Seamounts and Cobalt-Rich Ferromanganese Crusts

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For the ISA
Distribution of Co-Rich Crusts

- Aleutian Trench or Iceland to Antarctic Ridge on seamounts, ridges, and plateaus
- Most cobalt-rich, 800-2,200 m, mostly in and below oxygen-minimum zone (OMZ)
- Thickest crusts occur between the depths of $\approx$1,500-2,500 m, summit outer rim
Important Properties of Cobalt-Rich Crusts

- Very high porosity (60%)
- Extremely high specific surface area (300 m²/g)
- Extremely slow rates of growth (1-6 mm/Ma)

* These properties are instrumental in allowing for surface adsorption of large quantities of metals from seawater
The greatest number of samples collected come from the Pacific Ocean; most samples have growth rates of 1-6 mm/Ma.
C+W N. Pacific Average (n = 627)

- **Wt. %**
  - Mn: 20.8%
  - Fe: 17.1%
  - P: 0.74%

- **ppm**
  - Co: 5109 ppm
  - Ni: 3473 ppm
  - Pb: 1265 ppm
  - Ce: 1022 ppm
  - Cu: 973 ppm
  - Zr: 793 ppm
  - Zn: 565 ppm
  - Mo: 402 ppm
Trace Metal Maxima

![Graph showing ppm levels of various trace metals: Ce, Zr, Tl, Te, W, Bi, and Pt. The levels are as follows: Ce: 1222 ppm, Zr: 269 ppm, Tl: 206 ppm, Te: 185 ppm, W: 114 ppm, Bi: 3.0 ppm.]
Element Enrichment in Fe-Mn Crusts Relative to the Earth’s Crust
How Do Hydrogenetic Fe-Mn Crusts Form?

Simplified electrochemical model for the formation of Fe-Mn crusts by sorption of trace metal species on colloidal Mn oxide and Fe oxyhydroxide (Koschinsky and Hein, 2003)
Cobalt-Rich Fe-Mn Crust

Columnar Texture

Substrate

Sample # 60-01
Geographic Control of Fe-Mn Crust Chemistry

Co Ni
Si Mg
K Na
Nb Cr
Ba Be
V Zr
W Fe
Pb As
Mo Bi
U
Al Cr Li Zr Th Sc
Bi Ba Sb Be Pb
V As W Mo
Co Ni
Fe Si
K Na
Br Nb
Mg Ti Te
Tl
Ba Sb
Zr Pb As
Mo Bi
Be REE, V Zn
Ca P S Si Y Zn
Na Ti Te Fe Nb
Br Hf Ni Mn
Co Ni Pb
Cd Sr Ti U
Mn Mo
Mg Sb
Cu Fe Sc
Si Th
K Li REE

Depth (m)
1000
2000
3000
4000
5000
6000
180°
Typical Guyot

56 kilometers long
Terraces
Debris apron
Typical Conical Seamount
Typical Sampling Density

Tanoa & TauTau
Tokelau Seamounts

Contour Interval = 125 meters
Grid Size = 180 meters
Sun Azimuth at 340°
### Average Seamount
(Surface Area Statistics for 34 Seamounts)

<table>
<thead>
<tr>
<th></th>
<th>Total Surface Area (km²)</th>
<th>Surface Area above 2500m Water Depth (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1,850</td>
<td>515</td>
</tr>
<tr>
<td>Median</td>
<td>1,450</td>
<td>325</td>
</tr>
<tr>
<td>SD¹</td>
<td>1,150</td>
<td>470</td>
</tr>
<tr>
<td>Minimum</td>
<td>310</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>4,775</td>
<td>1,843</td>
</tr>
</tbody>
</table>

¹ Standard Deviation
Example of smooth seabed with crust pavement
Example of rough seabed with crusts
Horizon Guyot Seafloor
Types of Seamount Generated Currents

- Anticyclonic currents (Taylor Column)
- Internal Waves
- Trapped Waves
- Vertically propagating vortex-trapped waves
- Taylor Caps
- Attached counter-rotating mesoscale eddies
- Many others

Results
- Turbulent Mixing and upwelling
- Erosion and sediment movement

Controls
- Seamount height
- Summit size
- Types of ambient currents
- Energy of tidal flow
Seamount Biology

- Different communities occur on adjacent seamounts at the same water depth
- Sediment-hosted versus rock-hosted organisms
- Low density and low diversity populations beneath OMZ where crusts are thick and cobalt-rich
- High-energy summit margins can inhibit biological activity, but can also enhance some groups, such as corals + sponges
- Bacteria may promote uptake of metals in crusts
- Density and diversity are controlled by current patterns, topography, bottom substratum, seamount size, water depth, and size of OMZ, which is related to primary productivity
Dispersal and colonization

- Dispersal of the larval stage is the main mechanism of colonization
- No larvae in the water column above diffuse-flow fields
- Several snails lay egg cases on rocks. Veligers (larval stage) hatch from these egg cases and remain near the bottom. They quickly become protoconchs, the first stage of benthic existence.

