



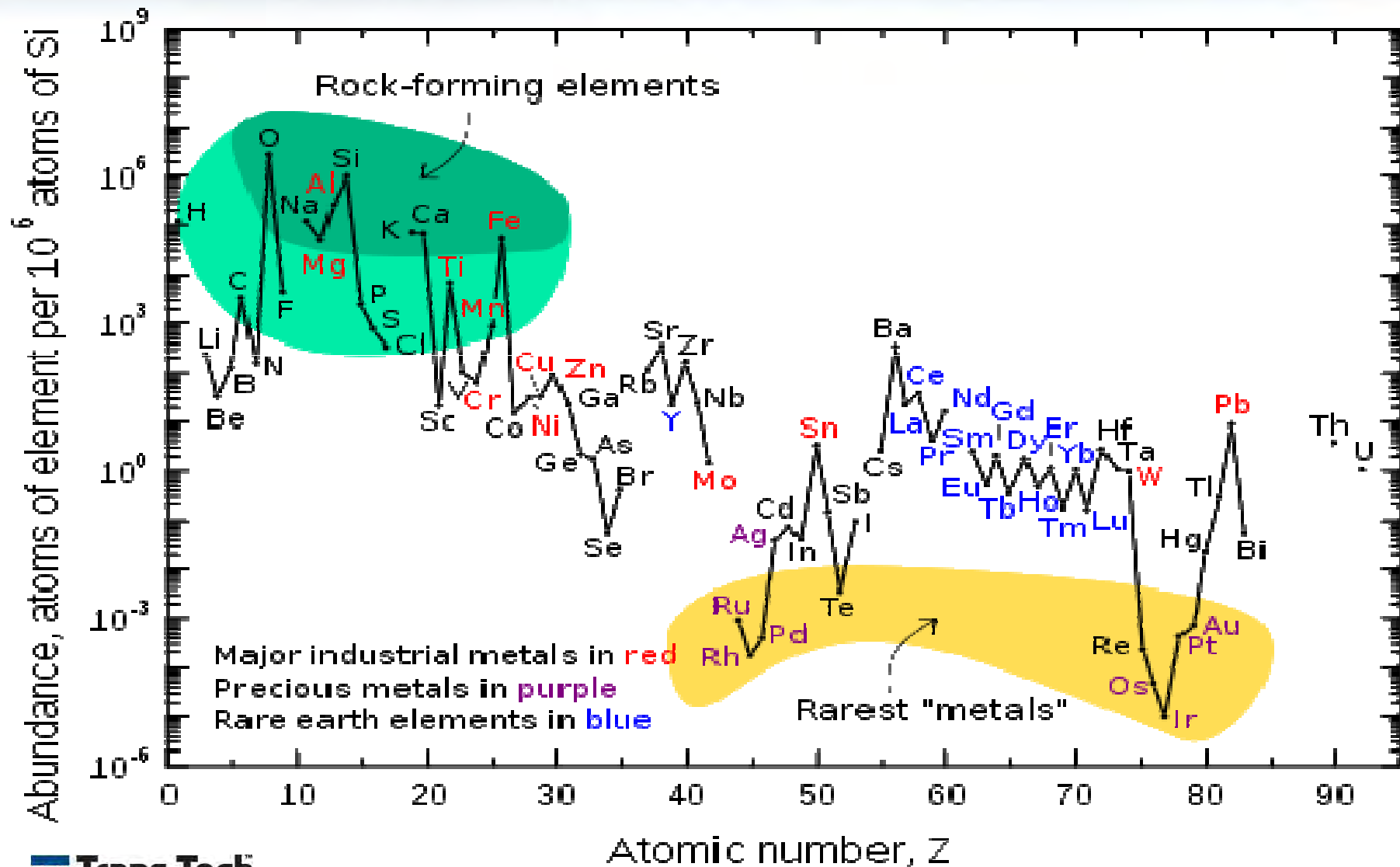
# **Raw Material Scarcity and its Impact on U.S. Ceramic Technological Development (An Industrial Perspective)**

Michael D. Hill

Skyworks Solutions, Inc. - RF Ceramics Division  
(Trans-Tech)

8/3/2011

# Terrestrial Abundance of Elements (U.S. Geological Survey)





**SKYWORKS**

Kawamoto, Quarterly Review April, 2008US DOE Critical Materials Strategy 2010

The diagram illustrates the periodic table categorized into four groups based on their availability and usage:

- non-metal elements:** H, C, N, O, P, S, Cl
- elements of hope (abundant):** Na, Mg, Al, Si, K, Ca, Fe
- critical elements (scarce, for specific applications only):** Ti, Cr, Mn, Cu, B, F, Ar, Br
- frugal elements (used with care):** Li, Be, Sc, V, Co, Ni, Zn, Ga, Ge, As, Sr, Y, Zr, Nb, Mo, PGM, Ag, Cd, In, Sn, Sb, Te, Ba, REM, Ta, W, Re, Au, Hg, Tl, Pb, Bi

- **Enough material in earth's crust to satisfy demand**
- **Through 20<sup>th</sup> century, mineral supply has kept up with demand. In last decade material scarcity has become an issue – real prices have doubled since 2002. (BRIC industrialization)**
  - China: 70% of global demand for Al, Cu and Zn (Hague Center for Strategic Studies 2010)
- **Large fraction of the world's reserves in developing countries (e.g. South Africa, Brazil etc.)**
  - Reserves in industrialized nations depleted
  - Reserves at lower grades and less geographically accessible
- **An economic, not a physical, variable. (Markets neither elastic nor efficient)**
  - It is about the amount of extraction that becomes profitable under existing market conditions.
  - Delay in price decreasing after new sources become available. (Tantalum roller coaster 2000-2006)

# Scarcity as an Economic Event



- **Speculation adds to supply/demand relationship**
  - Directly in some metals markets: Au, Ag, Cu, Pt
  - Indirectly since mining becoming increasingly energy intensive (price of oil)
- **Global Markets not established for many scarce materials.**
  - Bi-lateral deals in play; large price swings.
- **Limited Availability Geographically**
  - Monopoly governments (China with rare earths)
  - Political Instability (DRC, tantalum in 2001)
- **Raw Material costs strongly pegged to energy costs**
  - Increased Energy for Lower Grade Ores
  - Increased transport distance and associated fuel costs
- **Association with Environmental Regulations:**
  - Rare Earth Mining may involve the presence of radioactive (thorium containing) tailings
- **Static and Dynamic Paradigm**

# Static Scarcity Paradigm (Hague Center of Strategic Studies – Scarcity of Minerals 2010)



- **Assumptions:**

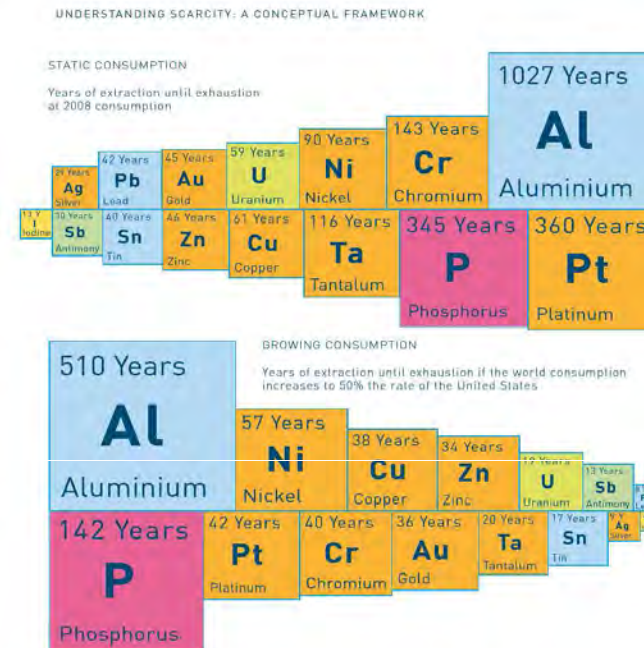
- Fixed amount of rare mineral reserves on planet
- Mining diminishes reserves
- Scarcity sets in when consumption depletes reserves and production struggles to meet demand

- **Static Range (Time left until depletion).** Amount of proven reserves divided by the consumption rate

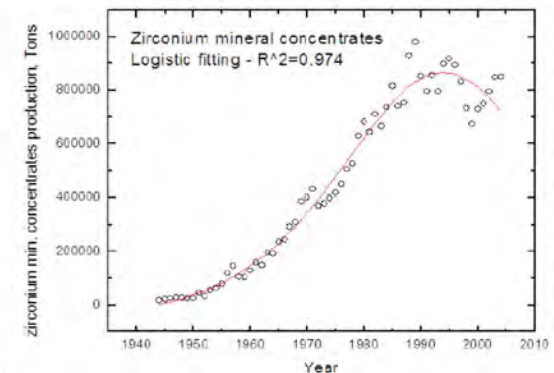
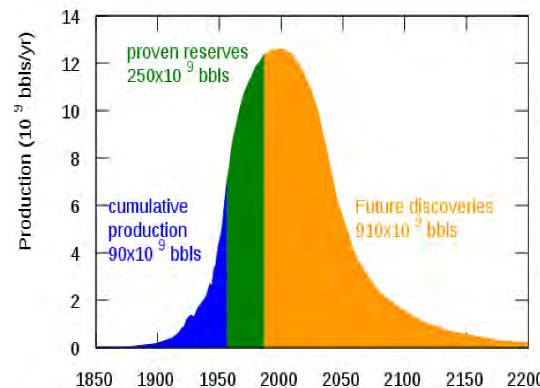
- **Static Paradigm paints overly grim picture. (Hubbert Peak)**

