The Future of Mineral Resources

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Azurite & Malachite, Ely, NV (J. Scovil photo)

Santa Cruz in-situ Cu project AZ (Hitzman photo)
The Future of Mineral Resources

• Demand for mineral resources will continue to grow.

• We are unlikely to run out of mineral resources.

• Nonetheless, there will be many challenges for both developed and less developed countries.

How can NAS/NRC contribute?
The Future of Mineral Resources

- Demand for mineral resources will continue to grow.
Iron-ore production (millions of tonnes)  
World population (millions)  
Per capita consumption (10X kg/person)  

~4X more population than 100 years ago  
~4X more per capita consumption than 100 years ago  
~18X more production than 100 years ago

Demand is high for nearly every mineral resource, due to rising population and average standard of living.

Source: USGS, CIA
Demand is high for nearly every mineral resource.

- Copper production has increased ~34X more than in 1900.
- Per capita consumption has increased ~8X more than in 1900.

Graph showing copper production, world population, and per capita consumption over time from 1900 to 2000.
Global copper production in 2012 (17.0 million metric tons) equaled over 100 years of production from the Bingham Canyon mine (17.0 million metric tons).
Demand is high for nearly every mineral resource.

~same per capita consumption for the last 100

~7X more production than in 1900 (historical high in 2012)
Global gold production in 2012 (2,700 metric tons) approximately equaled the cumulative production from the Carlin trend (2,400 tons), one of world’s top regions.
Demand is high for nearly every mineral resource – at historical record annual production for Cu, Fe, Au, coal, etc.
Annual global coal production (~7.7 billion metric tons) equals approximately 5.5 km$^3$ of coal, or ~1,800 km$^2$ of land with an average coal thickness of 3 m.
The number of mineral commodities in demand for products in society has increased markedly in the last 80 years.
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We are filling in the periodic table.
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Economic geologists have been quite successful in finding more ore deposits in known areas.

The Round Mountain gold mine in Nevada (volcanic-rock-hosted deposit) discovered in 1904, has yielded 13 million ounces of gold from 1977 to 2012 – continuous record of discovery around the initial deposit.
Gold production, 1835-2012

- **United States**
- **Nevada**

- **Goldfield (NV), Black Hills (SD), Cripple Creek (CO), porphyry Cu (AZ & UT) = 95M oz Au**
- **'49ers = 29M oz Au**

- **The current boom (1981-2012) = 247M oz Au**
  (mostly Carlin and other Nevada deposits = 174M oz)

Continuous discovery of new gold reserves in the United States.
Discoveries are being made in developed as well as less developed countries.
Archean (2.5 to 4.0 Ga) – Au, Ni, U

Proterozoic (542 Ma to 2.5 Ga) – Fe, Mn, V, Pt, Pd, Cr, Ni, Au, Cu, Co, U, Ti, diamonds

Discoveries continue to be made in traditional terrains, such as Precambrian cratons, throughout the world – limits are political and economic, not technical.
Economic geologists have been quite successful in finding more ore deposits in known areas and deposits in new areas.

Cut Ekati diamond, mounted into a piece of approximately 7-cm diameter kimberlite core, from an award made to Nora Dummett, in memory of Hugo Dummett, past president of the Society of Economic Geologists and leader of the BHP Billiton exploration team whose discoveries helped create the Canadian diamond industry.
We have barely started to explore the oceans – political/legal challenges probably more important than technical challenges.

Jurassic to Recent oceanic crust – potential for ore deposits of manganese nodules (Mn, Ni, Co, Cu), massive sulfide deposits & seafloor vents (Cu, Zn, Pb, Au, Ag), and phosphate nodule deposits (P)

Source for geologic map: www.OneGeology.org
Economic geologists have been quite successful in finding more ore deposits in known areas, deposits in new areas, and new types of deposits.
Examples of some new types of ore deposits recognized and brought into production in the last 55 years.

