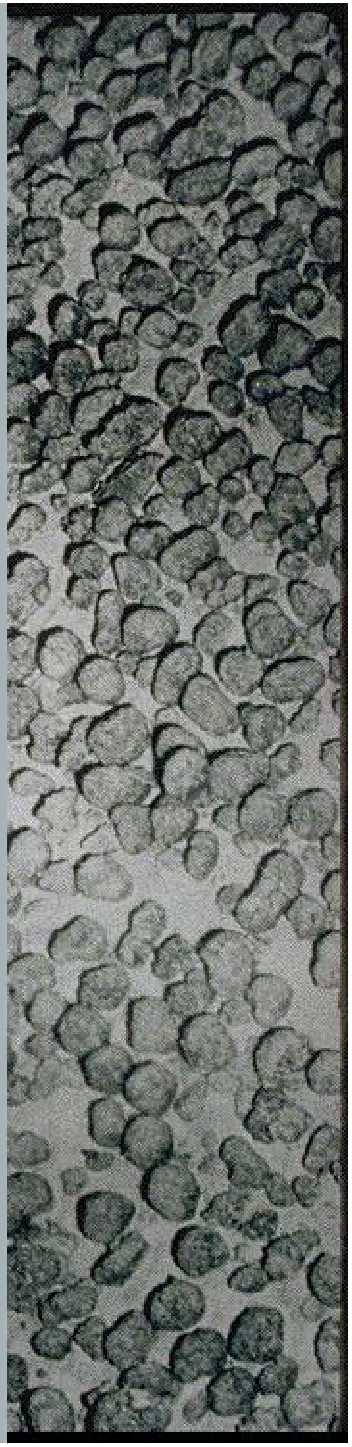
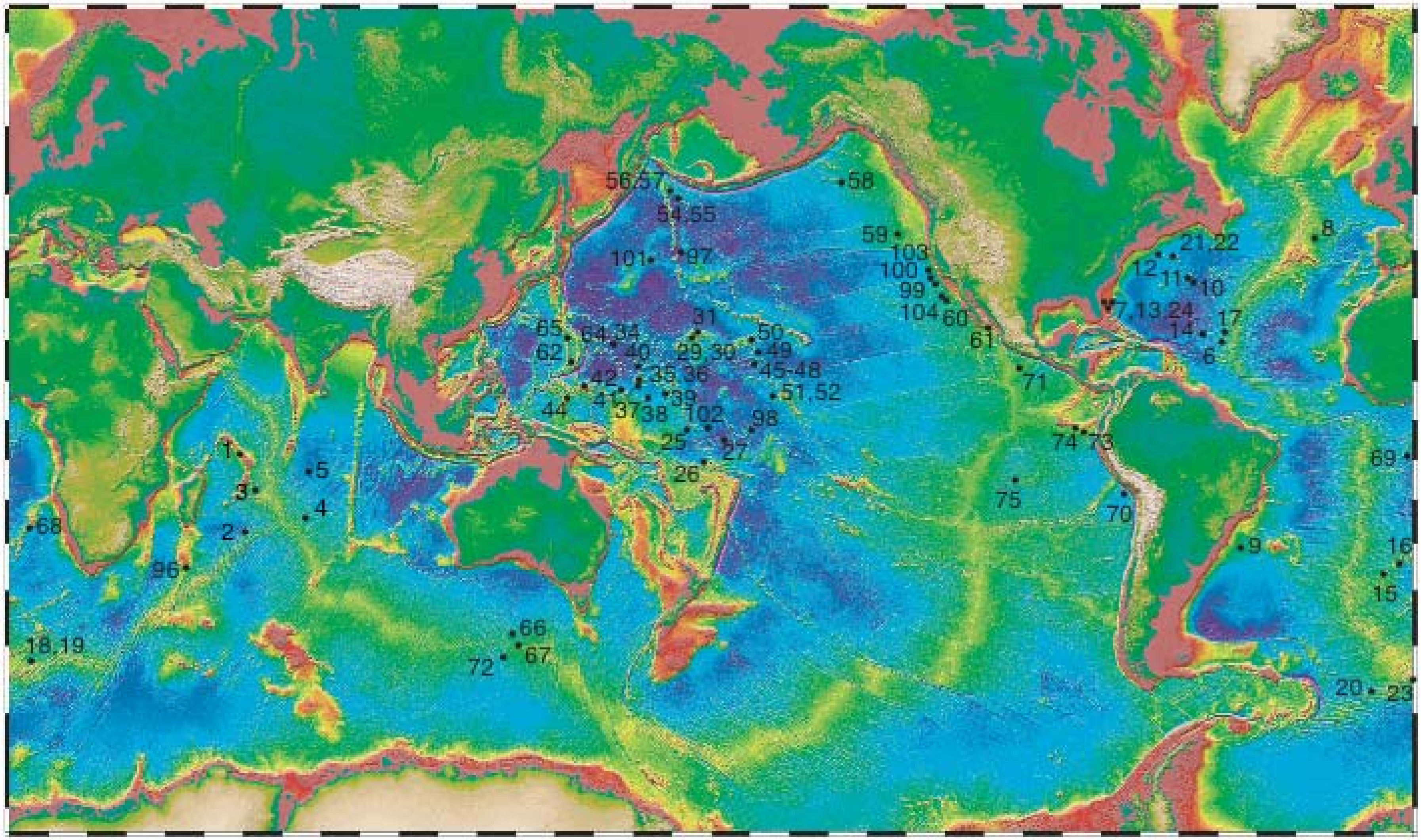
Seamounts and Cobalt-rich Ferromanganese Crusts

James R. Hein
U.S. Geological Survey




56,57
54,55
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64,34
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45-48
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41
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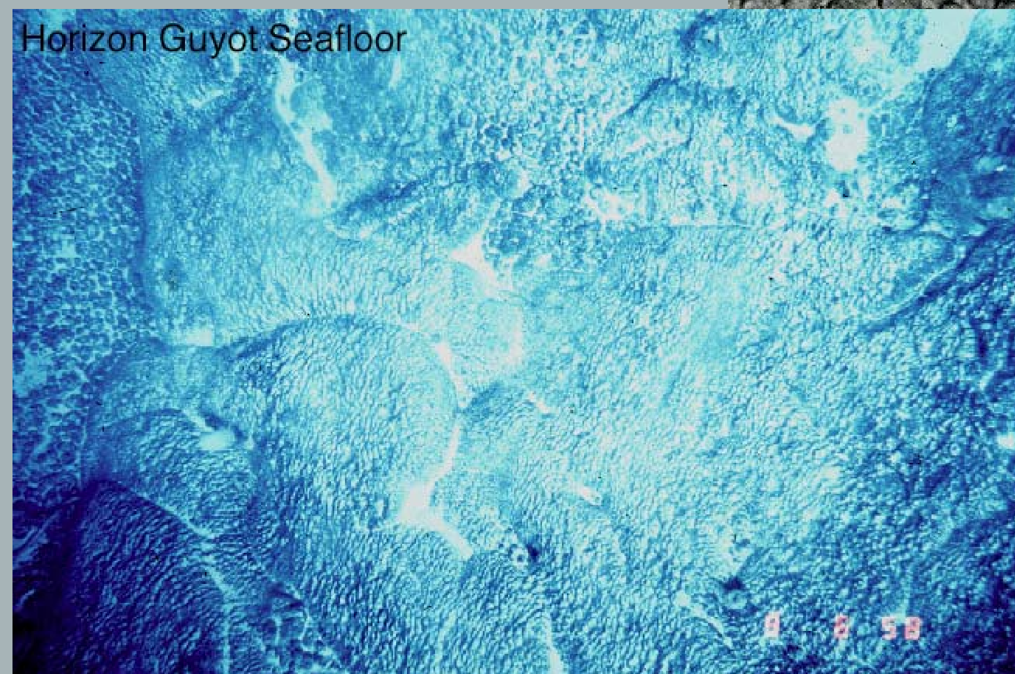
51,52
44
102
98
71
25
27
74
73
1
5
69
3
26
75
4
70
68
2
9
16
96
15
66
18,19
67
72
20
23

Distribution of Co-rich Crusts

- *Aleutian Trench or Iceland to Antarctic Ridge on seamounts, ridges, and plateaus*
- *Most cobalt-rich, 800-2200 m, mostly in and below oxygen-minimum zone (OMZ)*
- *Thickest crusts occur between the depths of ≈1500-2500 m, summit outer rim*

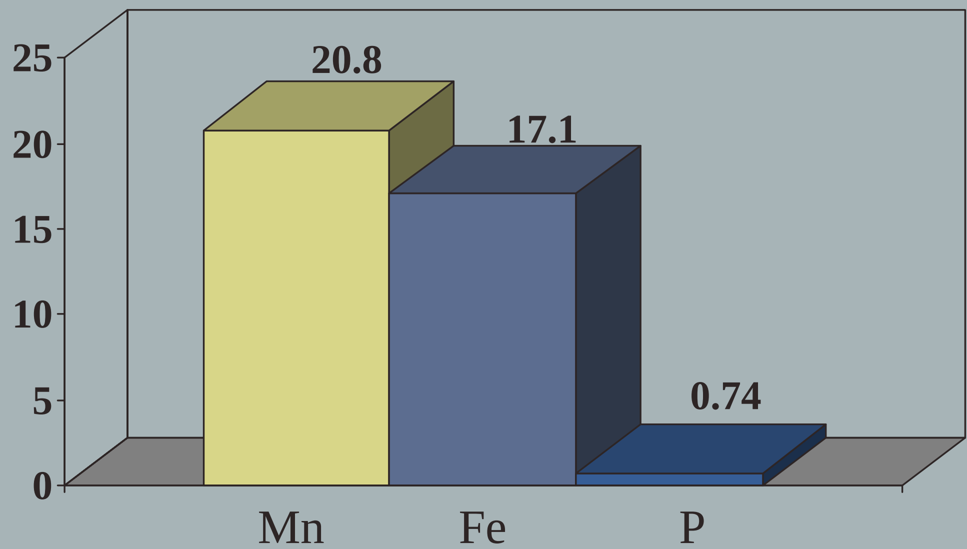


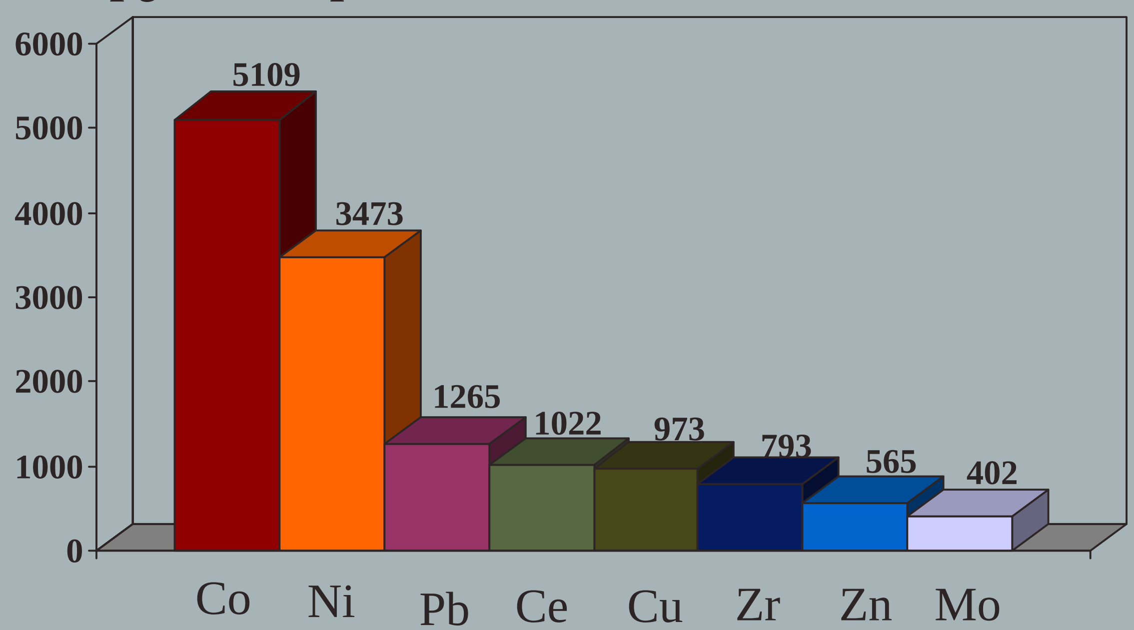
Important Properties of Co-rich Crusts

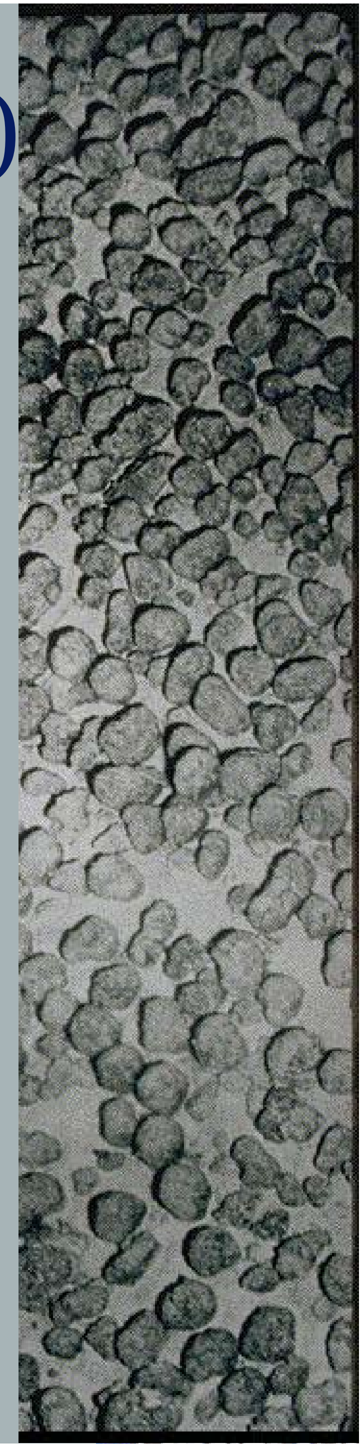
- *Very high porosity (60%)*
- *Extremely high surface area (300 m^2/g)*
- *Extremely slow rates of growth (1-6 mm/Ma)*

***** The above properties are instrumental in allowing for surface adsorption of large quantities of metals from seawater