- **Does not consider recycling or material substitution**

- **Does not consider mineral exploration or advances in mining technology**



Hague Center of Strategic Studies – Scarcity of Materials (2010)



Material Scarcity, An M2i Study, Wouters and Bol 2009

# Dynamic Paradigm

- Reserves are “profitable for extraction now or in the near future with existing technology or under current market conditions. Combined effect of evolving geological knowledge, changing market forces and improving extraction technologies. (HCSS 2010)
- In terms of material in earths crust, there is enough dysprosium for one million years even if production skyrocketed.
- Scarcity a dynamic phenomenon.
  - Supply: Mines previously considered uneconomical become feasible. (5-10 years)
  - Demand: Substitutes found. Recycling becomes profitable (>10 years)
  - Inelastic Response: Export restrictions, stockpiling, bi-lateral deals
- Predicting Scarcity a Complex Problem

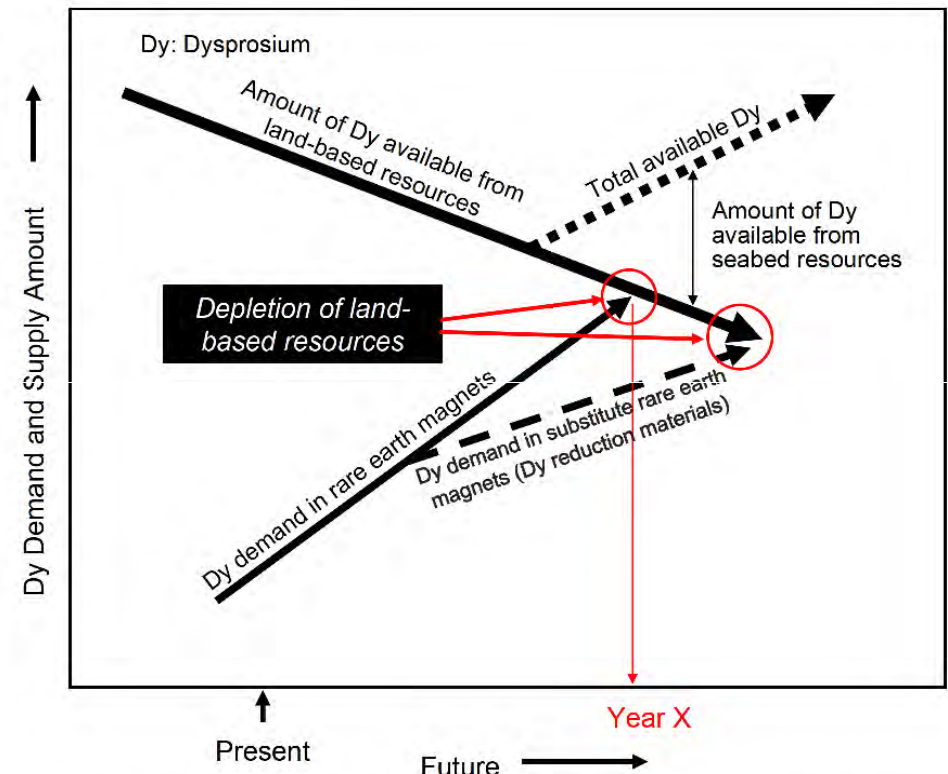


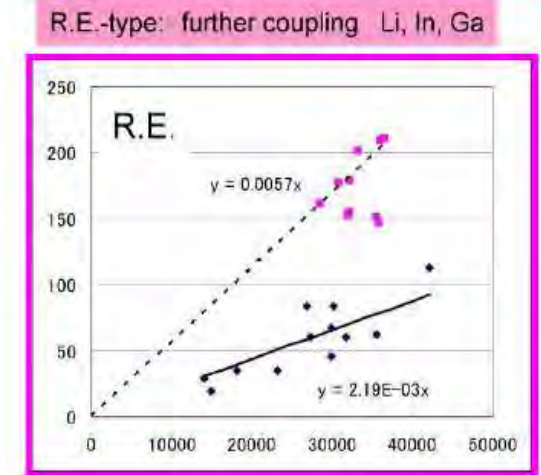
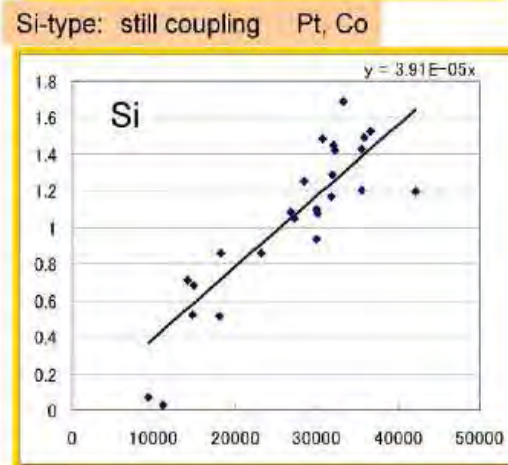
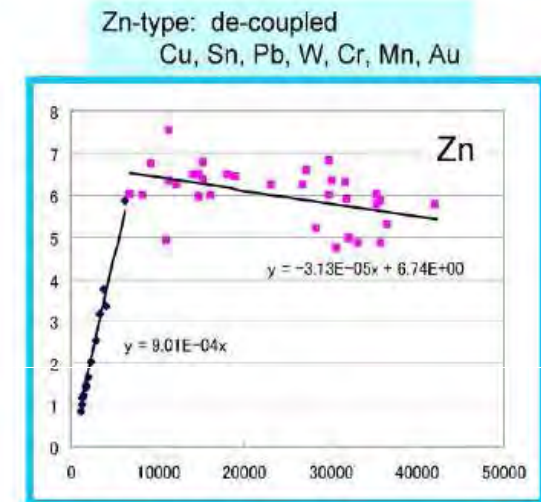
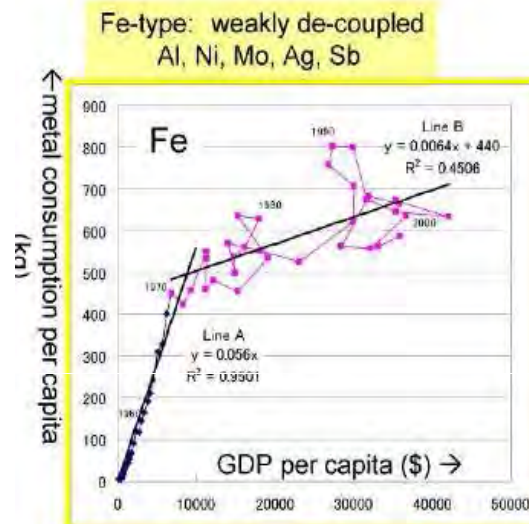
Figure 5 : Anticipated view of the supply and demand relationship of dysprosium in rare earth magnets

Figure from Kawamoto, Quarterly Review [27] 2008

# Historical Demand for Raw Materials (US-DOE)

- **1980s:** Supplies rose with mines opening in Latin America and Southeast Asia
- **1990s:** Large volumes of metals entered market after collapse of Soviet Union
- **2000s:**
  - Decline in U.S. dollar contributed to higher metal prices since most mineral markets priced in dollars
  - Boom in many commodities due to rapid Asian industrialization
  - Rising cost of metal production and capacity expansion delayed by economic crisis of 2009

As people become more affluent they use more energy and materials  
Study on Global Flow of Metals, Nat. Inst. Mat. Sci., Tsukabi City Japan 2008



# Profitable Mining

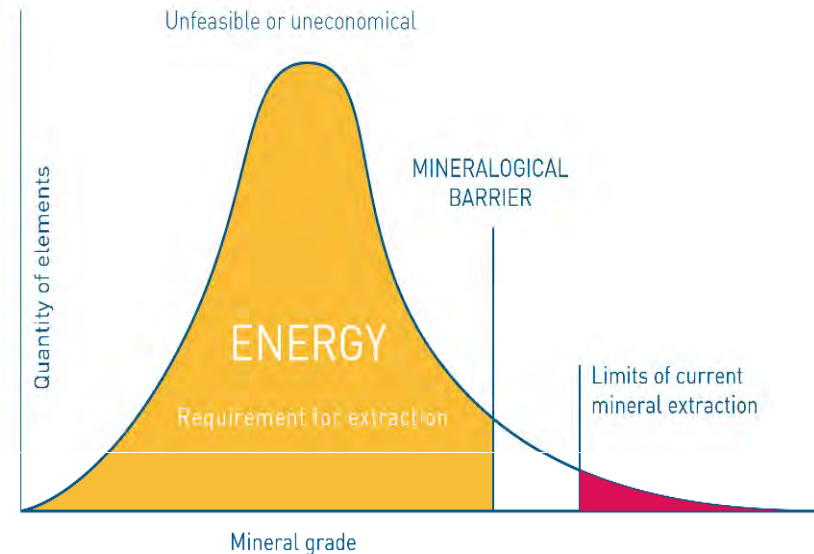
- **Mineralogical Barrier**

- Ore Deposits need Sufficiently High Concentration
- Deposits must be large enough to justify the large overhead costs of setting up a new mine
- Ore must be accessible for extraction. Deepest mine is 3.7 km in South Africa.