<table>
<thead>
<tr>
<th>Deposit type</th>
<th>Type locality (year discovered)</th>
<th>and new features</th>
</tr>
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<tbody>
<tr>
<td>Carlin Au</td>
<td>Carlin, Nevada (1961): disseminated gold in sedimentary rocks</td>
<td></td>
</tr>
<tr>
<td>Roll-front U</td>
<td>Wyoming, Kazakhstan (1960s): redox boundaries in sandstones</td>
<td></td>
</tr>
<tr>
<td>Granite-hosted U</td>
<td>Rössing, Namibia (1960s): U-rich granite</td>
<td></td>
</tr>
<tr>
<td>Unconformity U</td>
<td>Rabbit Lake, Saskatchewan (1968): high-grade U near unconformities</td>
<td></td>
</tr>
<tr>
<td>Iron oxide Cu-Au</td>
<td>Olympic Dam, S. Australia (1975): iron-oxide-rich ores in huge regional alteration systems</td>
<td></td>
</tr>
<tr>
<td>Intrusion-related Au</td>
<td>Fort Knox, Alaska (1980s): Au in granitic rocks, without Cu</td>
<td></td>
</tr>
<tr>
<td>Ion Absorption REE</td>
<td>South China (1980s): low-grade REEs with kaolinite in weathered granites</td>
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More new types of ore deposits will be discovered in the future...
Examples of some new types of ore deposits recognized in the past five years – most not yet understood

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Examples of some new types of ore deposits recognized in the past five years – most not yet understood

**Deposit type**  | **Type locality** *(year discovered)*
--- | ---
**Sedimentary Ni** | Enterprise, Zambia *(2010)*: High-grade hydrothermal nickel deposit in metasedimentary rocks with no directly associated mafic/ultramafic rocks. At least one other similar deposit discovered (by accident) since then in district.
Examples of some new types of ore deposits recognized in the past five years – most not yet understood

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Additional new types of ore deposits will be discovered in the future… requires luck and imagination.
We may not need to worry about mining on the Moon, Mars, or asteroids for some time. Though thinking about how ore deposits might form on such bodies could help us be more imaginative on Earth!
The Future of Mineral Resources

• Demand for mineral resources will continue to grow.

• We are unlikely to run out of mineral resources.

• Nonetheless, there will be many challenges for both developed and less developed countries.
China is #1 in terms of mineral-resource production.
China has approximately 19% of the world's population.
Selected commodities for which China produced ≥19% of the world’s total in 2012:

- Aluminum*, 42%
- Barite, 48%
- Cement*, 58%
- Fluorspar, 61%
- Gypsum, 32%
- Lead, 50%
- Mica, 69%
- Rare Earths, 94%
- Tungsten, 85%
- Antimony, 83%
- Bismuth, 81%
- Coal, 45% (2011)
- Germanium*, 70%
- Indium*, 58%
- Manganese, 19%
- Molybdenum, 42%
- Steel*, 48%
- Vanadium, 37%
- Arsenic, 57%
- Cadmium, 30%
- Diatomite, 21%
- Graphite, 68%
- Iron ore, 43%
- Mercury, 75%
- Phosphate, 42%
- Tin, 43%
- Zinc, 35%

* refined or processed, not mined
China produces ~45% of the world’s coal.
The amount of CO$_2$ released from burning of coal in 2011 would have been enough, without natural reduction from plant growth, rain, and other processes, to raise the concentration of CO$_2$ in the atmosphere by $\sim$2.9 ppmv, a bit more than the recent global trend of CO$_2$ increasing $\sim$1.8 ppmv per year.
With 19% of the population, China produces ~43% of the world’s iron ore and ~48% of the world’s steel.

China’s economy continues to boom, although 2012 iron-ore production suggests a slowdown.
China has been the #1 gold producing country since 2007.
Spectacular rise in REE prices (including Tb and Nd) in 2011.

