:
  - Consider **other critical metals**
  - Improved data is required on production
  - International collaboration necessary (USA/Japan/EU)
- Raw materials security diplomacy will be of growing importance
- **Recycling, substitution** and resource efficiency increasingly important

Sources of reference and acknowledgements

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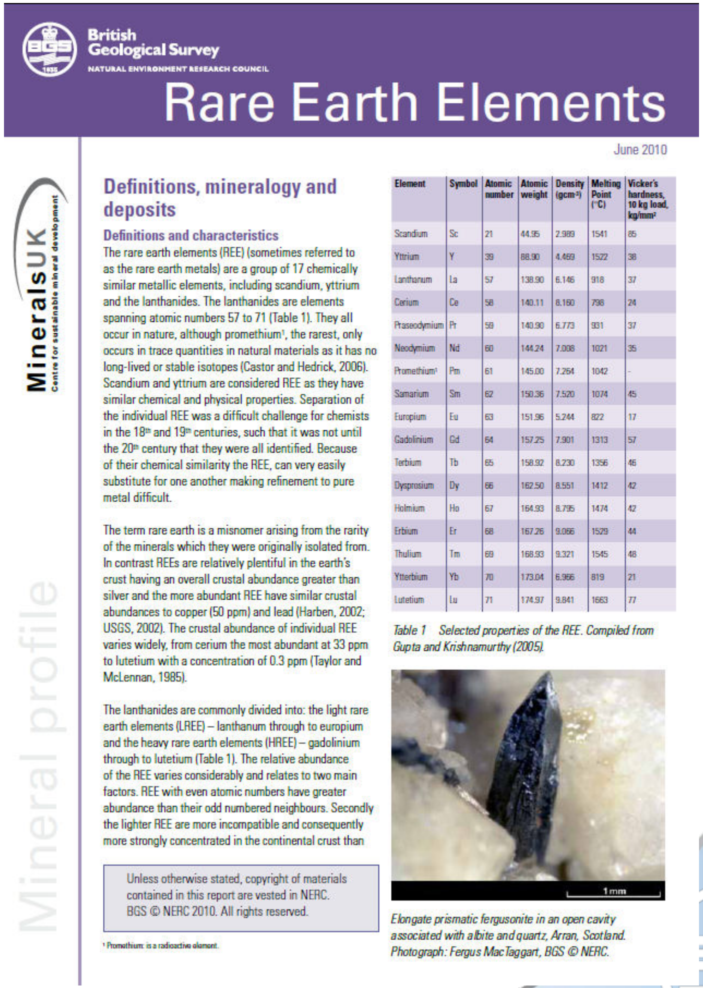
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Rare Earth Elements

June 2010

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 scandium, yttrium and the lanthanides. The lanthanides are elements spanning atomic numbers 57 to 71 (Table 1). They 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, such that it was not until the 20th century that they were all identified. Because 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 which they were originally isolated from. In contrast REEs are relatively plentiful in the earth's crust having an overall crustal abundance greater than silver and the more abundant REE have similar crustal abundances to copper (50 ppm) and lead (Harben, 2002; USGS, 2002). The crustal abundance of individual REE varies widely, from cerium the most abundant at 33 ppm to lutetium with a concentration of 0.3 ppm (Taylor and McLennan, 1985).

The lanthanides are commonly divided into: the light rare earth elements (LREE) – lanthanum through to europium and the heavy rare earth elements (HREE) – gadolinium through to lutetium (Table 1). The relative abundance of the REE varies considerably and relates to two main factors. REE with even atomic numbers have greater abundance than their odd numbered neighbours. Secondly the lighter REE are more incompatible and consequently more strongly concentrated in the continental crust than

[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	8.160	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).

1 mm

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