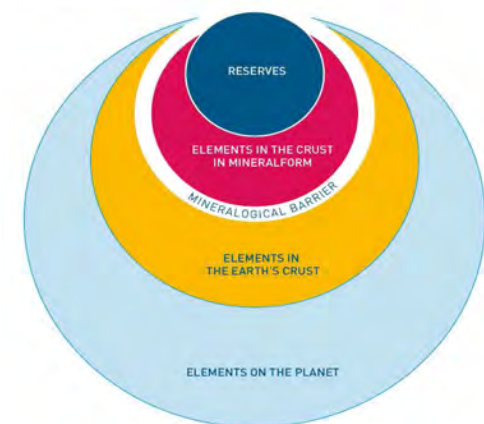
- **Reserve data dependant on economics. If scarcity occurs, there becomes economic incentive to open up new reserves.**

- **Larger concentration of mines in developing nations**

- In 1900 2/3 of worlds mineral production was in the US and Europe.
- In 2000 US and Europe at 1/5. Canada and Australia another 1/5.
- Depletion of economically competitive reserves
- Industrialization opening new mines in developing nations



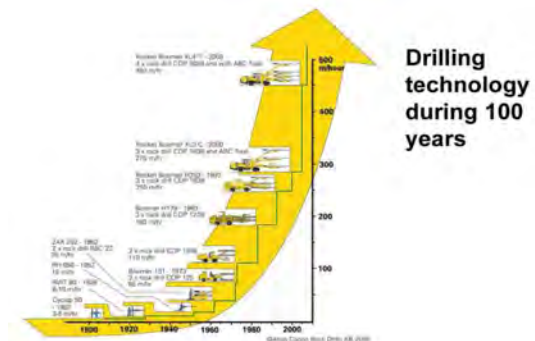
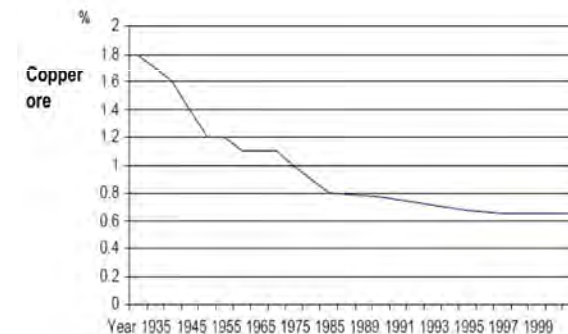
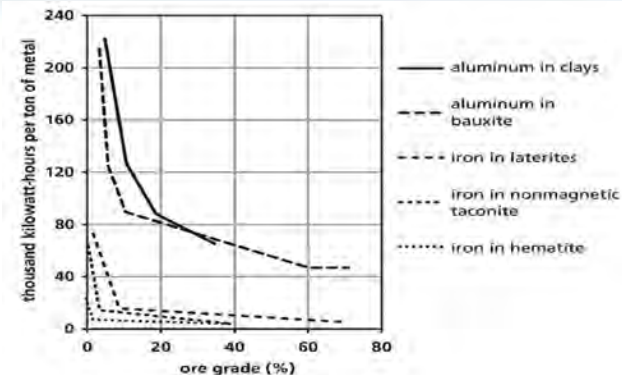
RESERVES = accessible mineral deposits that are technically and economically viable for production under current conditions



# Mining Technology

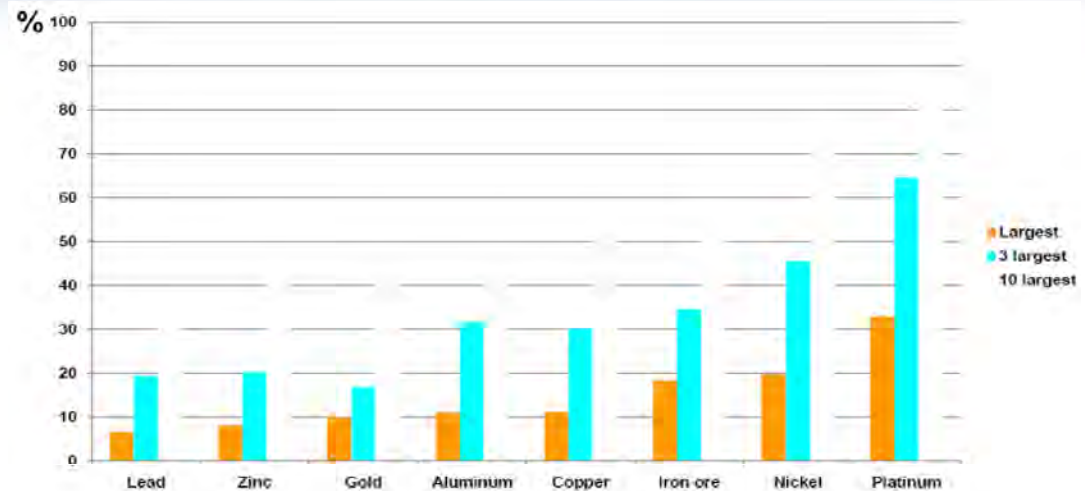


- **“Low-Hanging Fruit” picked**
  - High grade ores (geological)
  - Ores close to final customer
  - Ores near surface (or not underwater)
- **Improvements in mining, extraction and separation technology**
  - 90 times increase in the rate which solid rock formations can be displaced
- **Lower Grade Ores increase expense of processing**
- **Linkage with Energy Costs: 0.77 correlation of mineral prices with crude oil prices in the (1970-2000) range \_ (Hague Center for Strategic Studies 2010)**
  - Mining, Refining and Transporting Materials Energy Intensive
  - As the distance from mine to demand increases, so does the cost of freight. (Increase by a factor of 5.5 x) Another way that the cost of materials linked to that of energy



# Mining Industry

- Consolidating Rapidly
- Vertically integrating into metal (and oxide) production.
- For many commodity materials the largest few mining companies own 30% of world's business (50% for Ta and Nb).
- Rare metals priced with bilateral contracts and not metal markets. (China, South Africa, former Soviet Union)  
Producers tend to cut output since there is no mechanism to adjust price. Minor markets more fragile.

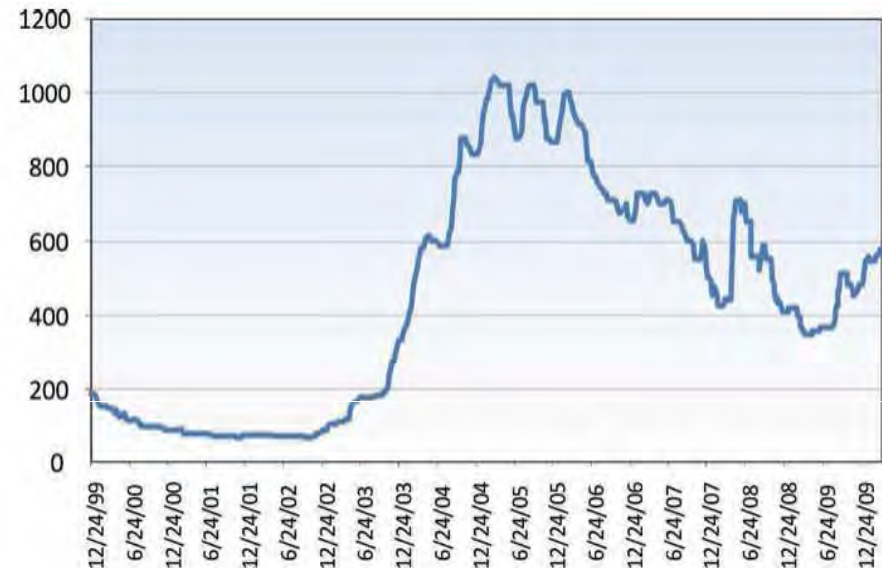


Minerals/Metals	Purchase option	Source of price info
Rare earth elements	Negotiated purchase, not traded on metal exchanges and therefore no spot or future market; however, illegally-traded REEs are sold through less formal channels and may possibly be sold on the spot markets	Trade journals, based on information from producers, consumers and traders
Cobalt (most), gallium <sup>64</sup> , tellurium, indium, lithium	Negotiated purchase, not traded on metal exchanges and therefore no spot or future market (except for indium and small amount of cobalt)	Trade journals, based on information from producers, consumers and traders
Cobalt (small share)	Cobalt became tradable on LME in February, 2010. Producers registered with LME for trading certain brands of cobalt so far maintain a combined warehoused amount of 115 tonnes, which is small compared with the 60,000 tonnes global cobalt market; spot market	Information available globally from the exchange
Nickel (Ni), copper (Cu), zinc (Zn)	LME, copper is also traded on COMEX (part of NYMEX)	Information available globally from the exchange; trade journals

Sources: Humphreys, forthcoming; USGS.<sup>65</sup>

# Elements Derived from Tailings

- **Minerals which are a by-product or co-product dependant on price of main product**
  - In - Zn industry
  - Te - Cu industry
  - Ga- By-product of bauxite mining
  - Co - 85% by-product of Ni or Cu mining
  - High Profit Rare Earths (Nd, Eu, Dy) - Low Profit Rare Earths (La, Ce, Sm)
  - Rare Earths – By product of Iron Mining
- **Recall that Zn industry decoupled to per Capita GNP. Mines close when unprofitable**
- **In (by product) not traded on markets. Zn shutdown impacts In price**
- **Increased In demand (ITO)**

