Contribution of Deep-Ocean Minerals to the Global Mineral Wealth

James R. Hein
U.S. Geological Survey, Santa Cruz, CA, USA

14th Brazilian Mining Congress, September 2011
Who Owns Deep-Ocean Mineral Deposits?

To adequately represent the interests of developing nations in portioning out mining rights (Common Heritage of Mankind)

Area beyond national jurisdictions “The Area”

EEZ (200 nautical miles)

U.S. EEZ

Compact of Freely Associated Nations with U.S.
Concern grows over China’s dominance of rare-earth metals

Demand for the elements is expected to surge in tandem with hybrid-electric vehicles, wind turbines, and other green technologies.

Physics Today May, 2010 David Kramer

SUPPORTING SOUND MANAGEMENT OF OUR MINERAL RESOURCES

Rare Earth Elements—Critical Resources for High Technology

Chinese Policies Could Pinch U.S. Efforts to Make Electric Vehicles

Nations Move to Head Off Shortages of Rare Earths

Looming scarcities of a handful of essential elements could shake the electronics industry, unless manufacturers and mining companies develop more sources soon

The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics

September 1, 2009

China Tightens Grip on Rare Minerals

By KEITH BRADSHIER

Ken Zweibel  Science Magazine Volume 328 May 7, 2010
<table>
<thead>
<tr>
<th>Element</th>
<th>Global production (tonnes)</th>
<th>Leading Producer</th>
<th>2nd Producer</th>
<th>3rd Producer</th>
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<tbody>
<tr>
<td>Aluminum2</td>
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<td>China (18%)</td>
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<td>Chromium</td>
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<tr>
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<td>Australia (12%)</td>
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</tbody>
</table>

(From Jonathan G. Price, Society of Economic Geologists Newsletter, No. 82, July 2010)
The Earth’s surface is 71% water covered

- Dry land 29%
- Ocean 71%

Pacific Ocean area is greater than the entire Earth’s land area
Deep-ocean mineral deposits

**Manganese nodules**
- Form on the vast deep-water abyssal plains

**Ferromanganese crusts**
- Form on 50,000 seamounts

**Phosphorites**
- Form in shelf to deep-water environments

**Seafloor massive sulfides**
- Form at hydrothermal vents along 80,000 km of ridges
Distribution of Marine Mineral Deposits
<table>
<thead>
<tr>
<th>Metal</th>
<th>Sulfides/Sulfates</th>
<th>Fe-Mn Crusts</th>
<th>Fe-Mn Nodules</th>
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<tbody>
<tr>
<td>Antimony</td>
<td>L</td>
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<td>L</td>
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<td>Cobalt</td>
<td>--</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>Copper</td>
<td>G</td>
<td>L</td>
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</tr>
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<td>G</td>
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<tr>
<td>Molybdenum</td>
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<tr>
<td>Platinum</td>
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<td>L</td>
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<td>REE-Y</td>
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<td>L</td>
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<tr>
<td>Silver</td>
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<td>Tellurium</td>
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<tr>
<td>Thorium</td>
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<td>G</td>
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<td>Titanium</td>
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<td>G</td>
<td>L</td>
</tr>
<tr>
<td>Tungsten</td>
<td>--</td>
<td>L</td>
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<tr>
<td>Zinc</td>
<td>G</td>
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</tr>
<tr>
<td>Zirconium</td>
<td>--</td>
<td>L</td>
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</tr>
</tbody>
</table>

G = Good Potential  L = Longer term Potential
In place metal tonnages (x $10^6$ metric tons)

<table>
<thead>
<tr>
<th></th>
<th>Clarion-Clipperton Zone Nodules</th>
<th>Global Land-Based Reserves(^a)</th>
<th>Pacific Prime Crust Zone</th>
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</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>5,929</td>
<td>5,200</td>
<td>1,718</td>
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<tr>
<td>Copper</td>
<td>224</td>
<td>1,000+</td>
<td>7.4</td>
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<td>Titanium</td>
<td>59</td>
<td>900</td>
<td>87</td>
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<tr>
<td>Zinc</td>
<td>29</td>
<td>480</td>
<td>5</td>
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<tr>
<td>REO</td>
<td>17</td>
<td>150</td>
<td>20</td>
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<tr>
<td>Nickel</td>
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<td>150</td>
<td>32</td>
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<tr>
<td>Zirconium</td>
<td>6</td>
<td>57</td>
<td>4.1</td>
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<td>Molybdenum</td>
<td>12</td>
<td>19</td>
<td>3.5</td>
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<tr>
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<td>50</td>
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<td>Tungsten</td>
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<td>6.3</td>
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<td>3</td>
<td>0.4</td>
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<tr>
<td>Bismuth</td>
<td>--</td>
<td>0.68</td>
<td>0.32</td>
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<tr>
<td>Yttrium</td>
<td>1.9</td>
<td>0.48</td>
<td>1.7</td>
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<tr>
<td>Tellurium</td>
<td>0.07</td>
<td>0.05</td>
<td>0.45</td>
</tr>
</tbody>
</table>

\(^a\)USGS (2010) reserve base. Nodule tonnage used is 21,100 million dry tons and crust tonnage used is 7,533 million dry tons (from Hein and Koschinsky, 2011)
Deep-ocean mineral deposits

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**Ferromanganese crusts**
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- Form at hydrothermal vents along 80000 km of ridges
Manganese Nodules