Price rise due to restriction of supply by China – major producer.
**REEs**

<table>
<thead>
<tr>
<th></th>
<th>Consumption tpa</th>
<th>Growth rate %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2006</td>
<td>2012</td>
</tr>
<tr>
<td>Battery alloy</td>
<td>17,000</td>
<td>43,000</td>
</tr>
<tr>
<td>Magnets</td>
<td>20,500</td>
<td>42,000</td>
</tr>
<tr>
<td>Catalysts</td>
<td>21,500</td>
<td>32,000</td>
</tr>
<tr>
<td>Polishing powder</td>
<td>14,000</td>
<td>21,000</td>
</tr>
<tr>
<td>Phosphors</td>
<td>8,500</td>
<td>14,000</td>
</tr>
<tr>
<td>Glass additives</td>
<td>13,000</td>
<td>14,000</td>
</tr>
<tr>
<td>Ceramics</td>
<td>5,500</td>
<td>9,000</td>
</tr>
<tr>
<td>Others</td>
<td>8,000</td>
<td>13,000</td>
</tr>
<tr>
<td>Total</td>
<td>108,000</td>
<td>188,000</td>
</tr>
</tbody>
</table>

- We currently utilize more REEs worldwide than we are producing (utilizing stockpiles).
- With expected growth rates it is easy to see why prices have increased.
## REEs — Chinese Export Quotas

<table>
<thead>
<tr>
<th>Year</th>
<th>Quota</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>65,609 t REO*</td>
</tr>
<tr>
<td>2006</td>
<td>61,821 t REO</td>
</tr>
<tr>
<td>2007</td>
<td>59,643 t REO</td>
</tr>
<tr>
<td>2008</td>
<td>56,643 t REO</td>
</tr>
<tr>
<td>2009</td>
<td>50,145 t REO</td>
</tr>
<tr>
<td>2010</td>
<td>30,258 t REO</td>
</tr>
<tr>
<td>(first half 2011)</td>
<td>14,508 t REO</td>
</tr>
</tbody>
</table>

* REO = rare earth oxides

- **Quota**: Domestic + foreign companies
- **2008**: Adjusted to an equivalent 12 month quota as there was a change in the dates for which they were issued.
# World Rare Earth Supply Chain

<table>
<thead>
<tr>
<th>Ore ➔ oxide</th>
<th>Metal ➔ alloy</th>
<th>Magnet</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>China produces 97%</td>
<td>• CAS Key Laboratory of Rare Earth Chemistry and Physics, China</td>
<td>• Zhejiang Tinna Group, China</td>
<td>• GM</td>
</tr>
<tr>
<td>• Sichuan Mianning Mining Co.</td>
<td>• Neo Materials, China</td>
<td>• Shin Etsu, Japan</td>
<td>• Ford</td>
</tr>
<tr>
<td>• Jiangxi Copper</td>
<td>• Santoku, Japan</td>
<td>• Hitachi Metals, Japan</td>
<td>• Toyota</td>
</tr>
<tr>
<td>• Baotou Steel Rare Earth</td>
<td>• GWMG, Canada/UK</td>
<td>• Aichi Steel Corp., Japan</td>
<td>• Nissan</td>
</tr>
<tr>
<td>• Sichuan Hanxin Mining Industrial Co.</td>
<td></td>
<td>• Arnold Magnetic Technologies, USA</td>
<td>• Honda</td>
</tr>
</tbody>
</table>

Rest of World: 3%

- Japan Oil, Gas and Metals National Corp., Japan
- Lynas, Australia (after 2011)
- Molycorp, USA (after 2012)
- Japan Oil, Gas and Metals National Corp., Japan
- Sichuan Hanxin Mining Industrial Co.
- Jiangxi Copper
- Baotou Steel Rare Earth

Source: Andre Gauthier – Matamec Exploration
Critical and strategic minerals do change with time.
CuIn\(_x\)Ga\(_{1-x}\)Se\(_2\), CdTe, GaAs, Ag, and Si\(_{1-x}\)Ge\(_x\) for solar panels

Fe\(_{14}(Nd,Dy)\)\(_2\)B, SmCo\(_5\), and Sm\(_2\)Co\(_{17}\) for magnets, e.g., in wind turbines

Li, La, Ni, and V for batteries

Pt, Pd for catalysts in fuel cells

Tb, Eu in fluorescent lights
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It’s not all rosy, for some elements there are issues…

Example: Tellurium

Tellurium is a rare element
Tellurium

- 0.0000001% of earth’s crust (compare gold -- 0.0000004%)
- Almost all comes from by-product of copper smelting
- Key in Cd-Te thin-film solar photovoltaics

USGS Mineral Commodity Summary
Solar Photovoltaics

Deployment of grid connected photovoltaic installations in the U.S. 2000-2010.