Many Mariana seamount taxa appear to produce larvae with limited dispersal potential. This in combination with the closed circulation around the seamounts may enhance larval retention and retard colonization.
Potential causes of high variability in colonization patterns

- Circulation that traps larvae and diminishes spread to other seamounts
- Abbreviated larval stage that remains near bottom
- Varying ages and stability of volcanoes
- Varying environmental conditions
NEW RESOURCES FOR COORDINATION OF SEAMOUNT BIOLOGY:

Census of Marine Life (CoML) (www.coml.org)

Global census of marine life on seamounts (CenSeam) (http://censeam.niwa.co.nz)

SeamountsOnline (http://seamounts.sdsc.edu/about_projects.html)

Biogeosciences Network (SBN) (http://earthref.org/events/SBN/2006/index.html)
AVERAGE COBALT PRICES 1919 - 2006
(in 2000 US Dollars)

- ZAIRE INVASION
- WORLD WAR II
- KOREAN WAR

PRICE (DOLLARS PER POUND)

YEAR

Price of Ni (top) and Cu (bottom) on the London Metal Exchange from 1 July 2000 through 30 June 2006
5 Year Platinum ($USD)
July 08, 2001 to July 07, 2006
HIGH $1331.00 on May 17, 2006 LOW $415.00 on Oct 02, 2001
Fe-Mn crusts provide the richest source of tellurium (Te) known (Hein et al., 2003)

Received by J.R. Hein in a recent e-mail concerning solar cells:

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

“We need a lot of Te, and CdTe is the most likely photovoltaic technology to reach truly low cost. This is actually important to the US and the world” (Ken Zweibel, National Renewable Energy Laboratory).
## Value of Metals in 1 Metric Ton of Fe-Mn Crust from the Central-Equatorial Pacific

<table>
<thead>
<tr>
<th>Metal</th>
<th>Mean Price of Metal (2006 $/kg)</th>
<th>Mean Content in Crusts (g/ton)</th>
<th>Value per Metric Ton of Ore ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>$32.41</td>
<td>6899</td>
<td>$223.60</td>
</tr>
<tr>
<td>Titanium</td>
<td>$18.03</td>
<td>12,035</td>
<td>$216.99</td>
</tr>
<tr>
<td>Cerium</td>
<td>$85.00</td>
<td>1605</td>
<td>$136.43</td>
</tr>
<tr>
<td>Zirconium</td>
<td>$22.00</td>
<td>618</td>
<td>$13.60</td>
</tr>
<tr>
<td>Nickel</td>
<td>$17.36</td>
<td>4125</td>
<td>$71.61</td>
</tr>
<tr>
<td>Platinum</td>
<td>$33,919.41</td>
<td>0.5</td>
<td>$16.96</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>$51.47</td>
<td>445</td>
<td>$22.90</td>
</tr>
<tr>
<td>Tellurium</td>
<td>$100.00</td>
<td>60</td>
<td>$6.00</td>
</tr>
<tr>
<td>Copper</td>
<td>$5.93</td>
<td>896</td>
<td>$5.31</td>
</tr>
<tr>
<td>Tungsten</td>
<td>$17.40</td>
<td>90.5</td>
<td>$1.57</td>
</tr>
<tr>
<td>Total</td>
<td>--</td>
<td>--</td>
<td>$714.97</td>
</tr>
</tbody>
</table>
Global Tonnage and Area of Ferromanganese Crusts

- **Area of seafloor with crusts:** 6.35 million km²
- **Total dry bulk mass of crusts:** 200 billion tonnes ($2 \times 10^{11}$ tonnes)
- **Total amount of cobalt metal:** 1 billion tonnes ($10^9$ tonnes)
Mining Systems

Operations
- Fragmentation
- Crushing
- Lifting
- Pick-up
- Separation

Ore Extraction Methods
- Bottom-crawling vehicle
- Articulated cutters
- Water-jet stripping
- Sonic fragmentation
- Continuous-line bucket
- In-situ leaching