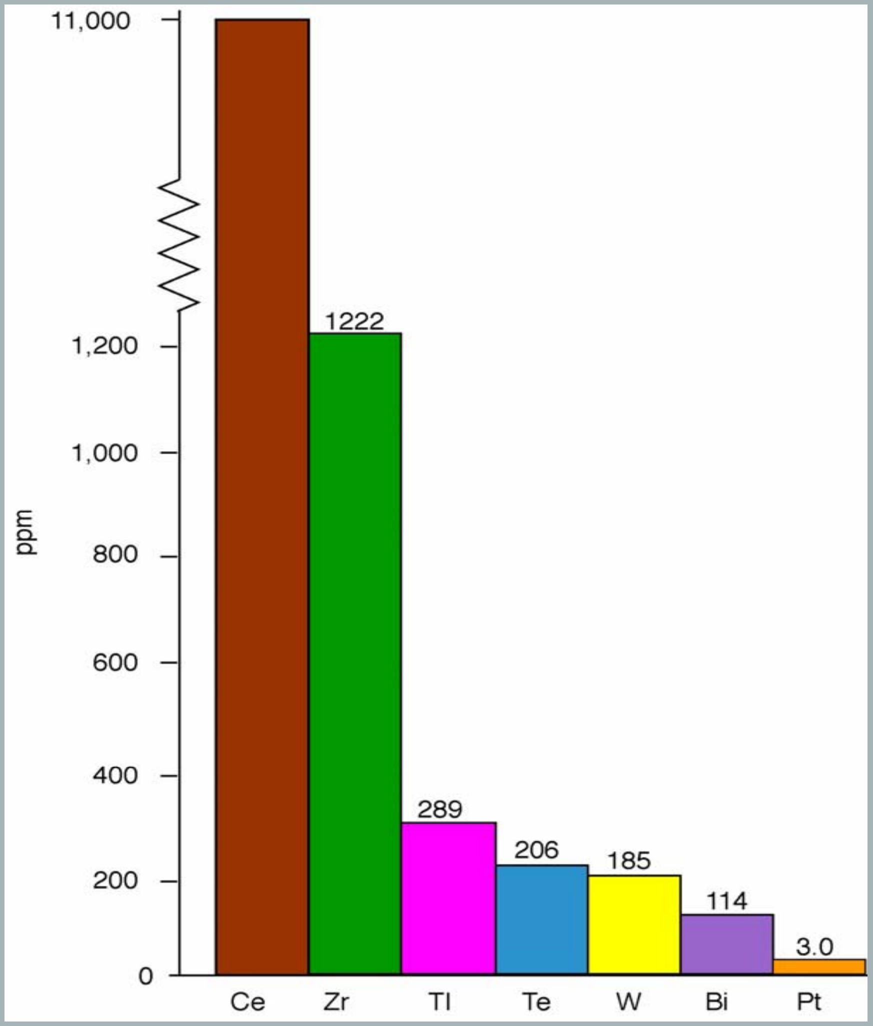
C+W N. Pacific Average (n = 627)