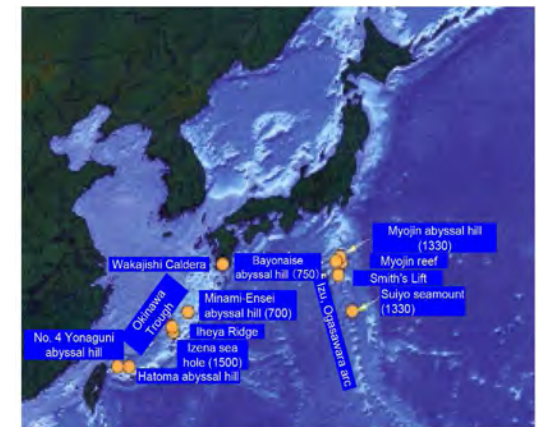
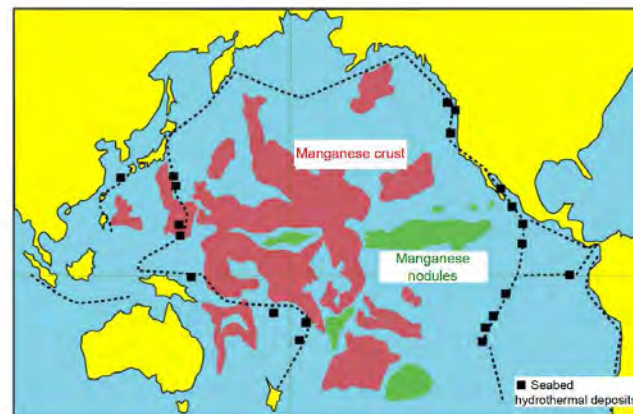
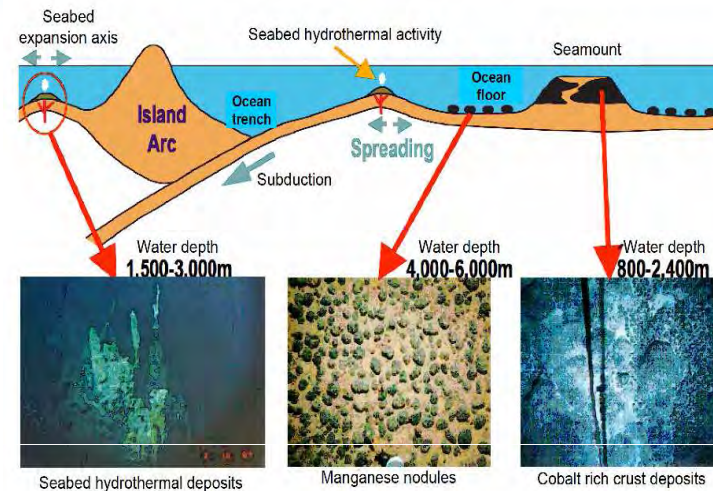


*Figure 3-8. Indium prices from 2000-2010 (99.99% pure metal in \$/kg)*  
*Source: metal-pages.com*

Material Scarcity, An M2i Study, Wouters and Bol  
2009

# Seabed Mining

- Potential for large reserves of many elements including, rare earths, gold, cobalt, PGM, etc.
- Very costly
- International Issues with Mineral Rights
- Extensive Japanese Investments
- Recently rare earth deposits near Hawaii show yield of 0.2% (comparable to mines in China)
- Rare Earths nearly thorium free
- Major environmental impact to be considered



Figures from Kawamoto, Quarterly Review [27] April 2008, JOGMEC 36 [3] p155

# Environmental Impact and the Energy Paradox



- **Many Elements being designed out of ceramic systems (RoHS):**
  - Pb, Hg, Tl, As, Sb, Cd, Cr, Be, Actinides, etc. Toxic Materials. Efforts to find substitutes underway regardless of scarcity considerations. Hazardous in tailings.
  - Ba, Co, Ni, V, Si to be used with caution.
- **Environmental Issues with material production**
  - Refining: (Rare Earths): Use of copious amounts of oxalic acid, HF, H<sub>2</sub>SO<sub>4</sub>, etc.
  - Tailings: Toxic waste products: Th from Monazite, Cd from Zn smelting
- **Ore grade reduced**
  - More earth needs to be processed to produce the same quantity of raw material
  - Seabed mining: Environmental impact needs investigation
- **Energy Paradox**
  - Clean Energy requires “scarce” materials such as Nd, Li and In which are energy intensive to process and may have an environmental impact.
  - Important to develop green mining and extraction technologies

# Geological Location of Critical Resources (EU-2010)

- Resources and Processing Inequitable Distributed
  - Cobalt – DRC
  - Lithium - Bolivia
- Processing Facilities for many materials concentrated in China

How stable is the mining environment in which these technology mineral reserves are located?

We have cross-referenced the top three technology mineral reserves' geographic location (where available) with widely available qualitative studies. The map opposite shows in visual form our analysis of these countries in terms of perceived risks. Our observations suggest that a significant proportion of these minerals are located in countries considered by these studies to represent a higher risk of instability.

Source: 2010 Rankings of countries for mining investment, Behr's Database Group Inc., via <https://www.databases.com/HS/Global/Investment/Country/Risk/Ratings/Analysis/US/22/76/2020> via <https://www.instituteforpeace.org.uk/> and Transparency International Corruption perception index 2009, via <https://www.transparency.org/Reserve/location> sourced from Mineral commodity survey, USGS, January 2010, Mikolajczak, Clair (Director of Metals and Chemicals) "Availability of Indium and Gallium", September 2009 via [www.indium.com](http://www.indium.com)

<sup>1</sup> Gallium reserve location was not available publicly so bauxite location was used as a proxy.

Key:

- Negligible risk
- Low risk
- Medium risk
- High risk
- Very high risk



HCSS 2010 report "Scarcity of Materials"

# Top Three World Producers of Critical Materials

Metal	First		Second		Third		Cumulative
	country	fraction [%]	country	fraction [%]	country	fraction [%]	
Rare Earth concentrates	China	95	USA	2	India	2	99
Niobium	Brazil	90	Canada	9	Australia	1	100
Antimony	China	87	Bolivia	3	South Africa	3	93
Tungsten	China	84	Canada	4	EU	4	92
Gallium	China	83	Japan	17	-		100
Germanium	China	79	USA	14	Russia	7	100
Rhodium	South Africa	79	Russia	11	USA	6	96
Platinum	South Africa	77	Russia	11	Canada	4	92
Lithium	Chile	60	China	15	Australia	10	85
Indium	China	60	Korea	9	Japan	9	78
Tantalum	Australia	60	Brazil	18	Mozambique	5	83
Mercury	China	57	Kyrgyzstan	29	Chile	4	90
Tellurium	Peru	52	Japan	31	Canada	17	100
Selenium	Japan	48	Canada	20	EU	19	87
Palladium	Russia	45	South Africa	39	USA	7	91
Vanadium	South Africa	45	China	38	Russia	12	95
Titanium	Australia	42	South Africa	18	Canada	12	72
Rhenium	Chile	42	USA	17	Kazakhstan	17	76
Chromium	South Africa	41	Kazakhstan	27	India	8	76
Bismuth	China	41	Mexico	21	Peru	18	80
Tin	China	40	Indonesia	28	Peru	14	82
Cobalt	D.R. Congo	36	Australia	11	Canada	11	58
Copper	Chile	36	USA	8	Peru	7	51
Lead	China	35	Australia	19	USA	13	67
Molybdenum	USA	34	China	23	Chile	22	79
Bauxite	Australia	34	Brazil	12	China	11	57
Zinc	China	28	Australia	13	Peru	11	52
Iron ore	Brazil	22	Australia	21	China	15	58
Cadmium	China	22	Korea	16	Japan	11	49
Manganese	China	21	Gabon	20	Australia	16	57
Nickel	Russia	19	Canada	16	Australia	13	48
Silver	Peru	17	Mexico	14	China	13	44
Gold	South Africa	12	China	11	Australia	11	34

# Recent Supply Disruptions



Year	Material	Major Source	Problem	Effect
1978	Cobalt	Dem Rep. Congo	Rebels invaded copper-cobalt mining region in Congo.	Rapid rise in price.
1993-1994	Antimony	China	Flooding was alleged reason though some industry sources believe Chinese suppliers withheld material to increase price.	Price per pound rose from USD 0.80 to USD 2.28 in 1995 and from USD 1.61 in 2005 to USD 2.25 in 2006.
1994	Titanium (rutile). Key in producing titanium metal.	Sierra Leone has one of the largest deposits of rutile.	Production suspended when rebels invaded mining sites.	Global shortage.
2001	Tantalite. Used for capacitors.	Australia	Closure of facility in Australia for long-term maintenance.	Shortage, price rise, and smuggling from central Africa.
2005	Tungsten	China dominates supply and restricts amount produced and exported.	Exports reduced due to alleged inadequate supplies within China, the largest consumer.	Steep price increase.
2005-2006	Rhenium. 65 percent goes to aerospace (jet engine blades and rocket nozzles).	75 percent from two companies—Molybmet in Chile (50 percent) and Redmet in Kazakhstan (25 percent).	Redmet exports blocked due to dispute over debt with copper company that supplies Redmet.	Price rose from USD 1,000/kg to USD 6,000/kg. Known future production increases are already sold.