- Form on sediment-covered abyssal plains (4000-6500 meters water depths)
- Composed of manganese-iron oxides, with significant amounts of nickel & copper
- Form by precipitation from cold ambient bottom water & from sediment pore fluids
Global nodule distribution

Source: ISA
Metal tonnages in the Clarion-Clipperton manganese nodule field; 9 Million km²

- Mn: 5900 Million Tons
- Ni: 278 Million Tons
- Cu: 224 Million Tons
- Co: 42 Million Tons

**AREAS RESERVED FOR CONDUCT OF ACTIVITIES BY THE INTERNATIONAL SEABED AUTHORITY IN THE PACIFIC OCEAN**

- Red: From COMRA (China)
- Yellow: From YUZHMORGEOLOGIA (Russian Fed.)
- Teal: From DORD (Japan)
- Pink: From Government of Korea
- Brown: From IFREMER/AFERNO (France)
- Green: From INTEROCEANMETAL (Bulgaria, Cuba, Czech Rep., Russia Fed., Slovak Rep., Poland)
- Light Gray: CONTRACTORS AREAS
Average C-C Zone Nodule Chemistry

Potential Ni-Cu ore (Co, Mn)

N=100-4000
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Ferromanganese Crusts

- Grow on hard-rock surfaces on seamounts, ridges, and plateaus
- Found at water depths of ~400-7000 meters
- Thicknesses range from <1 to ~260 millimeters
- Precipitate from cold ambient bottom water
Central Pacific Mean
(n = 627)--left column

Johnston Island Mean
(n = 103)--right column

Potential Co-Ni ore (Te, Ti, REEs, Mn)
Trace Metal Maxima

Mean Co = 0.67%
Mean Ce = 0.13%
Road Bump? President Obana’s efforts to promote electric-vehicle production may be stymied by getting access to rare-earth elements.
Light versus Heavy REE

Bayan Obo & Mountain Pass average <1% HREE
PCZ averages 6.3% HREE
CCZ averages 10% HREE

Price for 10 Rare Earth Elements
As of May 7, 2010

From 10,000 to 800,000 $/t

From C. Hocquard, 2010
Primary Ore versus Byproduct Production

Land-based: REE predominantly primary ore

PCZ: Byproduct of Co and Ni mining

CCZ: Byproduct of Ni and Cu mining

Thorium Concentrations

Bayan Obo and Mountain Pass contain 100s ppm Th

PCZ averages 11 ppm Th

CCZ averages 14 ppm Th
Ferromanganese crusts provide the richest source of tellurium (Te) known (Hein, USGS)

“Finding enough Te for CdTe is the largest barrier to the multi-terawatt use of CdTe for solar-cell electricity. It is widely regarded as the lowest cost photovoltaic technology with the greatest potential. This is important to the US and the world”

(Ken Zweibel, National Renewable Energy Laboratory)
Deep-ocean mineral deposits

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Phosphate Production and Demand

Million Tonnes Product

- North America: 31.4 (Production), 32.1 (Demand)
- Latin America: 6.2 (Production), 9.1 (Demand)
- Europe: 7.0 (Production), 0.9 (Demand)
- Middle East: 40.5 (Production), 22.0 (Demand)
- FSU: 11.7 (Production), 14.0 (Demand)
- Asia: 60.6 (Production), 68.2 (Demand)

Export: 3.0 (Production), 4.2 (Demand)

Domestic Sales: 79%

Export: 21%

Source: Fertecon, Potashcorp
Marine Phosphorite occurs as:

- Seamount and plateau deposits
- Insular and lagoonal deposits
- Shelf/slope deposits
- Epicontinental-sea deposits (in the geologic record, include giant deposits e.g. Phosphoria Fm (USA))
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Mid Ocean Ridge
basalt
tectonic setting
lithology
back-arc basin
felsic rocks
ultramafics
arc volcano
T/E-MORB

Active Hydrothermal Vents
Nautilus Minerals Tenements in Bismarck and Solomon Seas
Seafloor Massive Sulfides

- Precipitation from hydrothermal & magmatic fluids
- Black/white smokers produce sulfide/sulfate chimneys and mounds
- Rich in copper, zinc, lead, barium, silver, gold (Cd, Sb, As, Ga, In)
- Ephemeral vent fields
SMS deposit chemistry

Data from Nautilus Minerals Inc., Project-Solwara; MOR and BAR from Herzig and Hannington (1995)

Nautilus: N=49; MOR: N=890; BAR: N=317

Nautilus-PNG  Mid-ocean ridges  Back-arc ridges
Volcanic arc hydrothermal mounds

Contain significant rare metals: e.g. cadmium, antimony, gallium, indium
Social and environmental advantages for recovery of deep-ocean minerals

- Land-based mines leave a substantial footprint, impacted waterways, carbon emissions from heavy machinery, and millions to tons of waste rock

- Marine-based mine sites have no roads, surface ore-transport systems, buildings, or other infrastructure

- Less ore needed to provide the same amount of metal

- Three or more metals can be obtained at one site
Social and environmental advantages for recovery of deep-ocean minerals

- No overburden to remove, which on land can be 75% of material moved
- No indigenous or native populations to disrupt
- Ecosystems with generally low population densities and low diversity—needs to be verified for each site
Economic advantages to companies

- Lower capital start-up costs
- Moveable mining platform
- Smaller deposits can be mined
- High metal grades
Obrigado