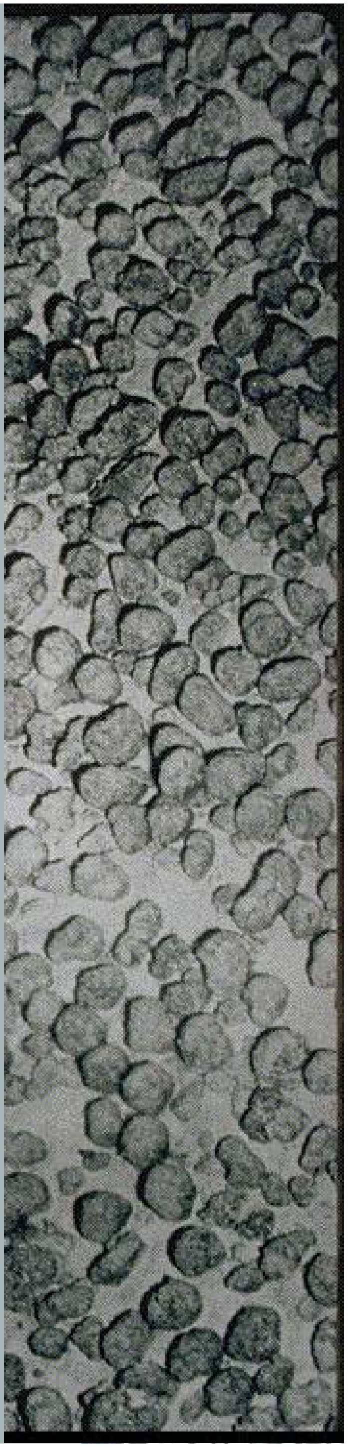




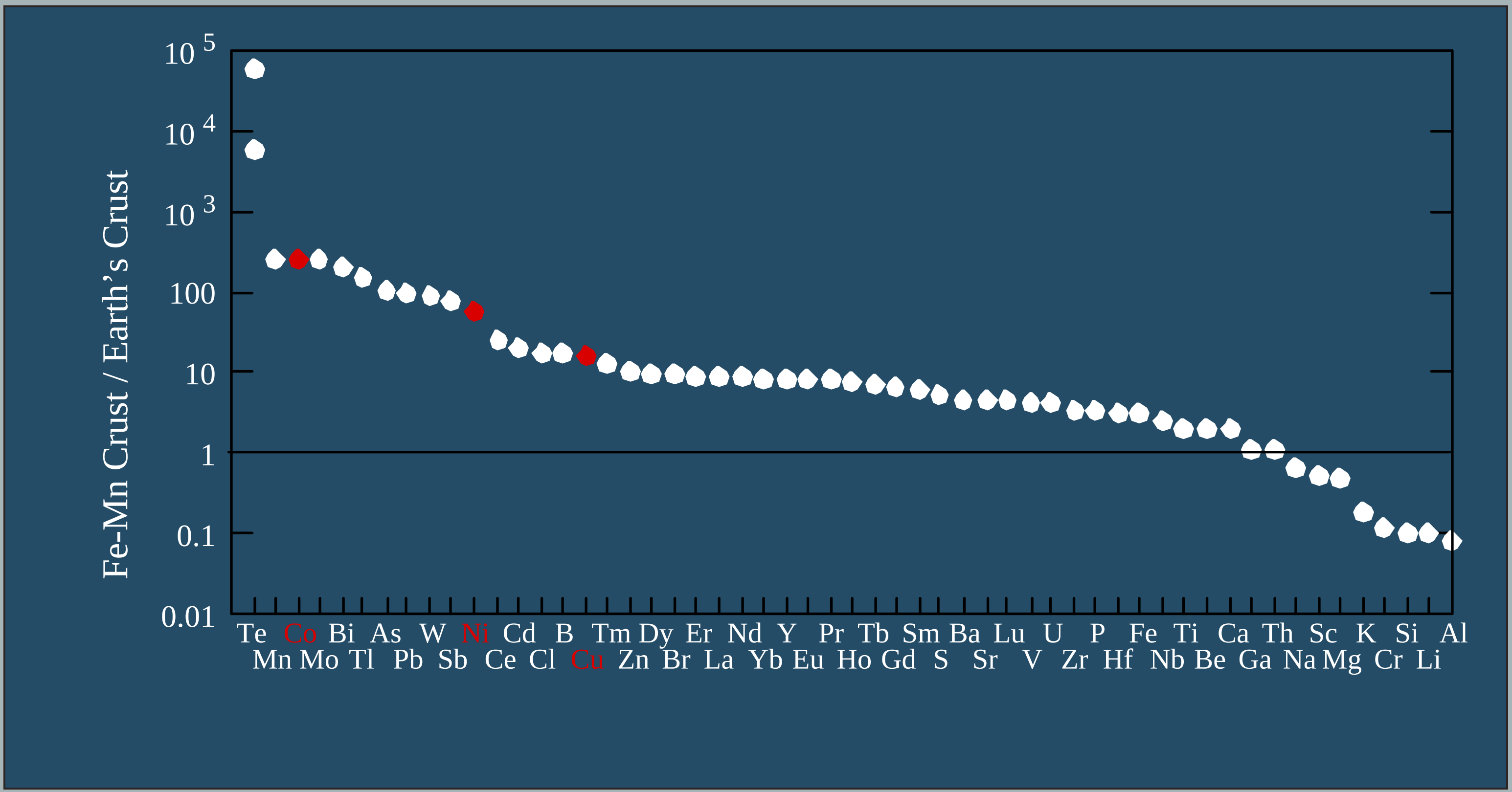


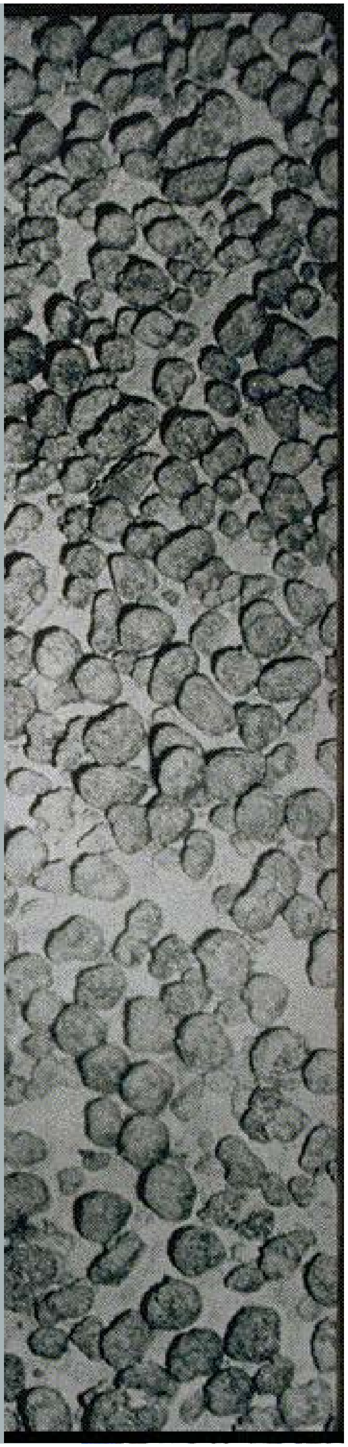
Trace Metal Maxima



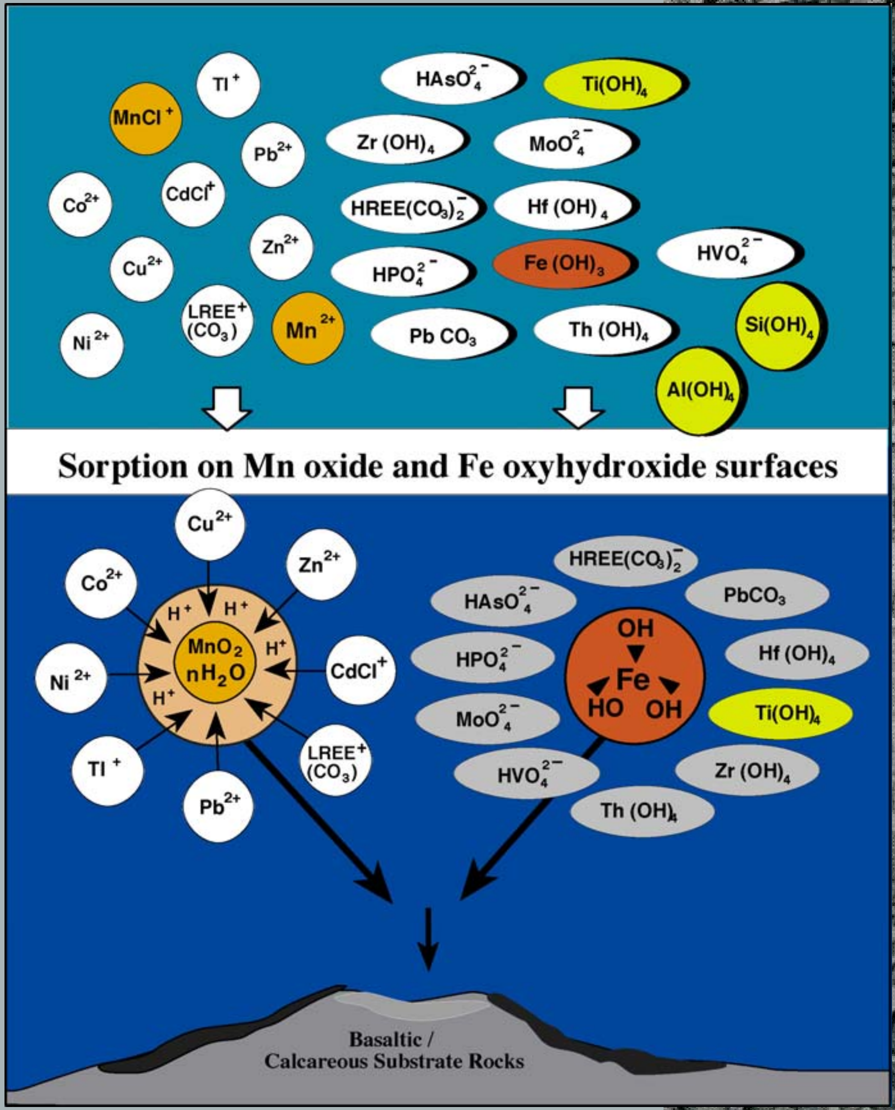


Element Enrichment in Fe-Mn Crusts Relative to the Earth's Crust

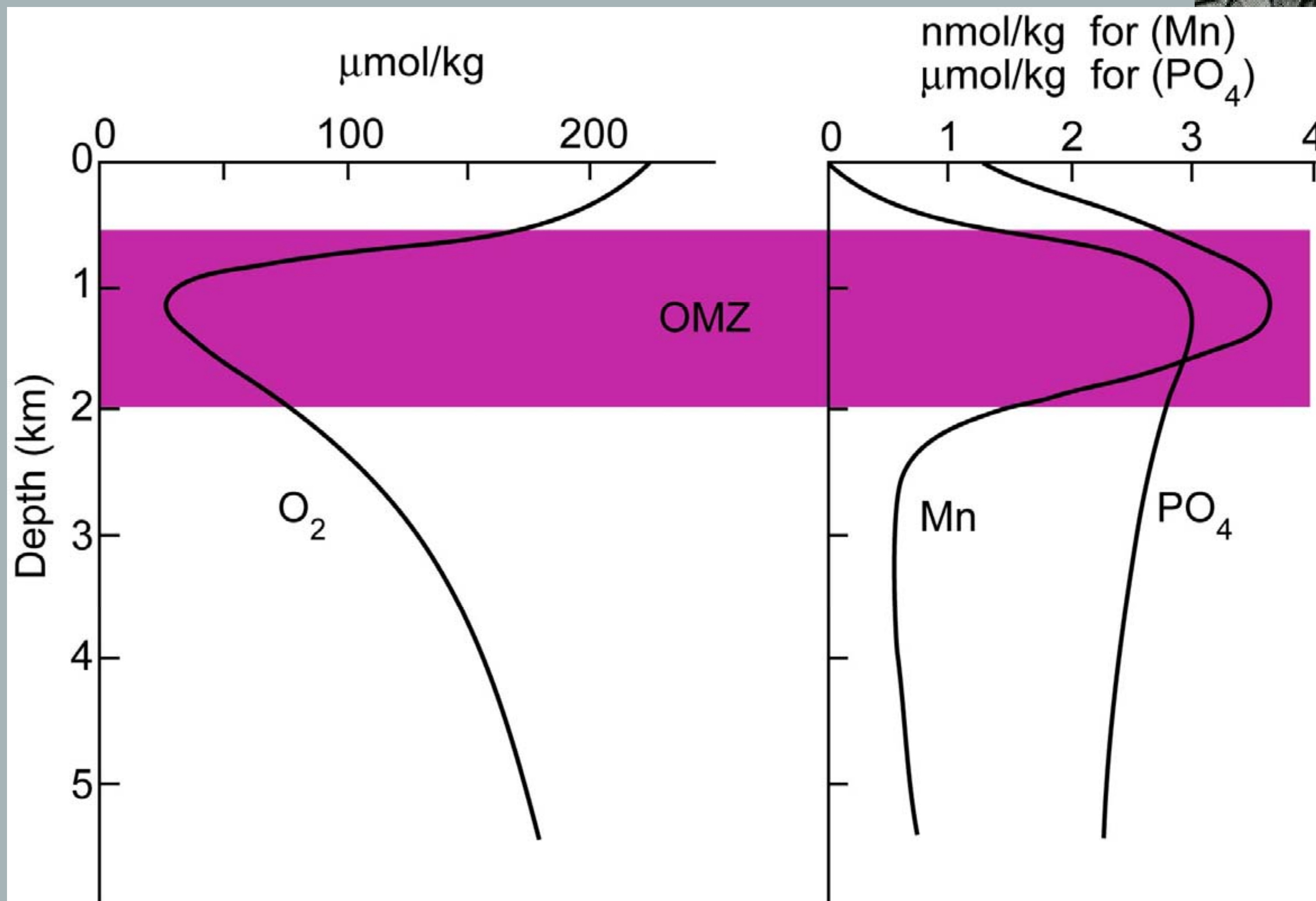




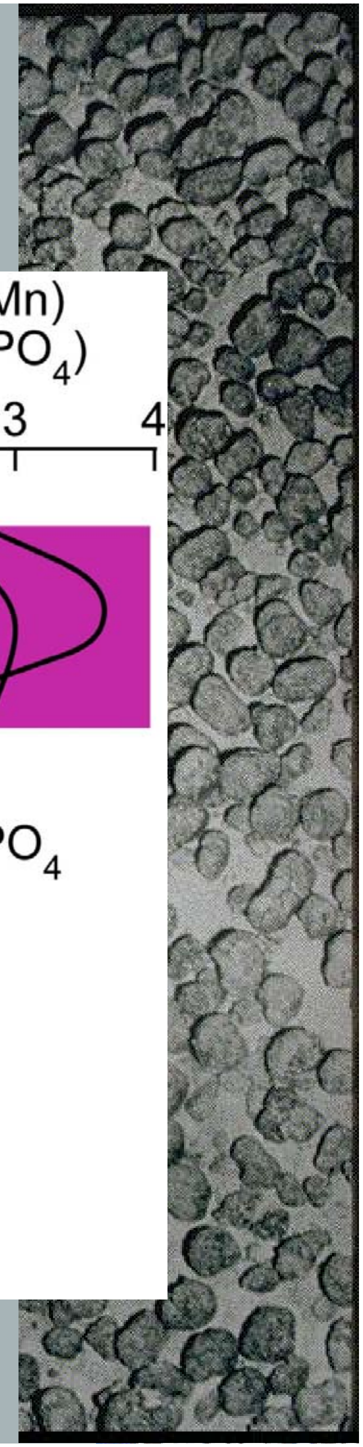
How Do Hydrogenetic Fe-Mn Crusts Form?



- *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)*

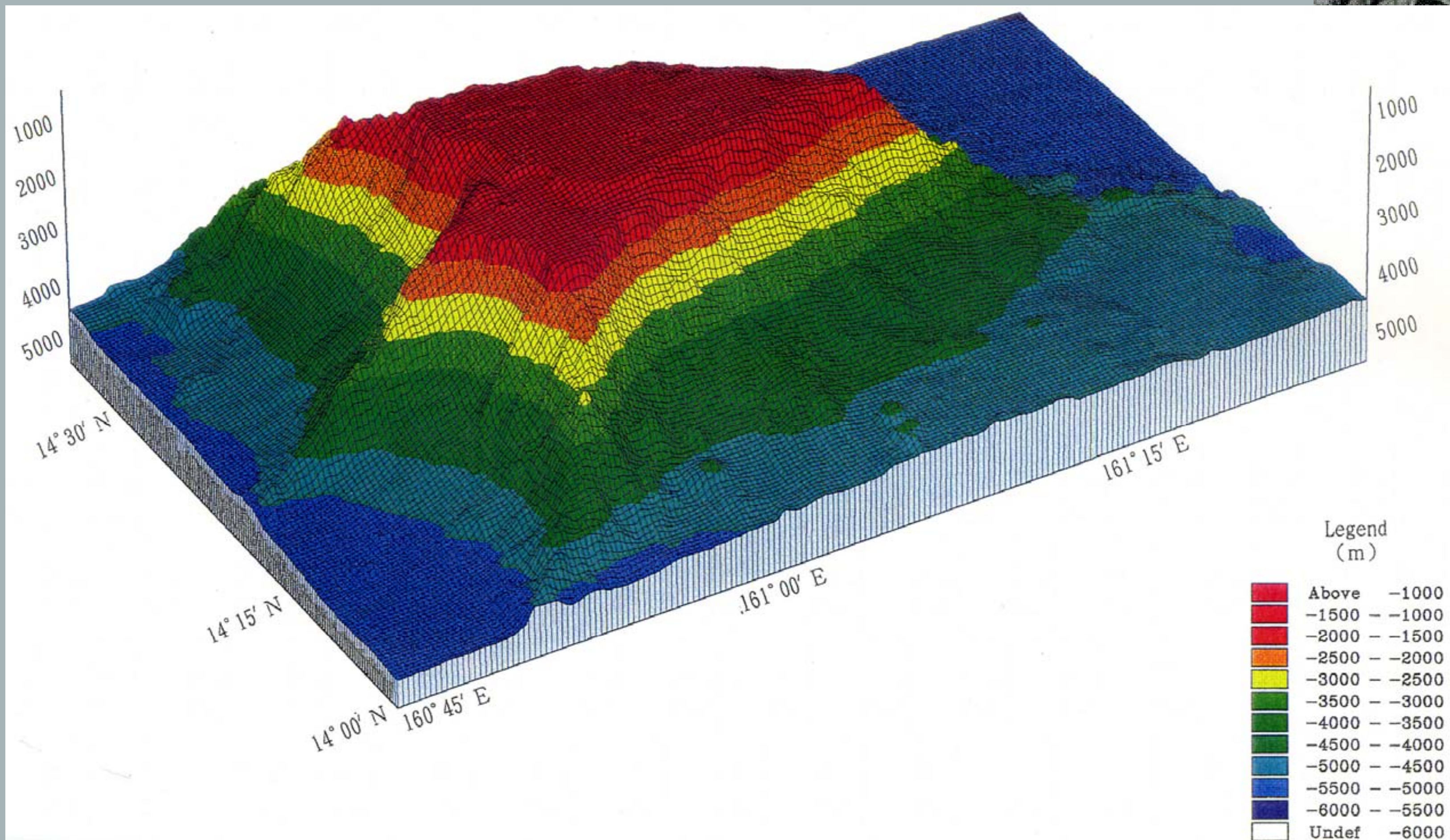


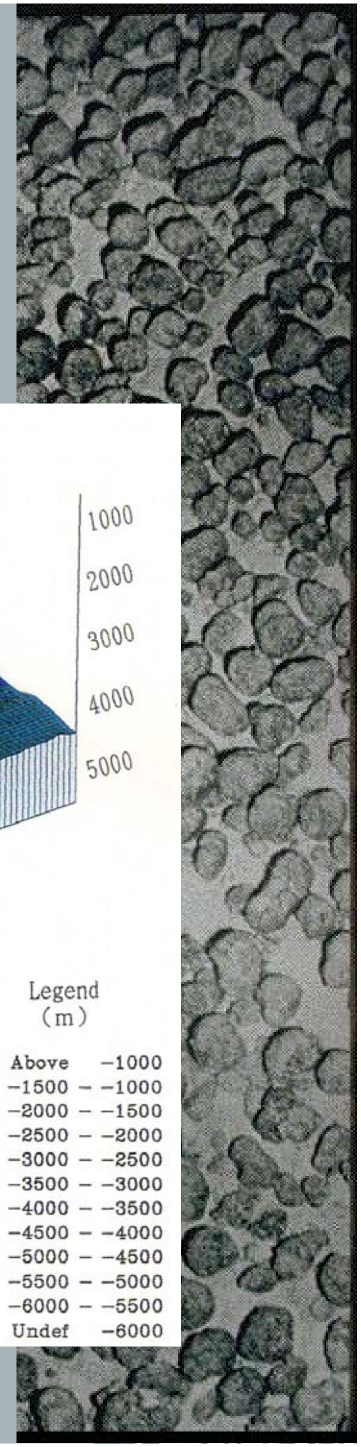
μmol/kg
0
100
200
nmol/kg for (Mn)
μmol/kg for (PO_4)
0
1
2
3
4
Depth (km)
0
1
2
3
4
5
OMZ
O_2
Mn
PO_4



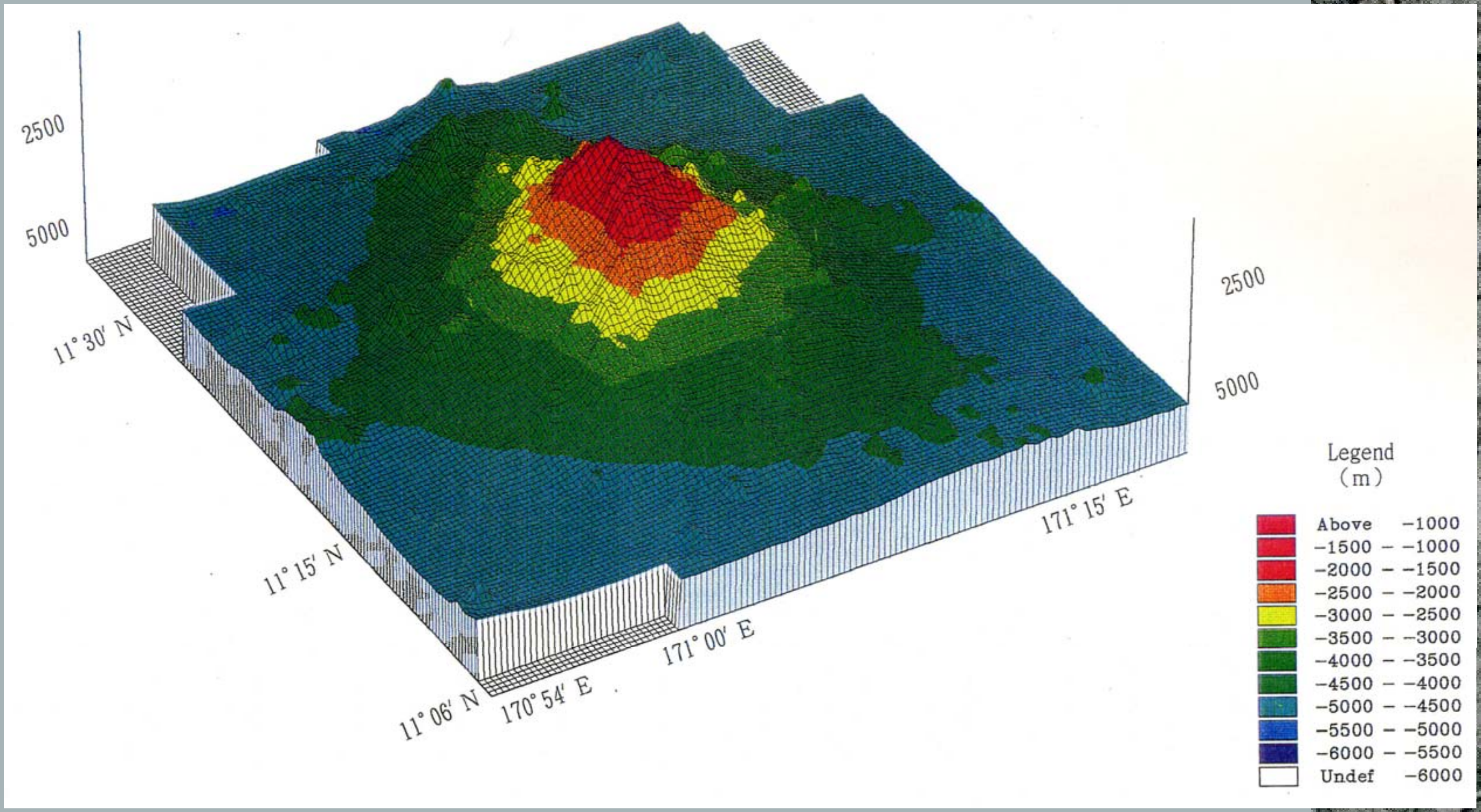
56 kilometers long
Terraces: smooth and rough
Large area above 2500 m
Debris apron

Typical Guyot



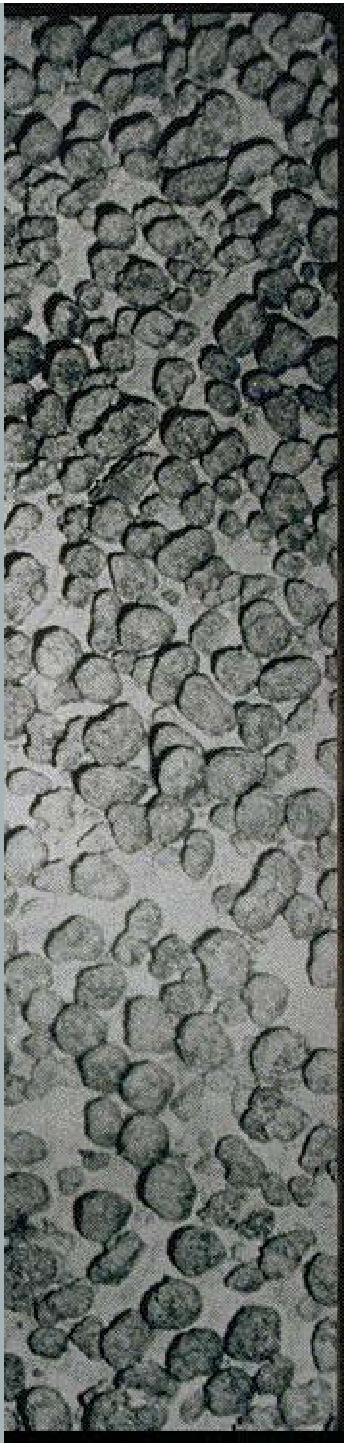


Typical Conical Seamount

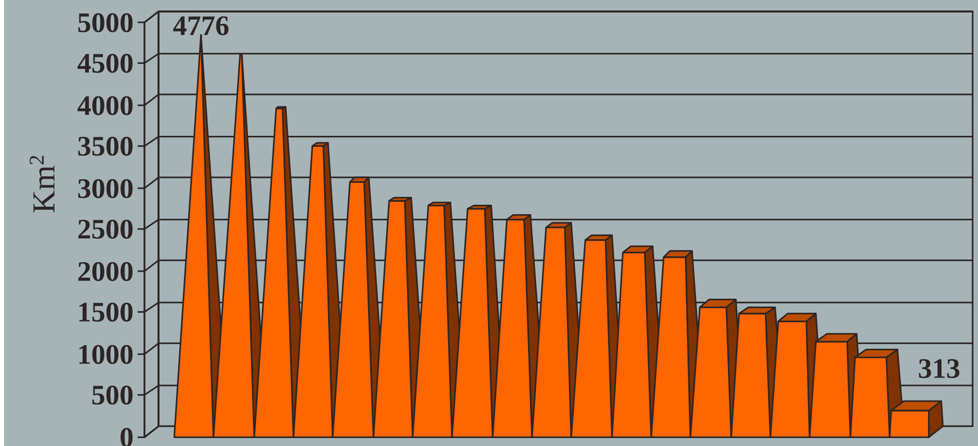


Area Calculation Details

- *Surface area of 34 seamounts calculated*
- *ArcMap's 3-D analyst used for area calculations*
- *Sediment vs. hard-rock calculated from side-scan sonar back-scatter images*