Material Scarcity, An M2i Study, Wouters and Bol 2009

- **OECD, Global Demand for minerals expected to double in 25 years**
- **HCSS Demand for metals in China has increased 17% annually over the past five years**
- **China: More than 70% of the global demand for Al, Cu and Zn**
- **Demand for many materials projected to skyrocket by 2030**

Raw material	2006	2030	Emerging technologies (selected)
Gallium	0.28	6.09	Thin layer photovoltaics, IC, WLED
Neodymium	0.55	3.82	Permanent magnets, laser technology
Indium	0.40	3.29	Displays, thin layer photovoltaics
Germanium	0.31	2.44	Fibre optic cable, IR optical technologies
Scandium	low	2.28	SOFC, aluminium alloying element
Platinum	low	1.56	Fuel cells, catalysts
Tantalum	0.39	1.01	Micro capacitors, medical technology
Silver	0.26	0.78	RFID, lead-free soft solder

Material Scarcity, An M2i Study, Wouters and Bol 2009

# Recycling and “Urban Mining”

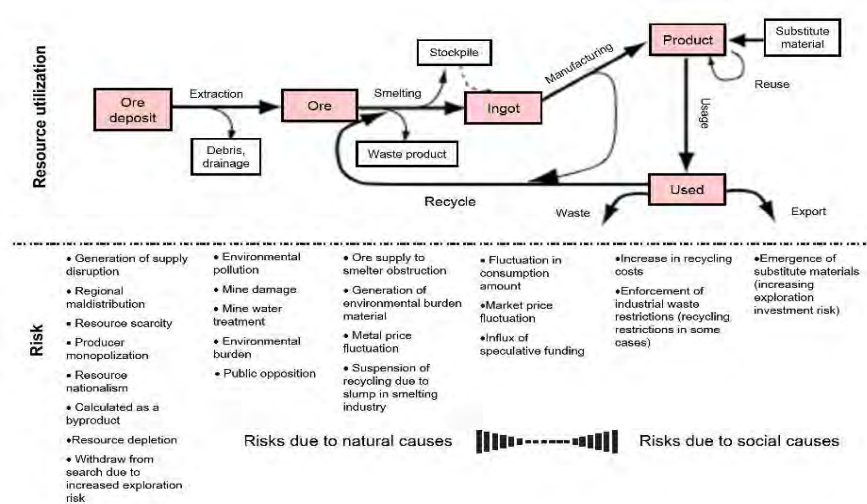
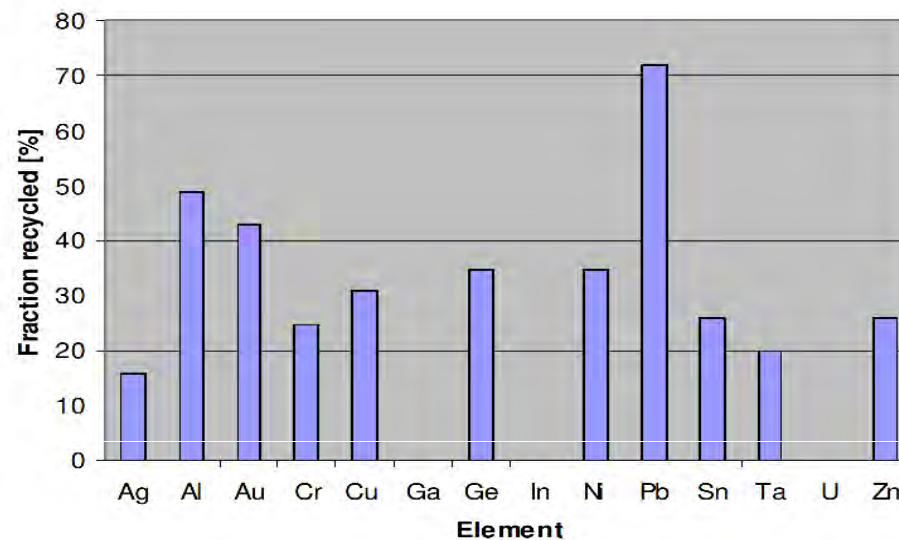
A sizeable fraction of global production of some materials comes from recycling.

For 15 elements, in the U.S., recycling accounts for 40-60% of amount of mined material

Recycling not yet feasible for rare earths and many metals

Research efforts in Japan and elsewhere into recycling materials from electronics (In).

Not yet feasible for most rare materials



# Raw Material Issues by Ceramic Technology Area



- **Energy Technology**
  - SOFCs: La, Y, Ce, Zr, Co
  - High Temperature Thermoelectrics: Co
- **Electronic Ceramics**
  - Displays: In (ITO), Y, Gd, Eu, Tb (Phosphors)
- **Consumer Electronics**
  - Wireless Infrastructure: Y, Gd (Microwave Magnetics), Nd, Co, Nb (Microwave Dielectrics)
- **Medical Technology**
  - Lu and Ge for x-ray tomography scintillators (PET scans)
- **Environmental Technology**
  - $\text{CeO}_2$  as automotive catalysts to reduce  $\text{NO}_x$  and  $\text{SO}_x$
- **Mechanical and Structural Ceramics**
  - Yttria stabilized Zirconia (High  $K_{1C}$  Ceramics- Thermal Barrier coatings)

# Research for Replacements



- **Small quantities of expensive materials in high value products can remain profitable. Bulk products with little added value. Search for substitutes is key.**
- **Active Research Areas for Substitute Materials**
  - Replacements for Indium in ITO Transparent Conductors ( $\text{CaO-Al}_2\text{O}_3$ )
  - Rare Earth free phosphors for solid state lighting ( $\text{ZnS:Cu}$ )
  - Fe-Ti-C nanostructures to replace WC (Nanostructure replacing metals!)
- **AIST**
  - Look at Sm-Fe-N permanent magnets without Dy
  - Vanadium instead of Palladium as a hydrogen separation membrane

Theme	Representative organization	Participating organizations	Summary of assignment
Development of steel plate surface treatment by molten Al alloy plating in place of zinc	Tokyo Institute of Technology	Tohoku University, National Institute for Material Science, JFE Steel Corporation, Nippon Steel Corporation, Nippon Light Metal Co. Ltd.	To develop surface treatment technologies by substituting zinc with aluminum alloy. To establish surface treatment technologies by abundant harmless elements Al-Mg-(Zn, Si) alloys by active use of current technology, manufacturing facilities.
Development of next-generation non-volatile memory using aluminum anodized film	National Institute for Material Science	GIT Japan	To substitute harmful rare elements such as praseodymium, cerium, ruthenium, and bismuth, etc., to produce promising candidates for next-generation variable resistance type memory (ReRAM) by aluminum anodizing.
New hydrogen induced function in subnano-lattice materials	Tohoku University	Fukuyama University, Iwate University, Kyushu University, Research Institute for Electric and Magnetic Materials, Toyota Motor Corporation, Nippon Mining & Metals Co., Ltd., Honda R&D Co., Ltd., Asahi Engineering Corporation, Future Products Co., Ltd., Shoen Chemical Inc., Toshiba Corporation	To understand the many facets of the effects of hydrogen and to drastically improve the characteristics of Al, Cu, and Ti alloys by grain refinement using hydrogen absorption and desorption heat treatment. Also, to study new functions induced by dissolved hydrogen in subnano lattices and to pursue the possibility of applying to materials.
New excavation of nanoparticle self-generating catalysts aimed at eliminating precious metals from catalysts	Japan Atomic Energy Agency (JAEA)	Daihatsu Motor Co., Ltd., Hokko Chemical Industry Co., Ltd., Osaka University	To greatly reduce the amount of precious metals (palladium, rhodium, and platinum) used in vehicle exhaust catalytic converters and organometallic compound catalysts, and furthermore achieving elimination of precious metals from catalysts. To develop the high-catalytic function peculiar to nanoparticles for the purpose of greatly reducing the usage amount of precious metals and for final elimination of precious metals from catalysts while at the same time establishing optimum nanoparticle synthesizing technology to serve the usage environment.
Creation of barium based new giant piezoelectric effect materials for developing piezoelectric frontiers.	Yamanashi University	Tokyo Institute of Technology, Kyoto University, Tokyo University of Science, National Institute of Advanced Industrial Science and Technology (AIST), Canon Inc.	To surpass lead-based piezoelectric materials, create new barium-based giant piezoelectric effect materials that do not include not only harmful lead and bismuth but also potassium, sodium, and lithium which are unsuited to silicon processing. To pioneer new applicable fields that straddle materials, electronics, and machinery for new device development based on the technology seeds of composition phase boundary design and domain structure control.
Development of $\text{TiO}_2$ based transparent electrode materials as a substitute for ITO	Kanagawa Academy of Science and Technology	Tokyo University, Asahi Glass Co., Ltd., Toyoda Gosei Co., Ltd.	To establish processes for depositing films of $\text{TiO}_2$ based transparent conductors (TNO) on glass using established practical methods (sputtering and CVD) for the purpose of substituting ITO needed in transparent electrodes with TNO. Also, to pursue the possibilities of using TNO as transparent electrodes for blue light emitting diodes.
Development of low rare element composition high-performance, anisotropic nanocomposite magnets	Hitachi Metals Ltd.	Nagoya Institute of Technology, Kyushu Institute of Technology, National Institute for Material Science	To aim at developing completely new magnetic materials with low rare earth element inclusion compositions that do not use heavy rare earth elements such as dysprosium and reduce the usage amount of rare earth elements such as neodymium. To develop high performance anisotropic nanocomposite magnets by coupling high saturation magnetic flux density soft magnetic phase with high coercivity hard magnetic phase.