Rising incredibly fast – that’s great – isn’t it?
Tellurium in Photovoltaics

- Will constraints on availability of tellurium obstruct the large scale deployment of CdTe thin film photovoltaics?

- Studies ask “is there enough Te to build … over… years?”

- Zweibel → “yes”
- Ojebouboh → “probably”
- Fthenakis → “maybe”
- Green → “maybe not”
- Feltrin & Freundlich → “no”
Tellurium

• Tellurium has been produced as a by-product of copper smelting (and often unwanted due to toxicity!)
• Tellurium production has gone down as more copper is produced from solvent extraction (SXEW) treatment of copper oxides rather than smelting of copper sulfides.
• There are undoubtedly high tellurium deposits out there – several known (Colorado, Mexico, Fiji).
• We have not developed geological models of how they form and how to find them.

Running out of tellurium is NOT the problem but disruptions and discontinuities in supply are likely.
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• The NRC has examined a number of issues critical for the future of mineral resources in the US (and the world)…
Will the USA be a major producer of hard rock mineral resources in the future?
What minerals will be critical for the country?
How will the USA deal with coal mining going forward?
NRC has no reports dealing with industrial minerals development in the US – is this a need?
Will the USA be a major producer of mineral resources in the future?

Or will we, perhaps by default, practice "environmental imperialism" – export the negative environmental, health, safety, aesthetic, and cultural aspects of mining to other countries?
NRC reports have dealt with US mine safety — should we also be looking more broadly?
Artisanal mining outside the US will likely continue as a health, safety, and environmental challenge for society, governments, and industry worldwide.

Four artisanal miners (galamsey) work unsafely, without personal protective equipment or ground support, near Kyereboso in Ghana in 2008.
Gold mill in Sulawesi (Larry James photo)
Recent reports (Science Oct. 2013) state that 70% of Hg pollution worldwide is from artisanal mining.

Using blowtorch to remove mercury from amalgam, Sulawesi (Larry James photo)
Can economists (and governments who invest in economic development throughout the world) better account for the environmental, cultural, social, and aesthetic aspects of mining?
Will the US government invest in research needed to discover, extract, and process mineral resources in an environmentally responsible manner?
Will the US government invest in research on improving the rate of recycling of mineral resources, and on finding substitutes for mineral resources that become too expensive for commercial or other applications?
More recycling can be accomplished by increasing collection rates of various products, better product design with recycling in mind, and improvements in recycling technologies. - Reck and Graedel (2012).
Do we have, and are we training, the people needed to ensure the US can meet its mineral and energy needs?
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*How can NAS/NRC contribute?*
The Future of Mineral Resources

What will be the critical issues that we should be focusing on for the future?
Will the US and other governments support the basic research, including geologic mapping, needed to understand where resources are likely to be found?
Will the US and other governments support the preservation of geological data and collections that stimulate discovery?
How do earth materials (and their production) influence human health?
What may be the unintended consequences of new mineral resource production?
Perhaps most importantly — will national and state geological surveys survive (in the US and elsewhere)?
It has been two decades since the NRC took a holistic view of the issue — is it time to revisit this for the 21st century?
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Given the changes in demand for minerals:

• *What science and information do we need?*

• *What infrastructure do we need to produce that science?*

• *What is the role of government?*

• *How do we address social challenges?*
The Future of Mineral Resources

Important political and social challenges:

• Social acceptance of the need for mining

• Social acknowledgment of the importance of geoscience to society

• Maintaining funding for critical “blue sky” / pre-competitive governmental research

• Maintaining strong means to obtain and preserve geologic data (geological surveys?)

NRC continues to have a critical national role to play
Santa Cruz (AZ) in-situ copper mining test project - US government funded (1986-1998)

Could more research projects like this stimulate a new industry – as DOE research did with shale gas/fracking?

Thank You!