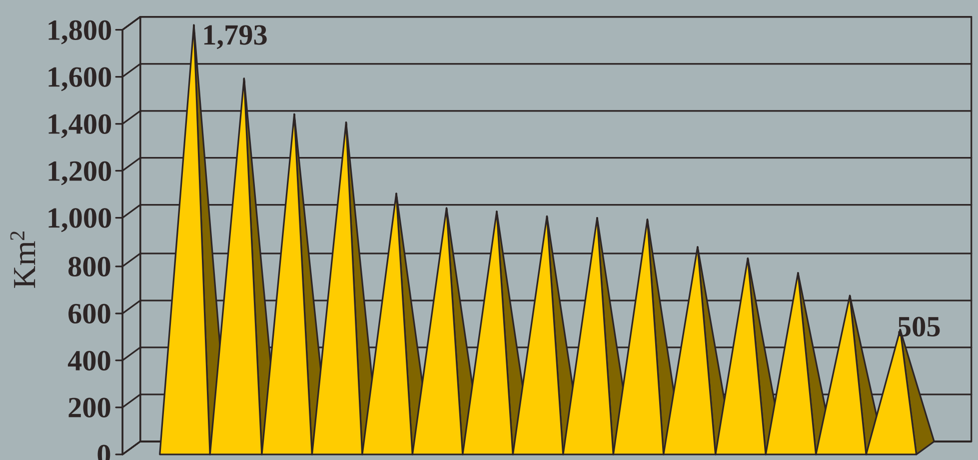
Total Surface Area of 19 Central Pacific Guyots

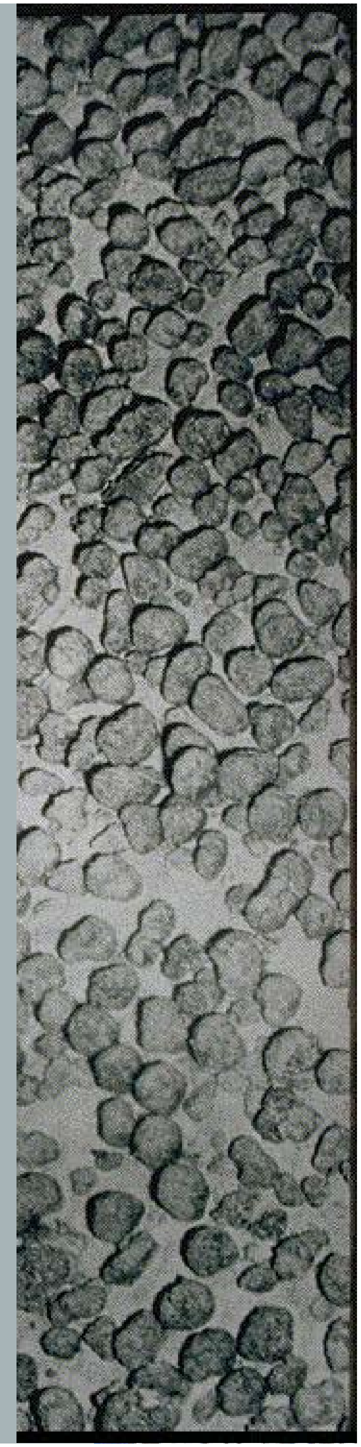


77 km²/yr mining area
1,540 km²/20 yrs mining site
7,500 km² for exploration for mine sites

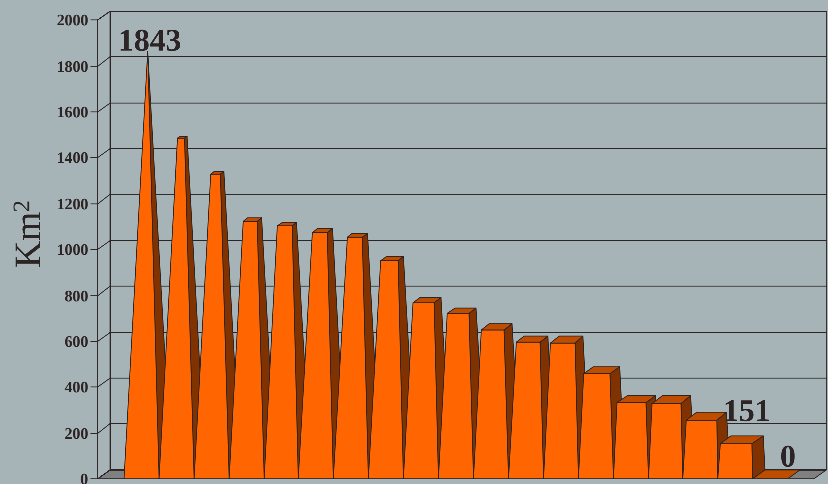
Total surface area of 34 seamounts: 62,250 km²
Geographic area hosting 34 seamounts: 506,000 km²

Total Surface Area of 15 Central Pacific Conical Seamounts





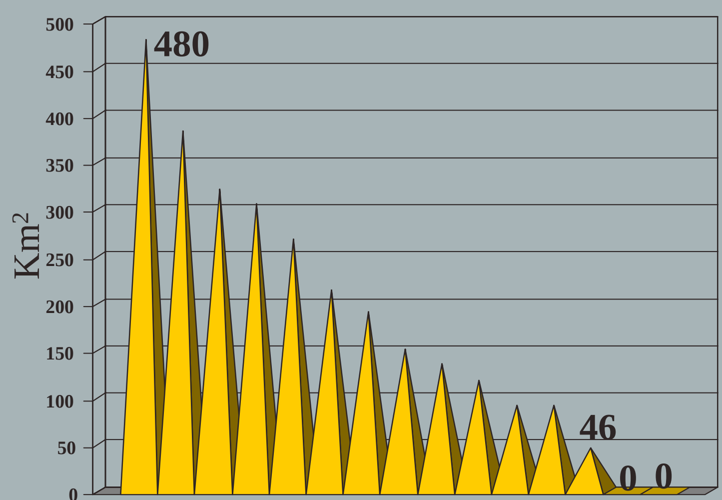
Total Surface Area of 19 Guyots above 2500 m water depth

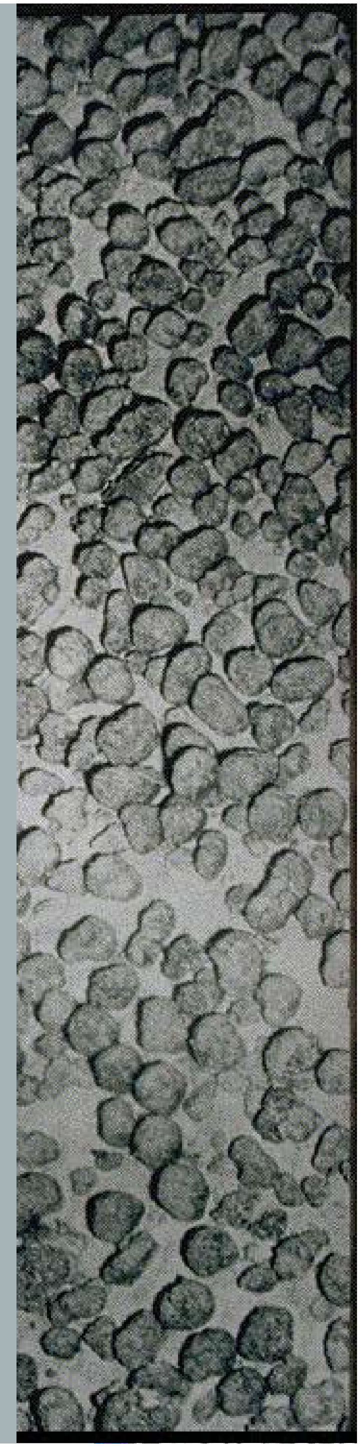


77 km²/yr mining area
1,540 km²/20 yrs mining site
7,500 km² for exploration for mine sites

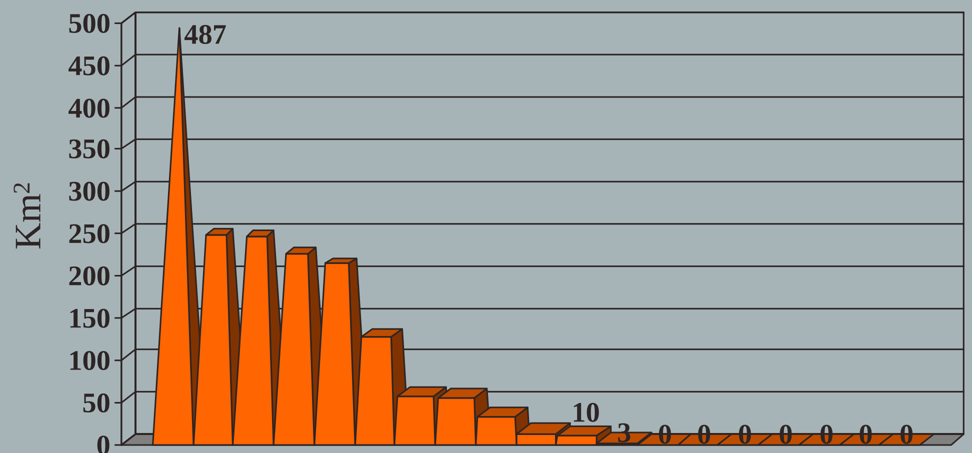
Total surface area of 34 seamounts above
2500 m: 17,470 km²

Total Surface Area of 15 Conical Seamounts above 2500 m water depth





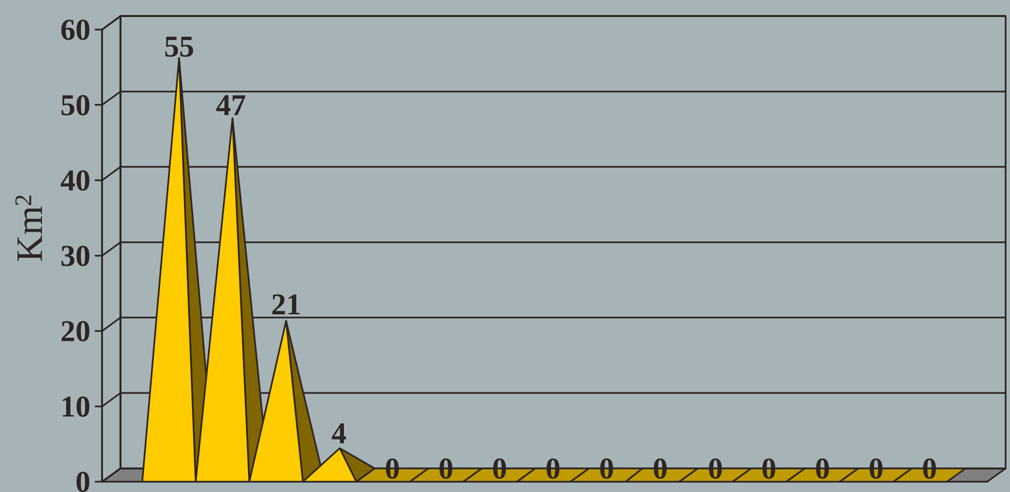
Total Surface Area of 19 Central Pacific Guyots above 1500 m water depth

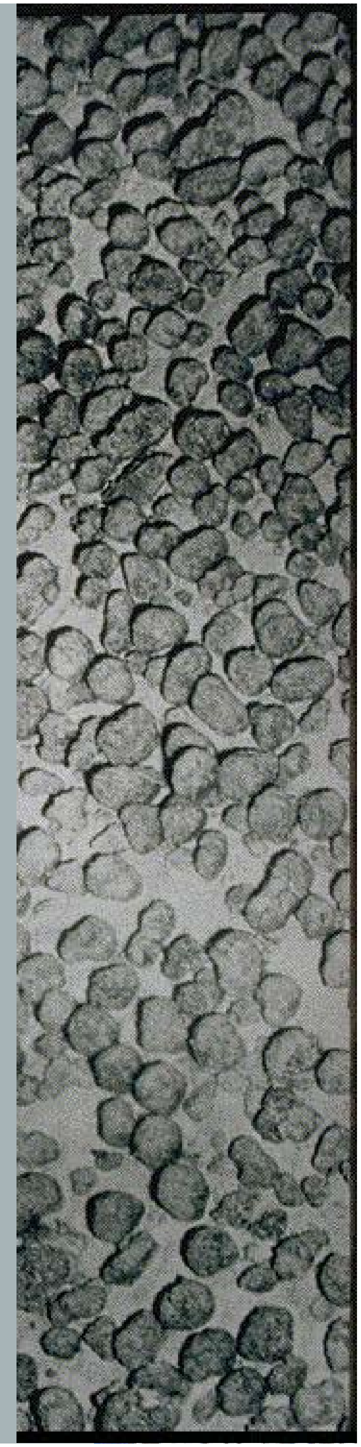


77 km²/yr mining area
1,540 km²/20 yrs mining site
7,500 km² for exploration for mine sites