- **Consumes R and D resources**
  - 2000 substitution of Nb for Ta in dielectric resonators
  - 2003 substitution of Zr for In in narrow linewidth garnets
  - Increased cost of processing to use lower purity or substitute materials.
  - Lanthanide blends for Ln containing dielectrics.
- **Major effort for U.S. Industrial R&D**
- **Rare Earths a difficult case for ceramics. Include all trivalent ions with medium to large ionic radii. Limited opportunity for substitution in ceramic oxide material. Trying to replace Ba-Nd-Ti-O microwave dielectrics**
  - $\text{Al}^{3+}$  Too small.
  - $\text{Ga}^{3+}$  Too small and too expensive
  - $\text{Bi}^{3+}$  Large ion. Asymmetric with lone pair.
- **Needs coordinated effort between government labs, universities and industry**

- **REEs**

- Not uncommon. Distributed throughout so that there are few concentrated sources
- Prior to 1930, no technology to separate from one another (Mischmetal)
- Light REOs - La, Ce, Pr, Nd, Sm
- Heavy REO's – Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y (Dy critical in magnet technology)

- **Indium Oxide**

- Critical in the production of ITO (Indium Tin Oxide), a transparent conductive material used in photovoltaic cells and flat screen televisions.
- China virtually only supplier
- Mined as a by-product of Zn and Pb production. As demand for Zn goes up, In becomes less scarce. 2003 price shock from reduced production of Zn mines and closure of several smelters.

- **PGMs:**

- Catalysts
- Pd (Hydrogen storage and filtration)
- Used as investment assets. Price up (especially during financially difficult times)

# Key Elements (Continued)



- **Tungsten**
  - Among group of metals used as carbide formers in steels (W, V, Nb, Ta, Mo)
  - China leading producer of tungsten
  - Tungsten carbide cermet a versatile material and difficult to replace
- **Lithium**
  - US DOE report indicates will get increasingly critical
  - Huge undeveloped reserves located in Bolivia
  - Demand expected to dramatically increase with lithium battery increase
- **Yttrium**
  - Grouped with heavy rare earths because of similar ionic radius
  - Phosphor Host
  - Stabilizing agent in zirconia (Tough ceramics, oxygen sensors, SOFC electrolytes)
  - Microwave Magnetics ( $Y_3Fe_5O_{12}$  based materials)
  - Potential use for high temperature superconductors (Replacement for Nd magnets)

# Uses for Rare Earth Elements (from Sigma Aldrich Presentation)



Element	Uses
<b>Mixed Rare Earth Oxide</b>	Petroleum Cracking Catalyst, Mischmetal, Lighter Flints, Ni metal hydride batteries, Polishing compounds
<b>Lanthanum</b>	Nickel Metal Hydride Batteries, Alloys, <b>Optical Lenses, Phosphor Host, SOFC, Fiberoptic Glasses, Night Vision Goggles</b>
<b>Cerium</b>	<b>Catalysts (automotive), Catalysts (Petroleum Cracking) Catalysts (water purification), Glass Additives, UV Light absorber (sunglasses), Polishing Media, Zirconia stabilizer, Phosphors, Alloying Agent</b>
<b>Praseodymium</b>	Additive to Nd-Fe-B magnets, <b>synthetic gems, glass coloring agent, x-ray tomography scintillators, welder's goggles</b>
<b>Neodymium</b>	Nd-Fe-B Permanent Magnets (Electric Motors etc.), Alloying agent, <b>Lasers (YAG:Nd), Metal Halide Lamps, synthetic gems, glass coloring agent, PTCR BaTiO<sub>3</sub>, Welder's Goggles</b>
<b>Samarium</b>	Sm-Co Permanent Magnets (Higher temperature than Nd-Fe-B), <b>Glass Colorant, Phosphors</b>
<b>Europium</b>	<b>Red Phosphors (TVs Lamps), LED's, Tomography Scintillators</b>
<b>Gadolinium</b>	<b>Phosphor Host (Fluorescent Lamps, Scintillators), MRI contrast agents, neutron absorber, x-ray intensifying screen, optical lenses, microwave garnets</b>
<b>Terbium</b>	<b>Green Phosphors (TVs Lamps), LED's, X-Ray Intensifying Screens, Terfenol-D magnetostrictive alloy, magento-optical disks</b>
<b>Dysprosium</b>	Additive to Nd-Fe-B permanent magnets, <b>phosphors</b> , Terfenol-D magnetostrictive alloy,
<b>Holmium</b>	Metal Halide Lamps
<b>Erbium</b>	<b>Fiber Optics, Lasers, Glass Colorant, Synthetic Gems</b>
<b>Thulium</b>	<b>X-Ray intensifying screens</b>
<b>Ytterbium</b>	<b>Optical Lenses, Pressure Sensors</b>
<b>Lutetium</b>	<b>Scintillation detectors, Optical Lenses</b>
<b>Yttrium</b>	<b>Host for Phosphors, YAG Laser Host, Y stabilized zirconia (Oxygen sensor, SOFC, structural ceramics, TBCs), YIG for microwave magnetics, Sintering aid for non-oxide ceramics, optical lenses, ceramic superconductors</b>

# Rare Earth Elements Supply Chain (Congressional Research Office)



- **World Demand estimated at 134,000 tons /year. Production around 124,000 tons annually. Difference covered by inventory.** Magnets dominated rare earth usage in 2008. Catalysts were second.
- **RE consumption in China tripled between 2000 and 2008**
- **United States responsible for 12% of global rare earth demand**
- **Short Term Problem: By 2014 demand expected > 200,000 tons/year. China's output at 160,000 tons**
- **USGS expects long term supply to meet demand. Shortfall in next few years as new mines open.**
- **Strategic Importance in military and alternative energy programs**
- **Rare Earth Mines**
  - Mountain Pass (USA) - Light Rare Earths. Bastnasite instead of Th containing Monazite
  - Thor Lake, Canada - Heavy Rare Earths (Dy, Tb and Eu)
  - Mount Weld (Australia)
- **Congress exploring bill for R&D to develop high Th Monazites**

# Rare Earths and China (IAGS March 2010)



- **Since 1980, several laboratories focusing on extraction and application of rare earth oxide materials.** Separation chemistry.
- **Chinese domination of RE magnet industry.** (Magnaquench purchased by Chinese consortium in 1995 and moved out of the United States in 2002).
- **Chinese Mines**
  - Baotou (Bayan Obo) in Inner Mongolia - Bastnasite and Monazite
  - Mine consolidation to enhance governmental control
- **Domestic Consumption is a Priority and expected to grow. Stockpiling.**
- **Seeking “value added” exports instead of raw metals/oxides**
- **China export quota for all rare earths. Price increases for light rare earths (La,Ce, Pr, Nd and Sm) even greater than for heavy rare earths.**
- **Smuggling**
  - In 2008, 20,000 tons of rare-earth smuggled out of China (1/3 of total volume)
- **Environmental Issues**
  - Radioactive tailings due to high Th content (Issue with Mountain Pass in 1980s)
  - Large amounts of oxalic acid, sulfuric acid and HF needed to separate oxides

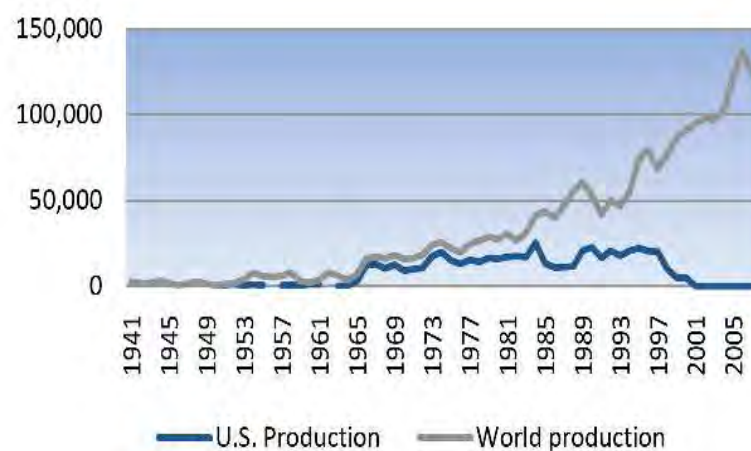
# Existing Rare Earth Mines

TYPE	LOCATION(S)	LIGHT				MEDIUM			HEAVY							
		Lanthanum (La)	Cerium (Ce)	Praseodymium (Pr)	Neodymium (Nd)	Samarium (Sm)	Europium (Eu)	Gadolinium (Gd)	Terbium (Tb)	Dysprosium (Dy)	Holmium (Ho)	Erbium (Er)	Thulium (Tm)	Ytterbium (Yb)	Lutetium(Lu)	Yttrium(Y)
Currently active:																
Bastnäsite	Bayan Obo, Inner Mongolia	23.0	50.0	6.2	18.5	0.8	0.2	0.7	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Xenotime	Lahat, Perak, Malaysia	1.2	3.1	0.5	1.6	1.1	0.0	3.5	0.9	8.3	2.0	6.4	1.1	6.8	1.0	61.0
Rare earth laterite	Xunwu, Jiangxi Province, China	43.4	2.4	9.0	31.7	3.9	0.5	3.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	8.0
Ion adsorption clays	Longnan, Jiangxi Province, China	1.8	0.4	0.7	3.0	2.8	0.1	6.9	1.3	6.7	1.6	4.9	0.7	2.5	0.4	65.0
Loparite	Lovozerkaya, Russia	28	57.5	3.8	8.8	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Various	India	23	46	5	20	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Various	Brazil	N.A.														