Ore Dressing Methods
- Froth flotation
- Magnetic separation
- Gravity concentration
- Vibration table
- Color intensity separation

Extractive Metallurgy
Future Research I

- Detailed mapping of selected seamounts, including analysis of small-scale topography
- Development of better dating techniques for crusts
- Ascertain the oceanographic and geologic conditions that produce very thick crusts
- Determine the processes that control the concentration of platinum-group elements and other rare elements in crusts
- Determine how much burial by sediment is required to inhibit crust growth; and to what extent crusts occur on seamounts under a thin blanket of sediment
- Develop remote-sensing technique to measure crust thicknesses
- Develop new mining technologies; and especially new, innovative processes of extractive metallurgy
Future Research II

- Determine the role of microbiota in the formation and growth of crusts
- Determine the extent and significance of organic complexing of metals that compose crusts
- Determine the effects of potentially toxic metals (i.e., arsenic, thallium) that occur in Fe-Mn crusts on biota that interact with the crusts; under what conditions can the generally non-bioavailable forms of the metals that occur in the crusts be transformed into bioavailable forms
- Provide environmental and ecological surveys of seamount communities and how they vary; the ranges of biodiversity and bioproductivity
- Establish the range of variability of endemism
- Determine the mechanisms and controls for the dispersal and colonization of seamount biota
- A greater effort in needed in taxonomy and genetic fingerprinting of seamount biota
- Determine the variability of currents, internal tides, and upwelling (physical oceanography) around seamounts; provide long-term monitoring
Largest Impediment to Exploration

- Real-time measurement of crust thicknesses with deep-towed instrument
  - Gamma radiation may offer the best potential
  - Multi-spectral wave velocities must surmount overlapping velocities of crusts and substrates
Thank You for Your Attention
Exploration Strategy

Six Regional Criteria
1. Large volcanic edifices as shallow as about 1500 m
2. Volcanic edifices older than about 20 Ma
3. Volcanic edifices not capped by large atolls or reefs
4. Areas of strong and persistent bottom currents
5. A shallow and well-developed oxygen-minimum zone
6. Regions isolated from input of terrigenous & hydrothermal debris

Six Site-Specific Criteria
1. Summit terraces, saddles, and passes
2. Slope stability
3. Subdued small-scale topography
4. Absence of local volcanism
5. Crust thicknesses ≥40 mm
6. Cobalt contents ≥0.8%
Reconnaissance Exploration Technique

- **Swath bathymetry maps, including back-scatter and slope angle maps; seismic profiles; and geophysics**
- **Choose sampling sites from data collected from swath bathymetry and seismic surveys**
- **Reconnaissance sampling includes about 15-20 dredges and cores per seamount**
- **Video-camera or ROV surveys for crust, rock, and sediment types and distribution; crust thicknesses if possible**
- **CTD-oxygen profiles**
Suggested Site-Specific Techniques

- Deep-towed side-scan sonar and swath bathymetry (from ship, ROV, or AUV)
- Tethered remotely operated vehicle (ROV) surveys
- Extensive sampling, dredges, cores, ROV, others
- Current-meter moorings
- Biological sampling and surveys
Ni consumption increased five fold in 10 years and continues to grow

From Antrim (2005)

Primary and Indirect Nickel Consumption in China
Projected world consumption of select metals

Graph showing the projected consumption of copper, cobalt, manganese, and nickel from 2000 to 2010. The graph indicates growth rates of 4.0% for copper, 4.25% for nickel, 6.0% for cobalt, and 1.0% for manganese. The data is from Antrim (2005).
Seamount mine-site characteristics

- Mining operations will take place around the summit region of seamounts on flat or shallowly inclined surfaces: Summit terraces and saddles. These are the areas with the thickest and most cobalt-rich crusts.
  - Much thinner crusts occur on steep slopes.

- Seamount summits will not be much deeper than about 2200 m. Terraces will not be deeper than about 2500 m.

- Little or no sediment will occur in the summit region. Therefore, an area of strong and persistent bottom currents.

- The summit region will be large, more than 500 km².

- The submarine flanks of islands and atolls will not be considered for mining.

- The seamounts will be of Cretaceous age.

- Clusters of large seamounts will be favoured.

- Seamounts with thick crusts and high grades (cobalt, nickel, copper).

- The central Pacific will be the most likely location.