Total surface area of 34 seamounts above 1500 m: 1,839 km²

Total Surface Area of 15 Conical Seamounts above 1500 m water depth





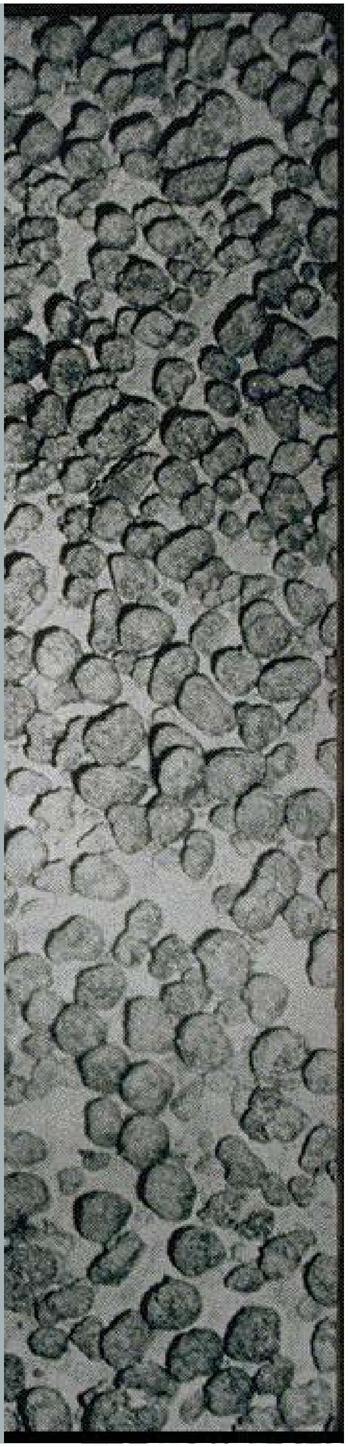
Average Seamount

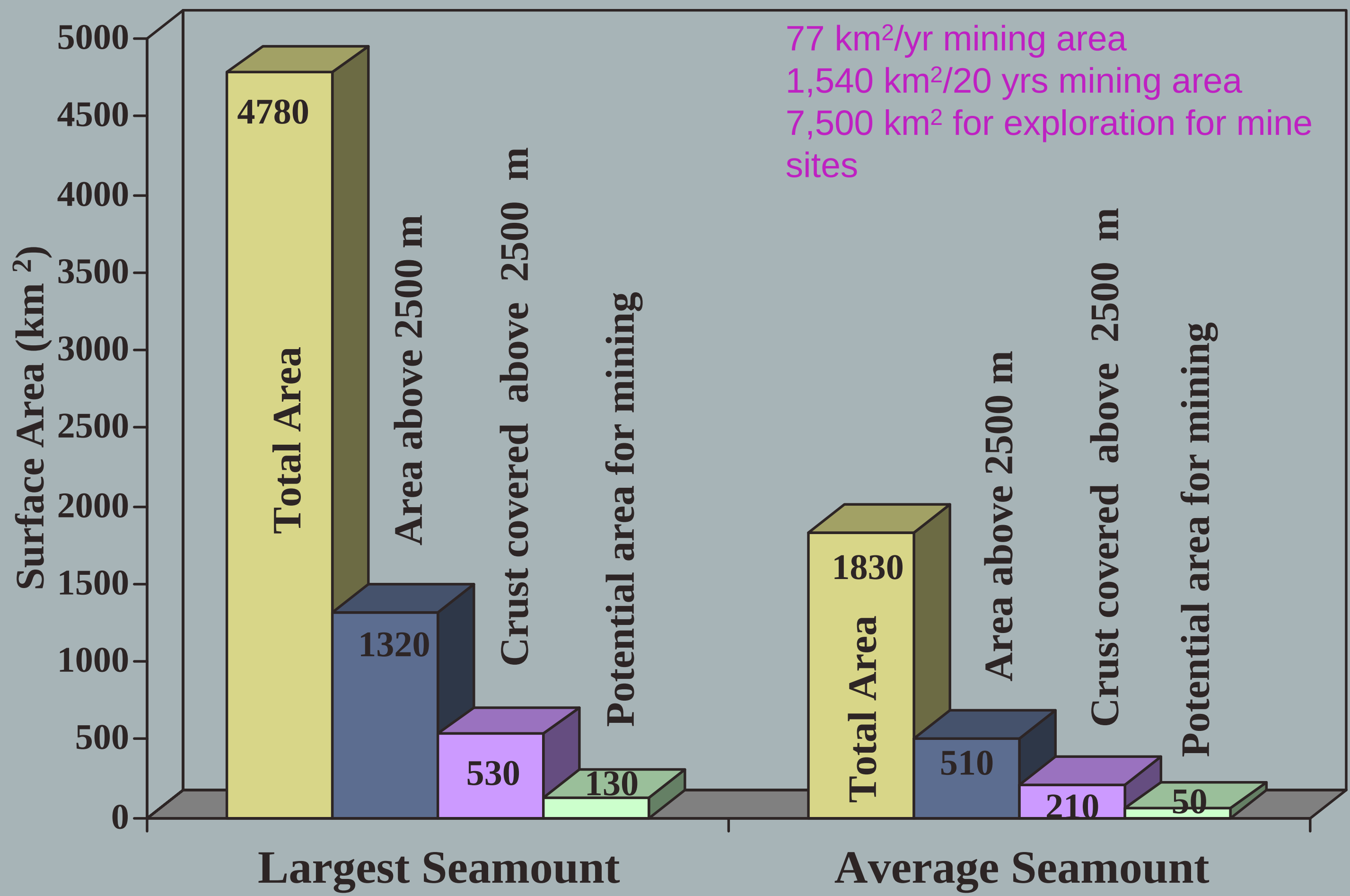
(Surface Area Statistics for 34 Seamounts)

	Total Surface Area (km^2)	*Surface Area above 2500m water depth (km^2)*
Mean	1,850	515
Median	1,450	325
SD[1]	1,150	470
Minimum	310	0
Maximum	4,775	1,843

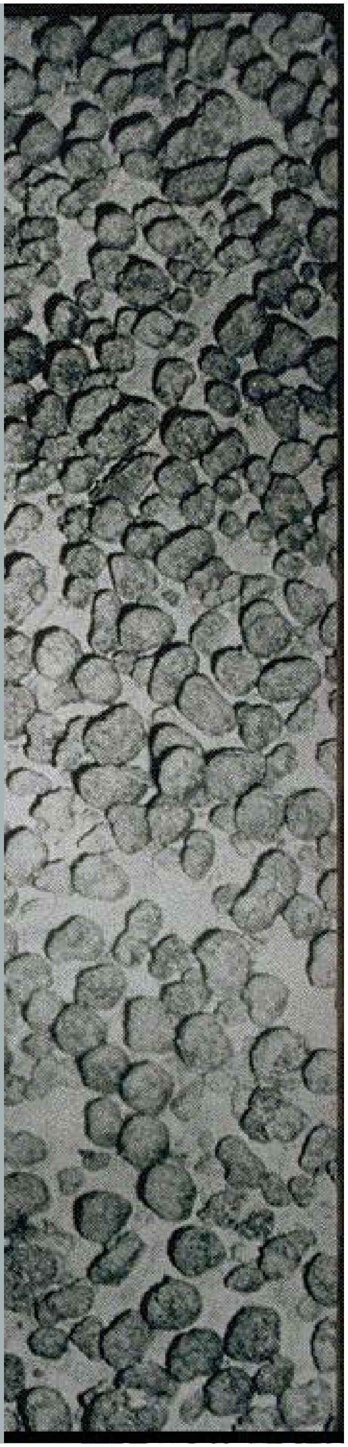
[1] Standard Deviation

77 km^2/yr mining area
1,540 km^2/20 yrs mining area
7,500 km^2 for exploration for mine sites

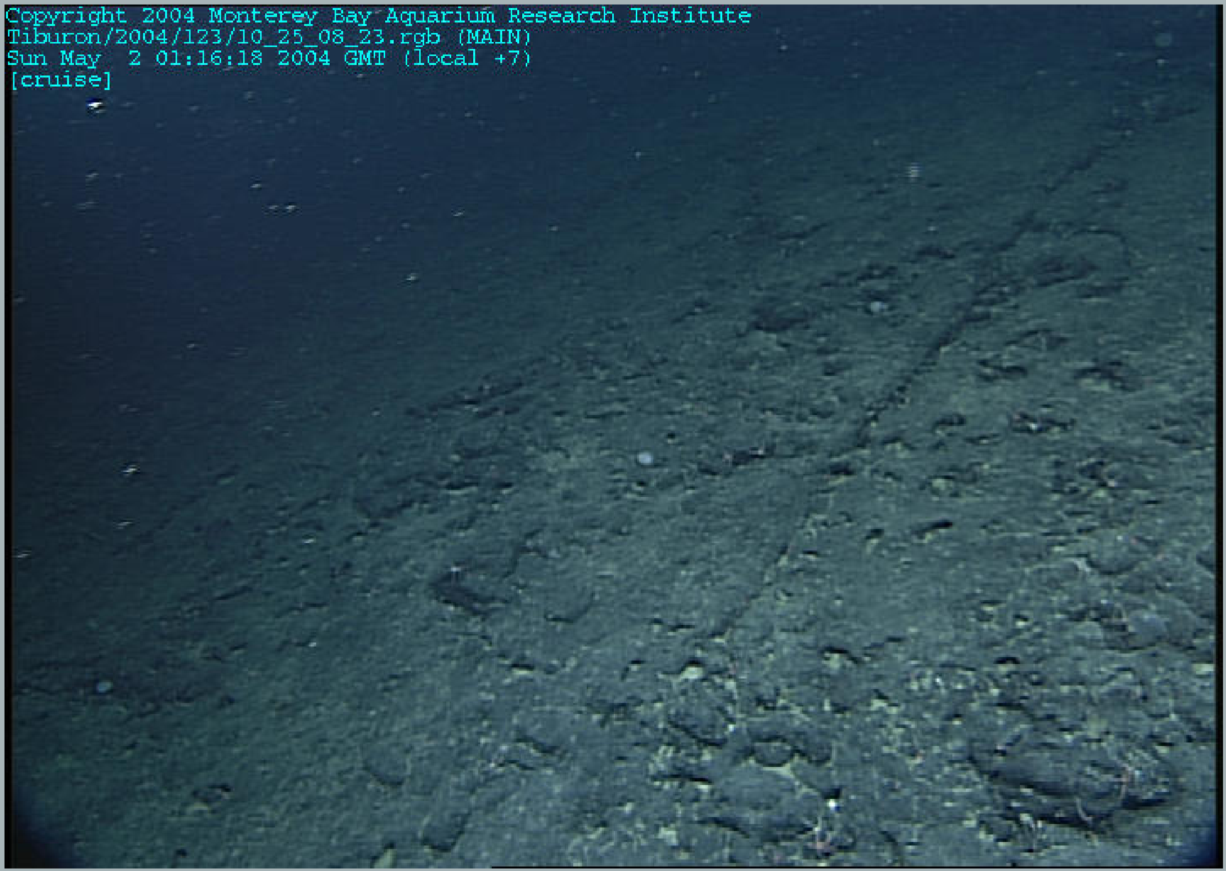


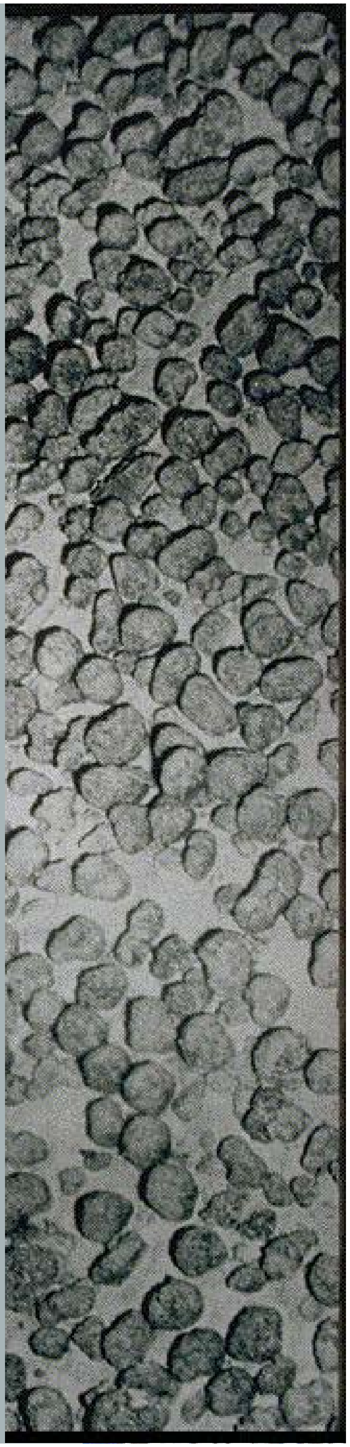


77 km²/yr mining area
1,540 km²/20 yrs mining area
7,500 km² for exploration for mine sites
Surface Area (km 2)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Total Area
4780
Area above 2500 m
1320
Crust covered above 2500 m
530
Potential area for mining
130
Total Area
1830
Area above 2500 m
510
Crust covered above 2500 m
210
Potential area for mining
50
Largest Seamount
Average Seamount

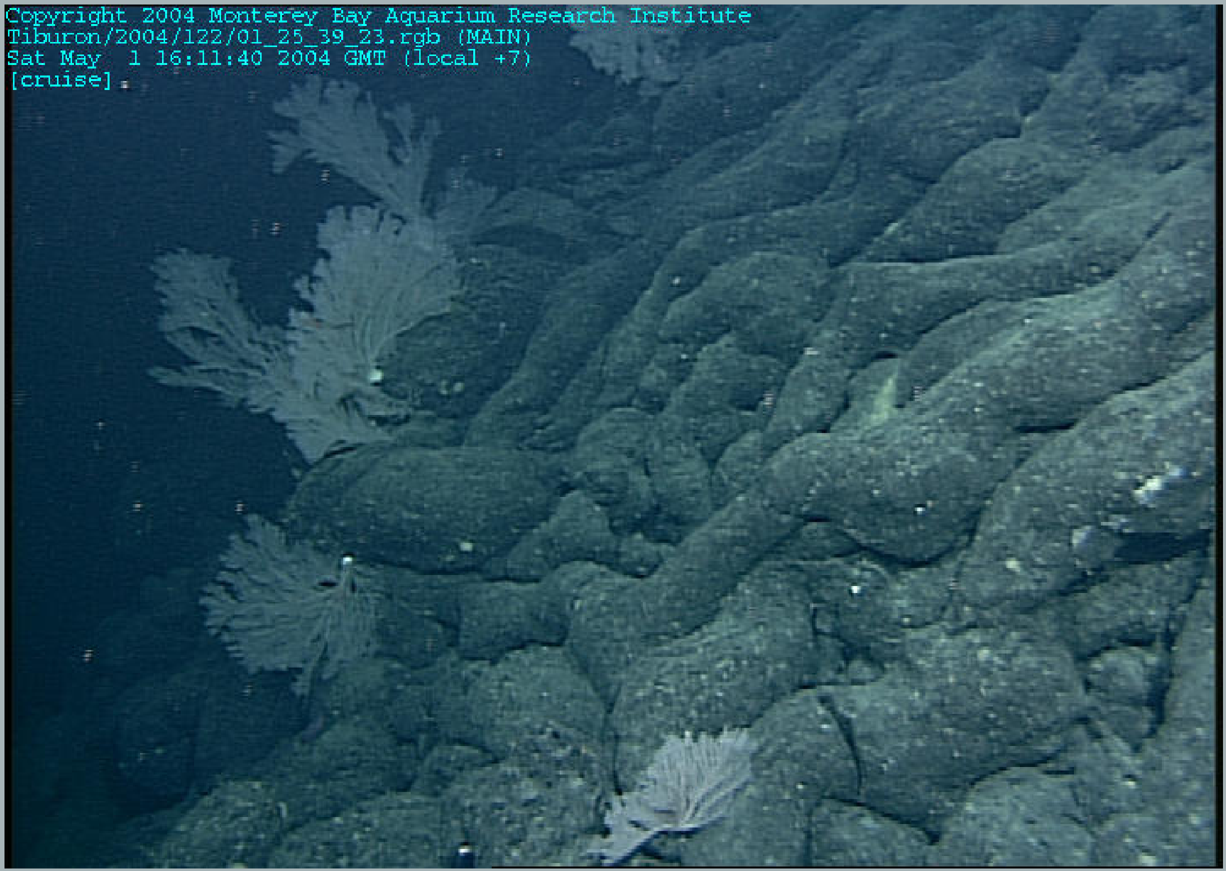


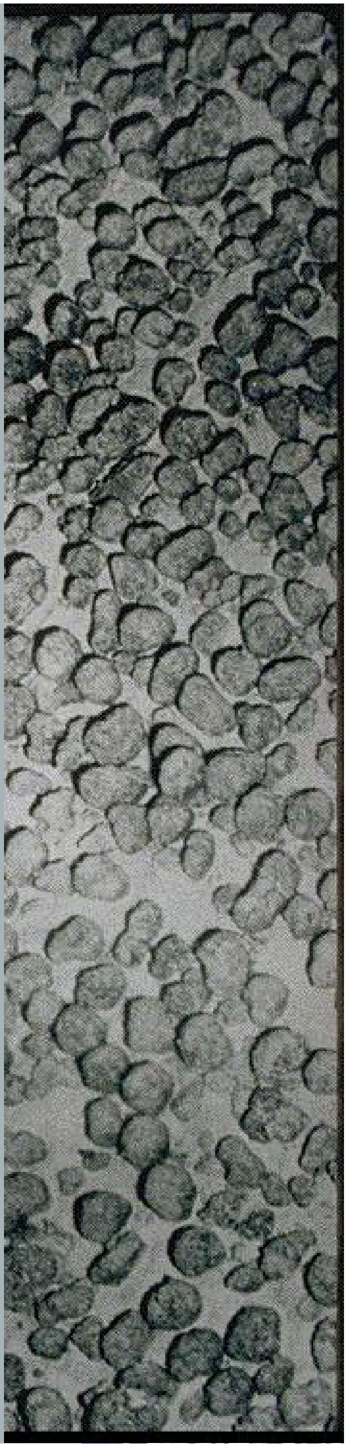
Example of smooth seafloor and crust pavement