Selected rare earth projects outside China



(1) Lynas Corp, (2) Molycorp Minerals, (3) (4) Great Western Minerals, (5) Alkane Resources, (6) Vietnamese govt/Toyota Tsusho/Sojitz, (7) Arafura Resources, (8) Avalon Rare Metals, (9) Kazatomprom/Sumitomo, (10) Stans Energy, (11) Greenland Minerals and Energy, (12) Rare Element Resources, (13) Pete Mountain Resources, (14) Quest Rare Minerals, (15) Ucore Uranium, (16) US Rare Earths, (17) Matamec Explorations, (18) Etruscan Resources, (19) Montero Mining, (20) Tasman Metals, (21) Neo Material Technologies/Mitsubishi



# Future Rare Earth Mines

## Possible to come online in the next 5 years:

Bastnäsite <sup>22</sup>	Mountain Pass, California, United States	33.2	49.1	4.3	12.0	0.8	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Monazite	Mount Weld, Australia	26.0	51.0	4.0	15.0	1.8	0.4	1.0	0.1	0.2	0.1	0.2	0.0	0.1	0.0	0.0
Apatite	Nolans bore, Australia	20.0	48.2	5.9	21.5	2.4	0.4	1.0	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Fergusonite <sup>23</sup>	Nechalacho, Canada	16.9	41.4	4.8	18.7	3.5	0.4	2.9	1.8	0.7	0.0	0.0	0.0	0.0	0.0	7.4
Bastnäsite & Parisite	Dong Pao, Vietnam	32.4	50.4	4.0	10.7	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.007
Alanite & apatite	Hoidas Lake, Canada	19.8	45.6	5.8	21.9	2.9	0.6	1.3	0.1	0.4	0.0	0.0	0.0	0.0	0.0	1.3
Trachyte	Dubbo Zirconia, Australia	19.5	36.7	4.0	14.1	2.5	0.1	2.1	0.3	2.0	0.0	0.0	0.0	0.0	0.0	15.8

## Not likely to be producing in the next 5 years:

REE thorium minerals	U.S. Rare Earths Lemhi Pass quadrangle, Idaho and Montana	7.0	19.0	3.0	18.0	11.0	4.0	11.0	0.5	4.0	0.5	0.2	0.2	0.5	0.2	20.9
Monazite	Nangang, Guangdong, China	23.0	42.7	4.1	17.0	3.0	0.1	2.0	0.7	0.8	0.1	0.3	0.0	2.4	0.1	2.4
	Eastern coast, Brazil	24.0	47.0	4.5	18.5	3.0	0.1	1.0	0.1	0.4	0.0	0.1	0.0	0.0	0.0	1.4
	North Capel, Western Australia	23.9	46.0	5.0	17.4	2.5	0.1	1.5	0.0	0.7	0.1	0.2	0.0	0.1	0.0	2.4
	North Stradbroke Island, Queensland, Australia	21.5	45.8	5.3	18.6	3.1	0.8	1.8	0.3	0.6	0.1	0.2	0.0	0.1	0.0	2.5
	Green Cove Springs, Florida, United States	17.5	43.7	5.0	17.5	3.1	0.8	1.8	0.3	0.6	0.1	0.2	0.0	0.1	0.0	2.5

Sources: USGS 2010j, Roskill 2010 and IMCOA 2010.

# Industrial Response to Scarcity Issues



- **Purchasing Consortia to increase buying power.** (Large customers may buy raw materials and reserve).
- **Route part of manufacturing supply chain in source country**
  - Non-IP sensitive
  - Semi-Finished Products
- **R&D to use lower grades of materials -  $\text{LnAlO}_3\text{-CaTiO}_3$**
- **R&D to reduce usage (example: Thin Pt layers on catalytic converters)**
  - Adds to recycling costs (Lower grade ore for urban mining)
- **Recycling**
  - Increase efficiency of factory
  - Outsource recycling efforts
- **R&D for material substitutes (long time frame)**
- **Increasing amounts of R&D and Engineering effort will be geared toward economical utilization and/or replacement of scarce materials.**

- **Direct sourcing to China. Eliminating middlemen except in extreme cases.**
- **U.S. companies (e.g. lighting manufacturers) hold key IP rights regardless of where manufactured. Counting on staying ahead of R&D curve. This allows for control of supply chain.**
- **Material Scarcity creates exigent R&D Situation**
- **Case 1: Tantalum shortage in 2000-2001. (Closure in facility in Australia. Demand for tantalite capacitors). Coltan wars in DRC**
  - Needed for  $\text{Ba}_3\text{ZnTa}_2\text{O}_9$  based microwave dielectrics
  - Prices spiked from \$250/kg to > \$700/kg
  - Development of niobate based materials  $\text{Ba}_3(\text{Zn},\text{Co})\text{Nb}_2\text{O}_9$  - Nb electrolytic capacitors
  - Permanent reduction in Ta demand
- **Case 2: Indium Shortage 2003-2004. (Zn mines closed – Environmental Issues)**
  - Price from \$300/kg to near \$1,000/kg
  - Indium used as an octahedral site substituent in YIG.
  - R&D to replace In with Zr

# What can Governments Do? (Hague Center for Strategic Studies – Scarcity of Materials 2010)



- **National Governance**
  - Geological Survey, Coherent Policy, National Transparency
- **Trade restrictions (China quotas on Rare Earths)**
  - Tariffs, Excise Taxes and Quotas
- **Technology Advancement**
  - Mining and Separation Technology, R&D for Substitutes, Recycling
- **Pro-Active Acquisition (Japan rare earth deal with Vietnam)**
  - Stockpiling, Bilateral Deals, Strategic Partnerships
- **Development Co-operation**
  - Development Aid, Transparency
- **Global Governance**
  - International Market, Collaborative Governance

# Military and Strategic Considerations (HCSS)



- **Strategic Factors (HCSS)**

- A number of elements have unique properties. No replacement (Dy, In)
- “Uneven” Geographic Distribution of Elements. Protectionist measures may seek industries to relocate to get preferential access to certain minerals

- **Impact of Strategic Considerations**

- Lack of transparency in markets (Bi-Lateral deals)
- Minerals mined where it is not economically feasible to do so in order to gain some self sufficiency
- Companies and countries compete for concessions in resource rich countries even if investments unprofitable and governments have poor human rights and environmental records.
- Conflicts over resources
  - Angola (1975-2002) Oil and Diamonds
  - DRC (1996-2008) Copper, Coltan, Diamonds,

MINERAL	SHARE <sup>50</sup>	EXPORT QUOTA (2010)	MAIN APPLICATIONS
DYSPROSIUM	99%	Full export ban	Permanent magnet (electrical vehicles; wind turbines)
LANTHANUM	95%	ca. 9.000 tonnes <sup>51</sup>	NiMH battery (electrical vehicles)
NEODYMIUM	95%	ca. 5.000 tonnes <sup>52</sup>	Permanent magnet (electrical vehicles; wind turbines)
ANTIMONY	87%	57.500 tonnes	Semiconductors, solder
TUNGSTEN	84%	14.300 tonnes	High-performance steel; industrial cutting tools
GALLIUM	83%	-	Semiconductor (solar energy; LEDs; defense)
GERMANIUM	79%	-	Semiconductor (solar energy; fiber optics; infrared)
INDIUM	60%	233 tonnes	Semiconductor (LCD displays; solar energy; LEDs)
MAGNESIUM	48% <sup>53</sup>	1.330k. tonnes	Light-weight alloys (e.g. car bodies, airplanes)
TIN	40%	21.000 tonnes	Solder, tinplate (e.g. conservatives)
VANADIUM	38%	-	High-performance steel (e.g. jet engines)
MOLYBDENUM	28%	25.500 tonnes	High-performance steel (e.g. rocket engines)

# US-DOE Critical Materials Strategy



- Focus on Clean Energy Technologies
- Detailed report of impact of raw materials on clean energy technologies

CLEAN ENERGY TECHNOLOGIES AND COMPONENTS					
	Solar Cells	Wind Turbines	Vehicles		Lighting
MATERIAL	PV films	Magnets	Magnets	Batteries	Phosphors
<b>Rare Earth Elements</b>					
Lanthanum				•	•
Cerium				•	•
Praseodymium		•	•	•	
Neodymium		•	•	•	
Samarium		•	•		
Europium					•
Terbium					•
Dysprosium		•	•		
Yttrium					•
Indium	•				
Gallium	•				
Tellurium	•				
Cobalt				•	
Lithium				•	