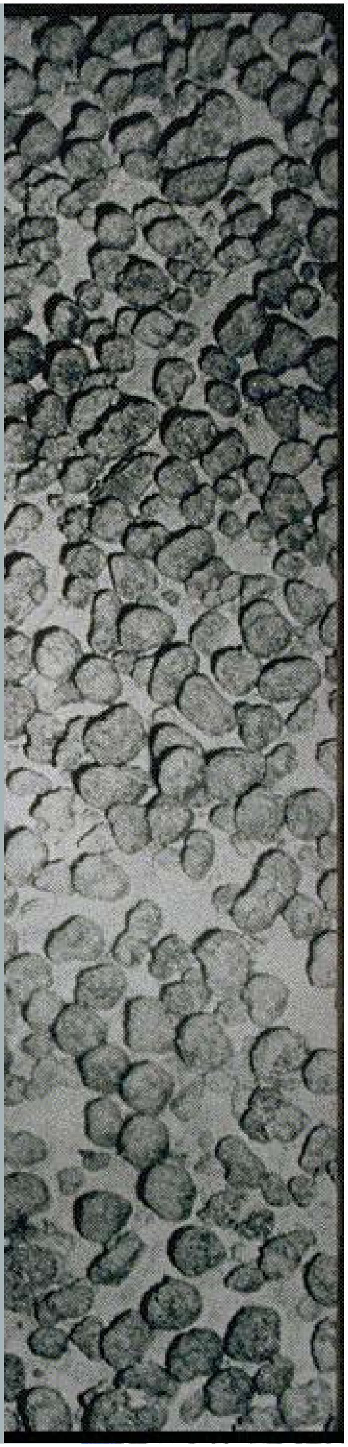
Example of rough seafloor with crusts





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 km*^{2}
- *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*



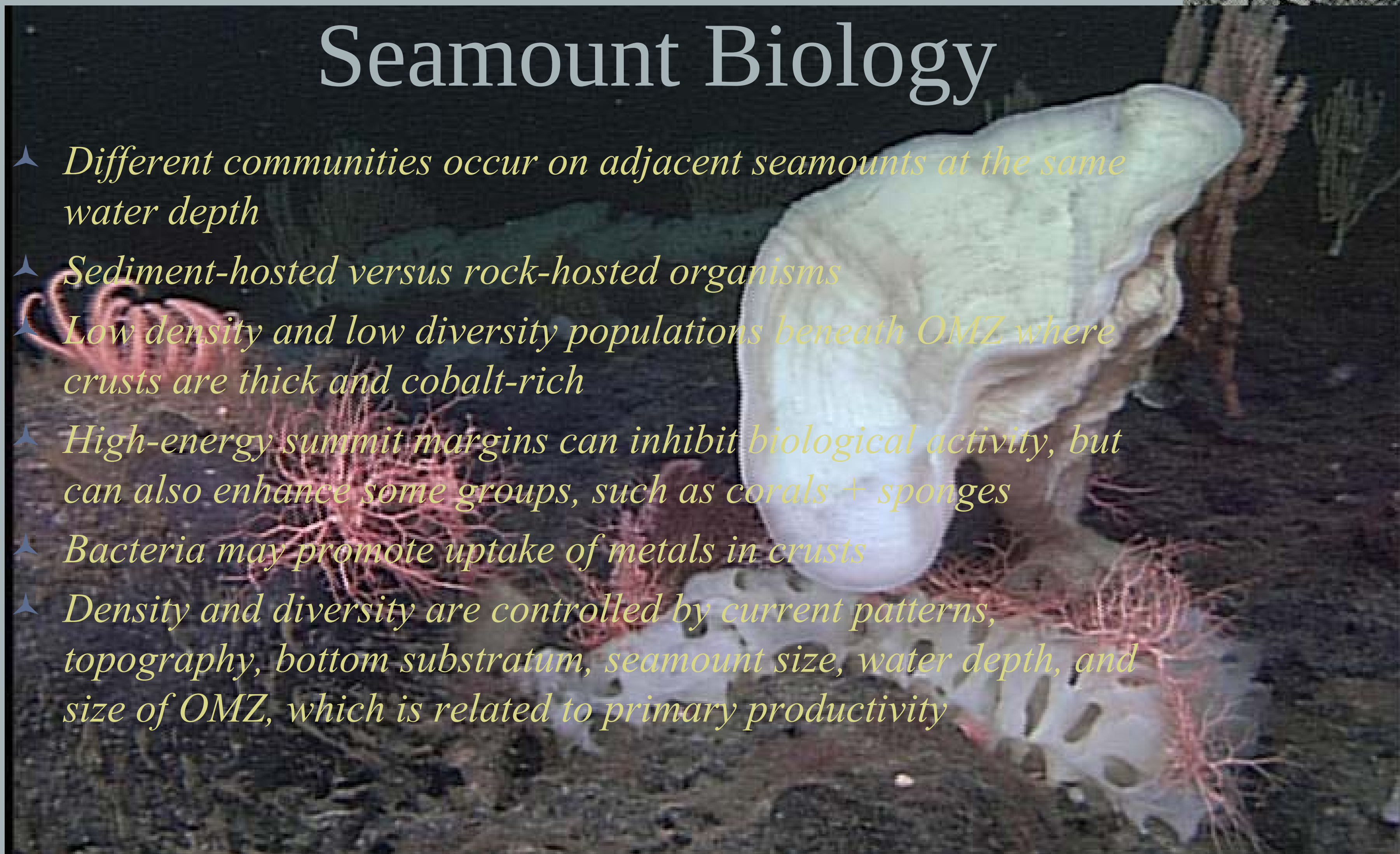
Types of Seamount Generated Currents

- *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*

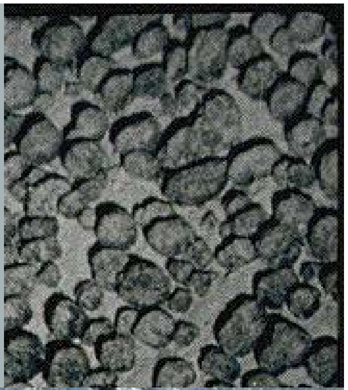
Seamount Biology

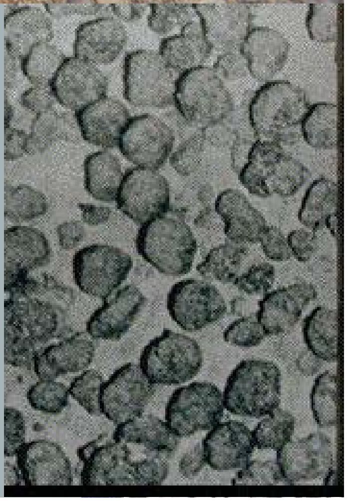


- *Different communities occur on adjacent seamounts at the same water depth*
- *Sediment-hosted versus rock-hosted organisms*
- *Low density and low diversity populations beneath OMZ where crusts are thick and cobalt-rich*
- *High-energy summit margins can inhibit biological activity, but can also enhance 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*

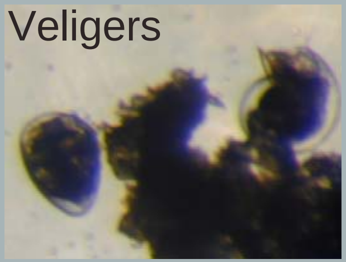
Dispersal and colonization

- 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.





Veligers



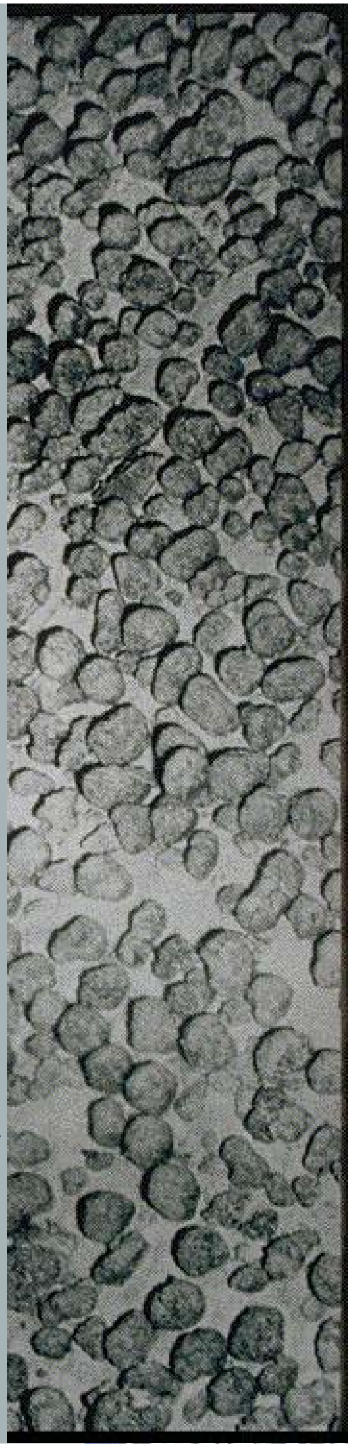
Protoconch

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*

There is greater similarity between Alice Springs and the Forecast field in the back arc than adjacent seamounts in the Arc!



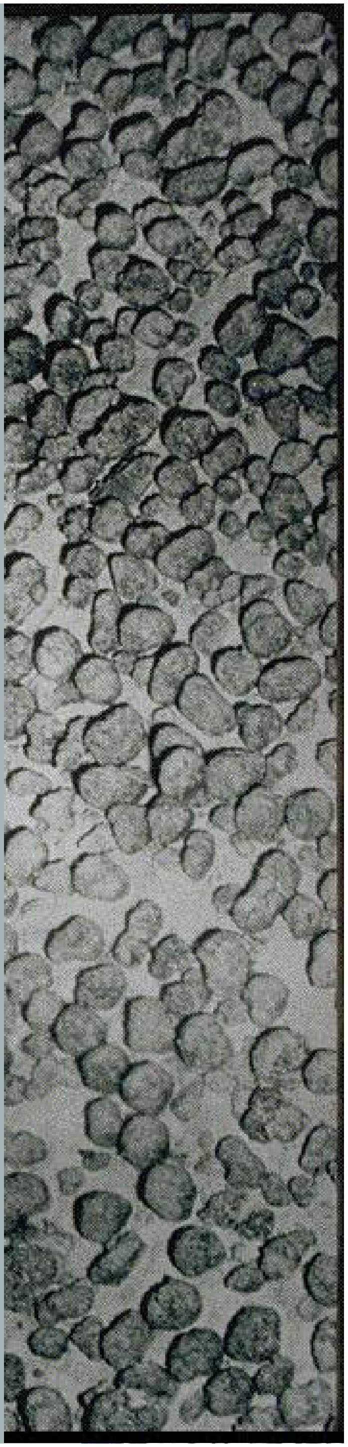
NEW RESOURCES FOR COORDINATION OF SEAMOUNT BIOLOGY:

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

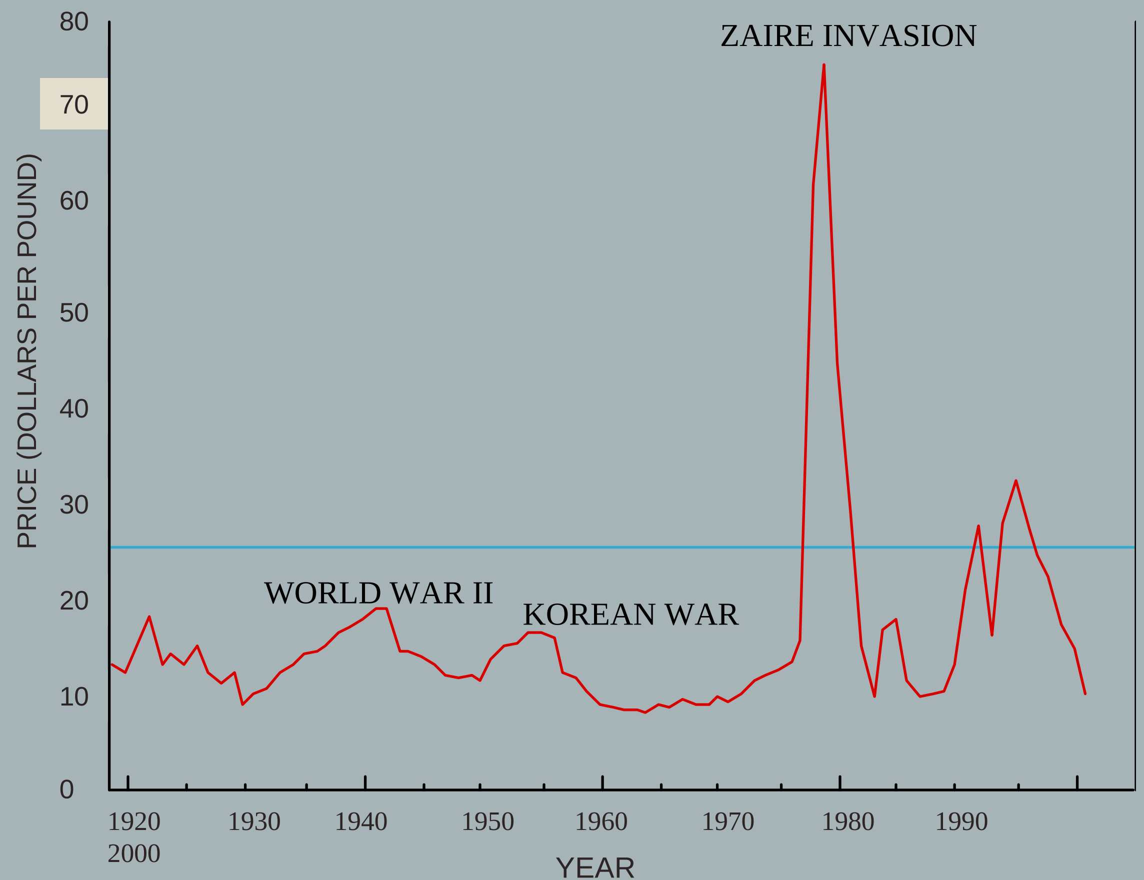
Global census of marine life on seamounts (CenSeam) (http://censeam.niwa.co.nz)

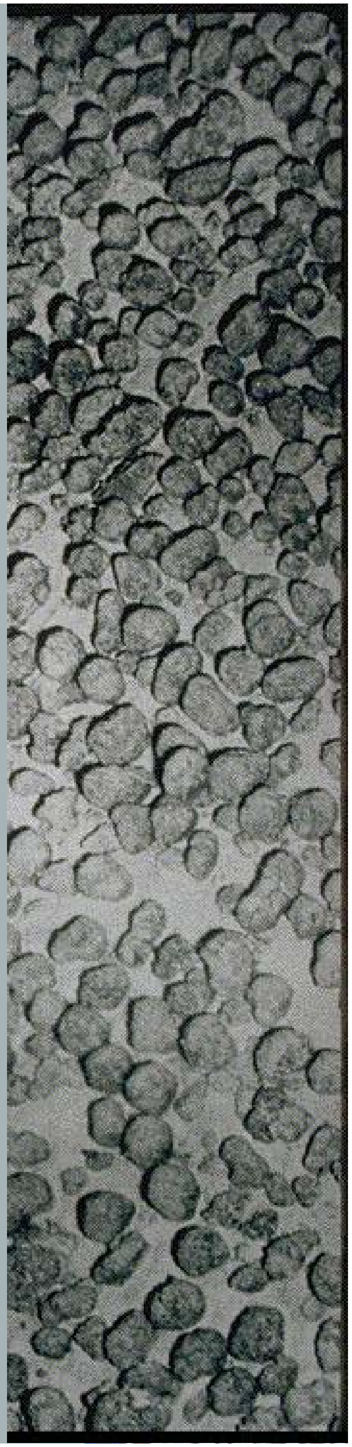
SeamountsOnline (http://seamounts.sdsc.edu/about_projects.html)

Biogeosciences Network (SBN) (http://earthref.org/events/SBN/2006/index.html)



AVERAGE COBALT PRICES 1919 - 2001
(in 2000 US Dollars)





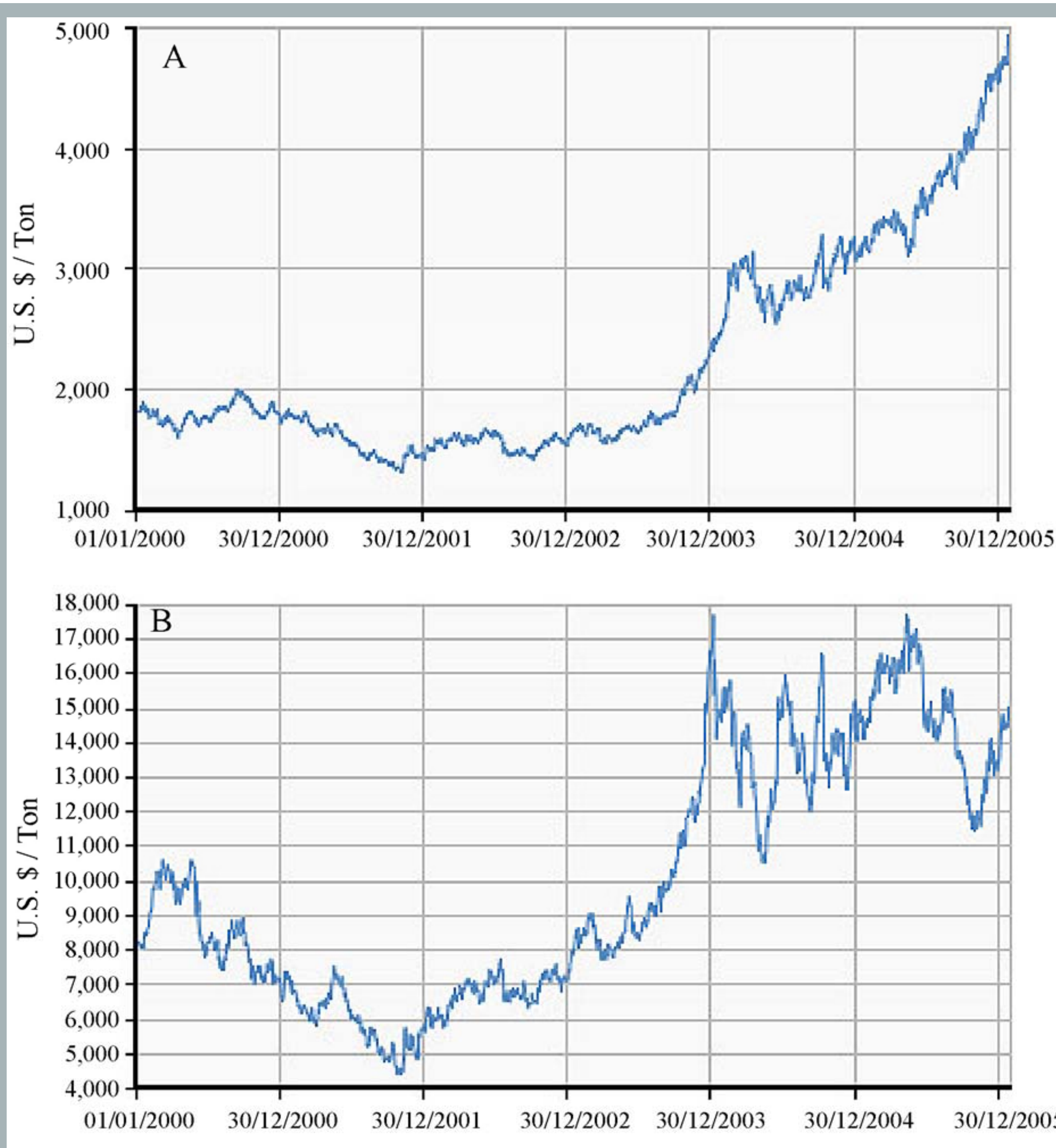
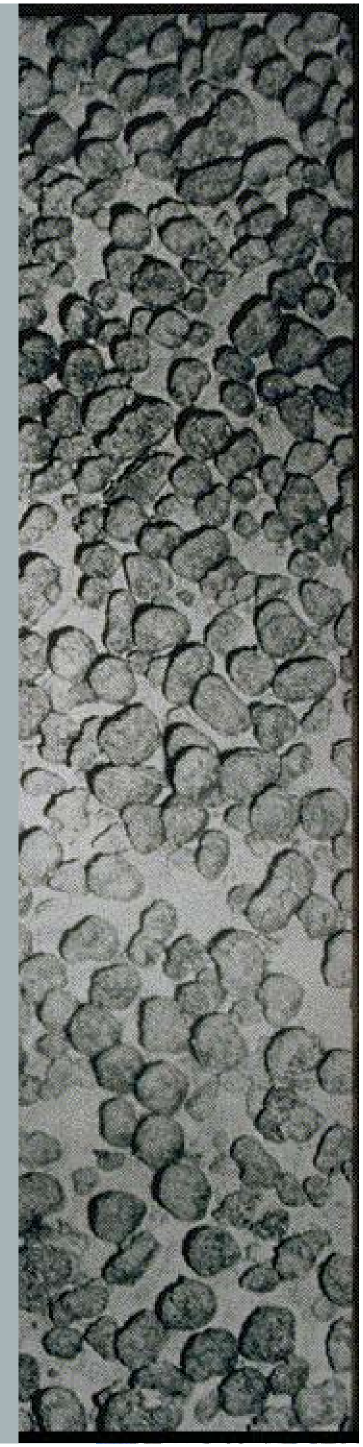
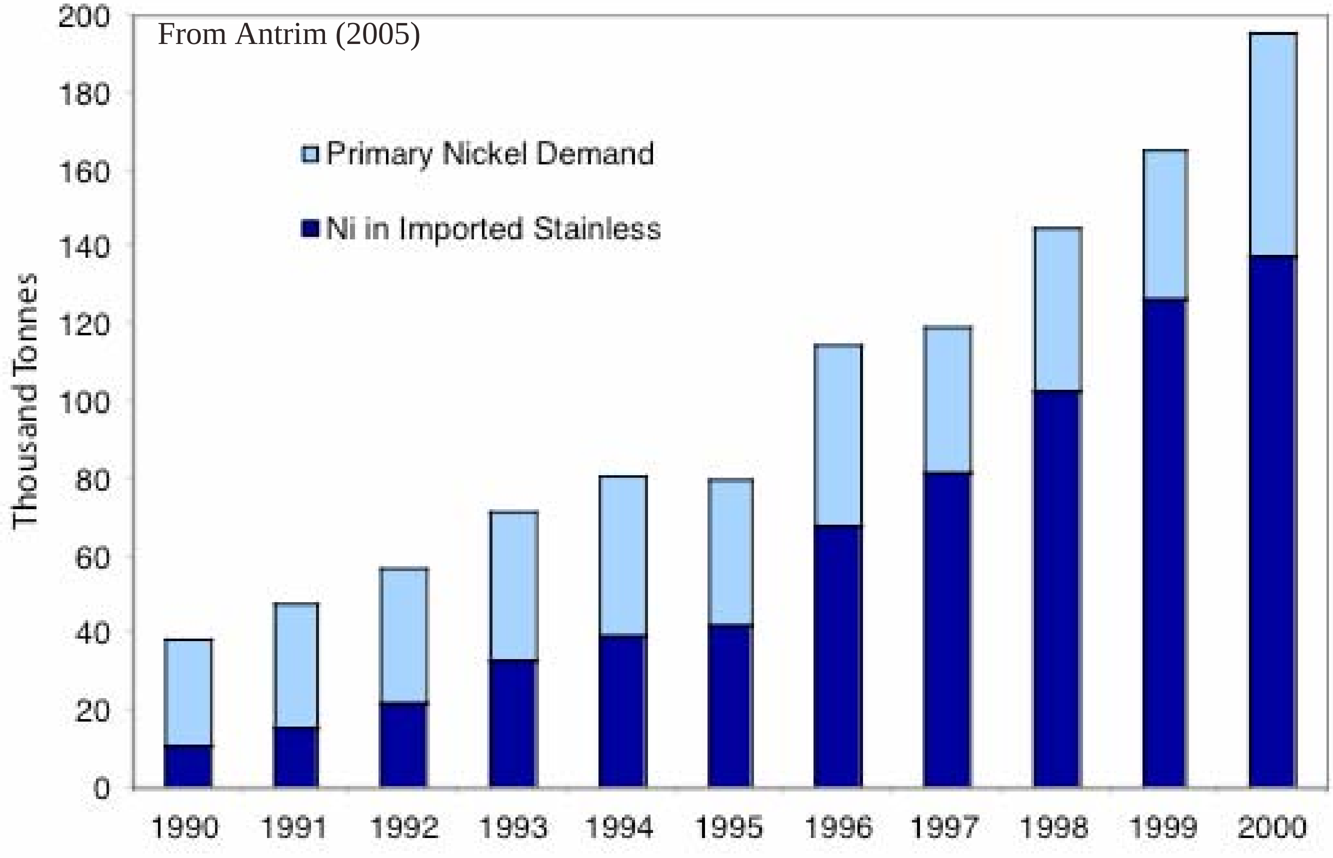


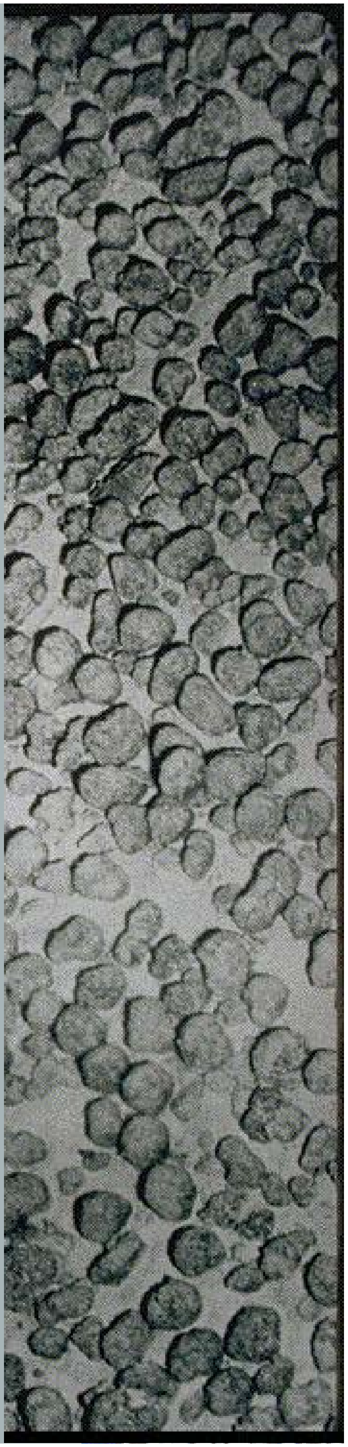
Figure 11. Price of copper (A) and nickel (B) on the London Metal Exchange for the period 1 January 2000 through 1 February 2006



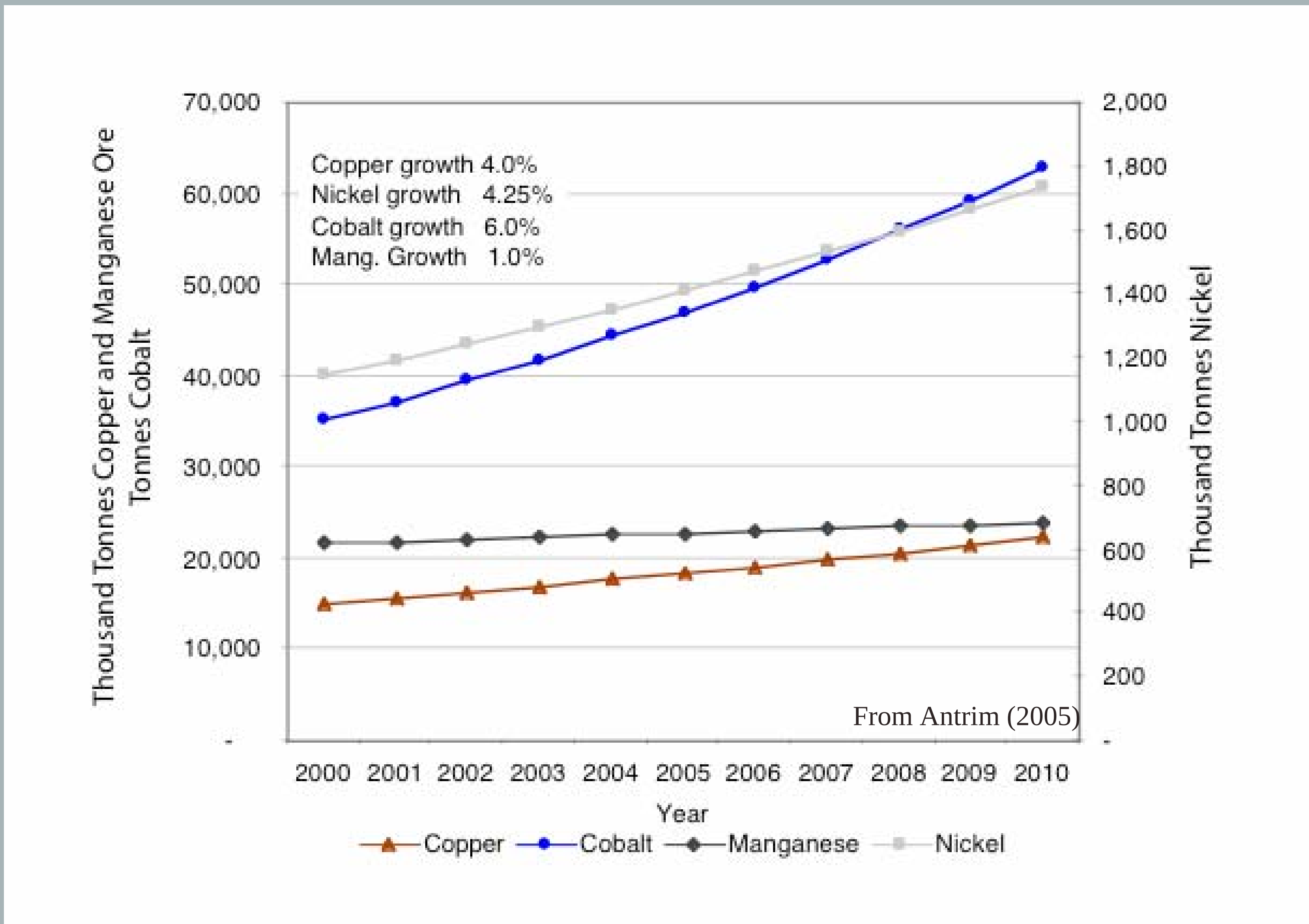
Ni consumption increased five fold in 10 years and continues to grow