US DOE Critical Materials Strategy 2010

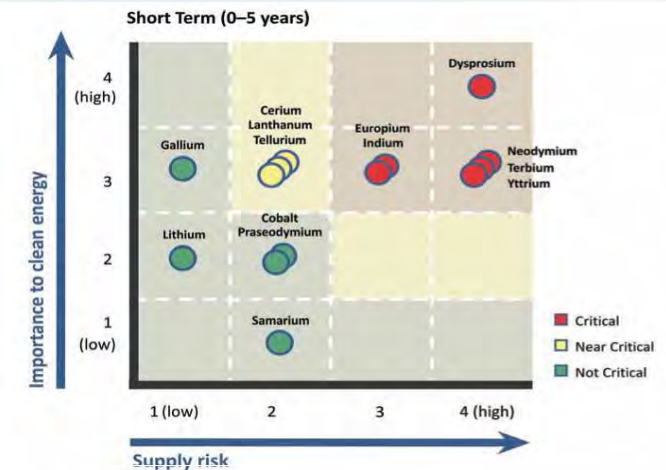


Figure ES-1. Short-term criticality matrix

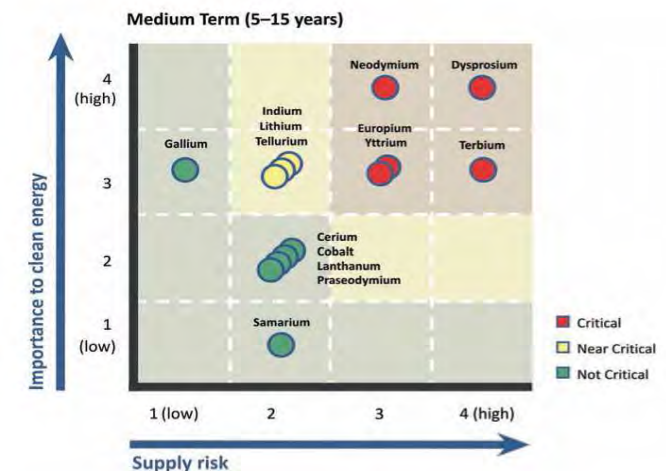


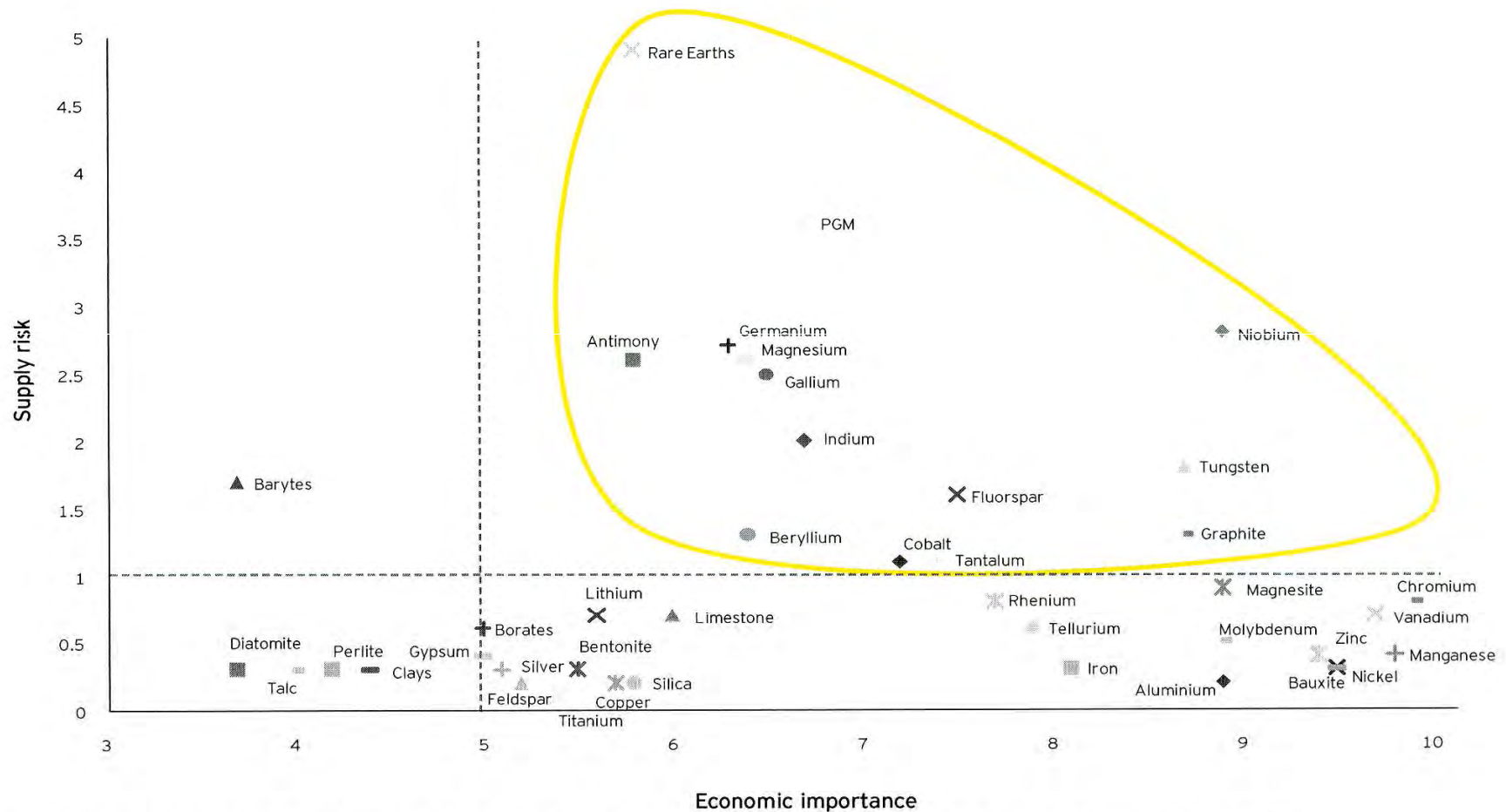
Figure ES-2. Medium-term criticality matrix

# International Responses to Material Scarcity (US-DOE Report)



Nation	Concern	Commercial Policy	R&D Policy	Materials of Interest
Japan	Stable Supply of Raw Materials	Funding Mineral Exploration Stockpiling Loan Guarantees for High Risk Projects	Substitutions Exploration Research (Seabed Mining)	Ni,Mn,Co,W, Mo,V, Rare Earths, PGM,In
EU	Limit Impact of Raw Material Shortages	Mineral Trade Policy on Open International Markets Recycling	Substitutions Increased Efficiency Recycling	Co, Ga,In, Nb, Rare Earths, PGM, Ta, W
China	Maintain Stable Supply for Domestic Use	Excise Taxes and Quotas Foreign Mining Prohibition Industry Consolidation	Rare earth separation Chemical Sciences of Rare earths	Rare Earths, Sn, W, Fe, Hg, AL, Zn, V, Mo
South Korea	Stable Supply of Raw Materials	Funding Mineral Exploration Stockpiling Free Trade Agreements	Substitutions Increased Efficiency Recycling	Ti, Co,In, Mo, Mn, Ta, Ga, V, W, Li and Rare Earths
Australia	Invest in Mining Industry Tax Resource Depletion	High Tax on Mine Profits Rebates for Exploration	Promote Sustainable Development Practices in Mining	Ta, Nb, V, Li and Rare Earths
Canada	Sustainable Development Protect Environment	Recycling Industry Environmental Stewardship	Innovative Mining Processes Value Added products	Al, Ag, Au, Fe, Ni, CU, Mo

# Raw Material Security and Scarcity (EU Criticality Map 2010)



Source: Critical raw materials for the EU: report of the Ad-Hoc Working Group on defining critical raw materials, European Commission, June 2010.

- **La, Ce, Pr, Sm** - The supply of light rare earths will increase as new mines (Mountain Pass, etc.) come on line. The increased supply with modest demand should cause prices to drop in the five year timeframe.
  - Good for SOFC Industry (Long Term) and Catalyst Industry
- **Nd** – Increased supply balances increased demand from magnet industry
  - Nd used for niche markets in ceramics – YAG:Nd lasers, microwave dielectrics
- **Li** - South American reserves (Bolivia) largest in the world.
  - Supply plentiful but unevenly distributed. Potential competition for access to supply
  - Ceramic demand in Li batteries
- **In, Ga, Co, Te** - Elements associated with the tailings of major non-ferrous metals.
  - Increase in Zn and Bauxite production should increase production
  - Increased demand may lead to trading on metals markets
  - 83% of Ga comes from China
  - Ceramics uses include ITO, thermoelectrics, WC-cobalt cermets, some microwave materials etc.

# Predicting the Future (Elements of Concern)



- **Eu, Gd, Tb, Dy, Ho, Yb etc.** - Supply of heavy rare earths from outside China will take longer to come online.
  - Impacts phosphor industry, white LEDs , specialty magnetics
- **Y** - Supply of heavy rare earths from outside China will take longer to come online.
  - Phosphor Industry
  - YSZ SOFC electrolytes, oxygen sensors, high fracture toughness ceramics
  - Microwave Magnetics industry
  - Numerous niche ceramic applications
- **W** – 84% of tungsten produced in China
  - Critical for tungsten carbide cermets, niche applications
  - Mo (similar +6 material): United States main producer
- **Nb, V, Ta** – Associated with steel industry. 90% of Nb comes from Brazil
  - Microwave Dielectrics, Electronic Ceramics
- **Ge** - 79% of material produced in China
  - Niche ceramic applications

# What to Expect in the Future?



- **Short term**

- Temporary Shortages of certain elements with Price fluctuations
- Trade Conflicts over Mineral Resources
- Government Sponsoring of R&D on substitutes and recycling
- Push for “rare metal “ markets to be established
- Boom in ferrous and non-ferrous metal prices associated with BRIC industrialization
- Metals associated with tailings to become more plentiful

- **Long Term**

- Decreasing availability of certain elements
- Energy and Environmental Barriers for mining
- Substantial increase in R&D to find substitutes
- Flourishing recycling industry
- Transition from cheap, disposable materials to expensive, re-useable materials

Conclusions derived from Material Scarcity, An M2i Study, Wouters and Bol  
2009 and US DOE Critical Materials Strategy 2010