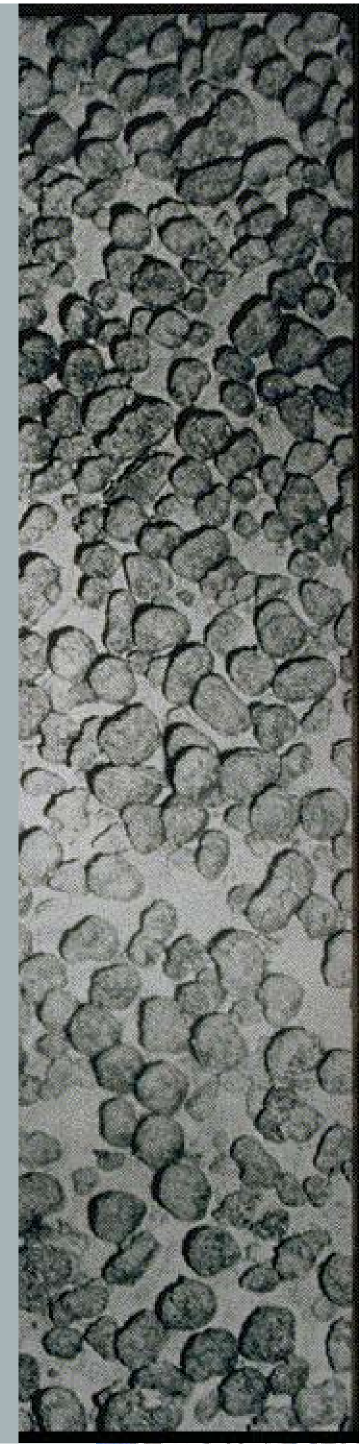
Primary and Indirect Nickel Consumption in China



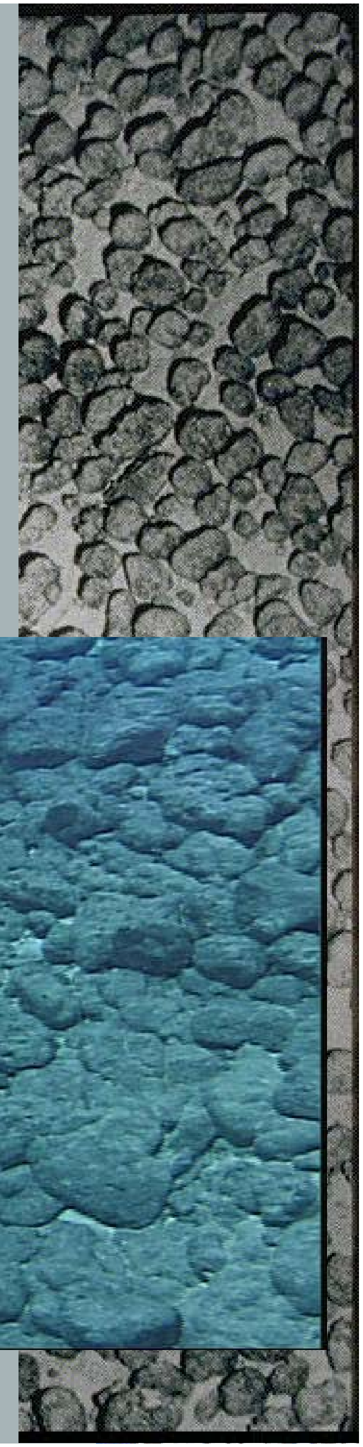
Projected world consumption of select metals



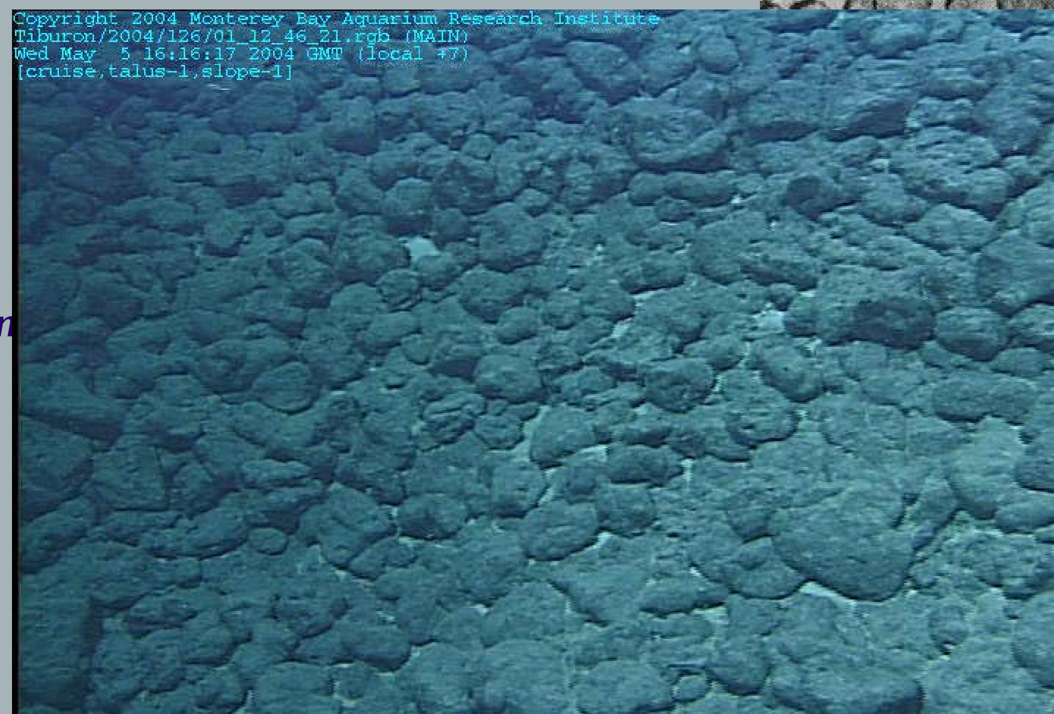
From Antrim (2005)



Global Tonnage and Area of Ferromanganese Crusts

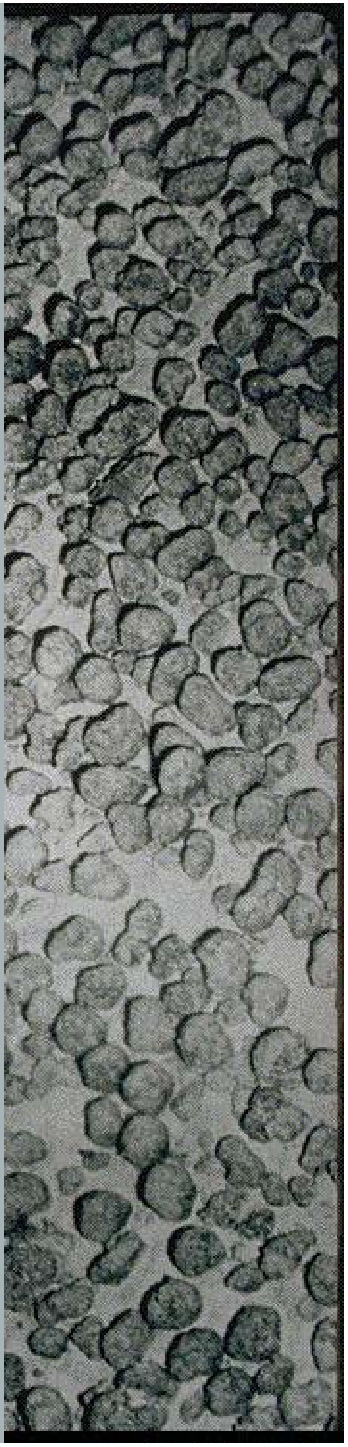


- ***Area of seafloor with crusts: 6.35 million km^2***
- ***Total dry bulk mass of crusts: 200 billion tonnes (2 x 10^{11} tonnes)***
- ***Total amount of cobalt metal: 1 billion (10^9) tonnes***



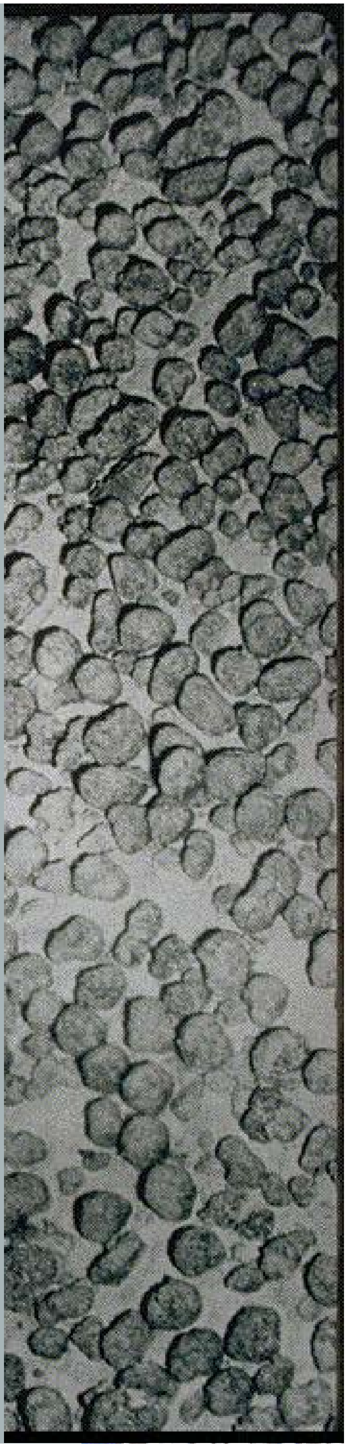
Value of Metals in 1 Metric Ton of Fe-Mn Crust from the Central-equatorial Pacific

	Mean price of metal (1999 $/Kg)	Mean Content in Crusts (g/ton)*	Value per Metric Ton of Ore ($)
Cobalt	39.60	6899	273.20
Titanium	7.70	1,2035	92.67
Cerium	28.00	1605	44.94
Zirconium	44.62	618	27.58
Nickel	6.60	4125	27.23
Platinum	13024.00	0.5	6.51
Molybdenum	8.80	445	3.92
Tellurium	44.00	60	2.64
Copper	1.65	896	1.48
Tungsten	5.93	90.5	0.45
Total	--	--	480.62



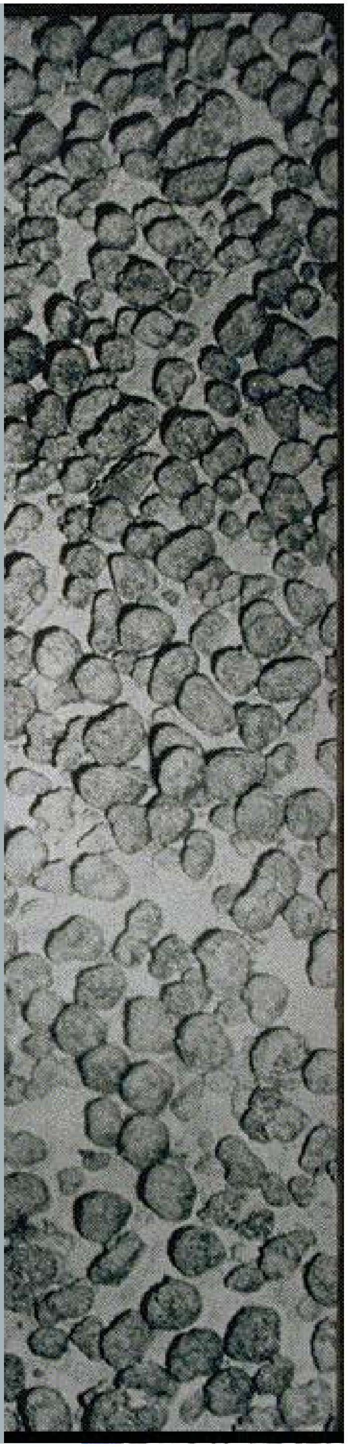
Future Research I

- 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

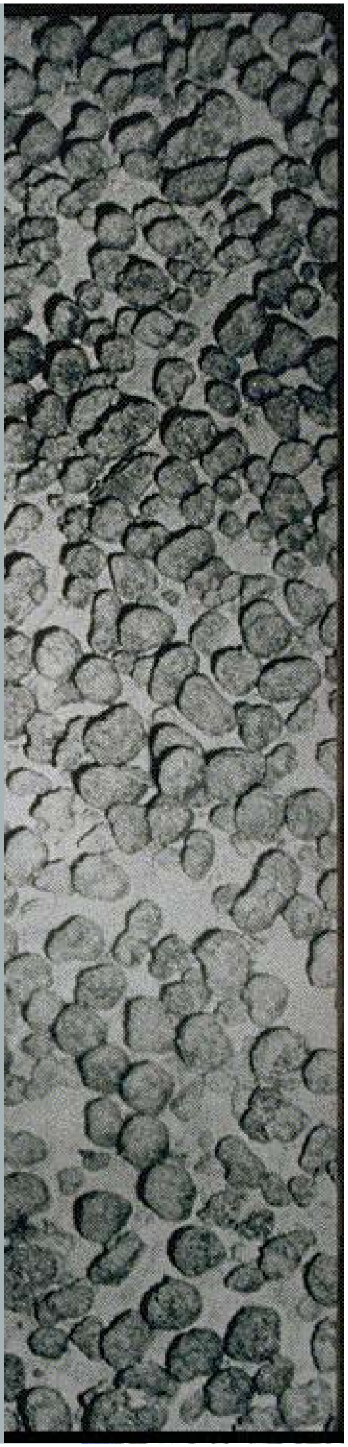
- Determine the role of microbiota in the formation and growth of crusts
- Determine the extent and significance of organic complexing of metals that compose crusts
- Determine the effects of potentially toxic metals (i.e., arsenic, thallium) that occur in Fe-Mn crusts on biota that interact with the 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



Thank You for Your Attention


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*



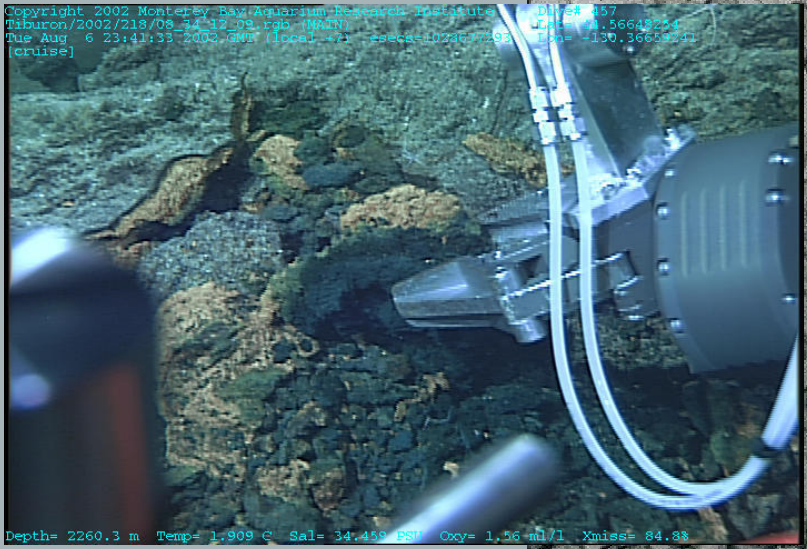
Exploration Strategy

Six Regional Criteria

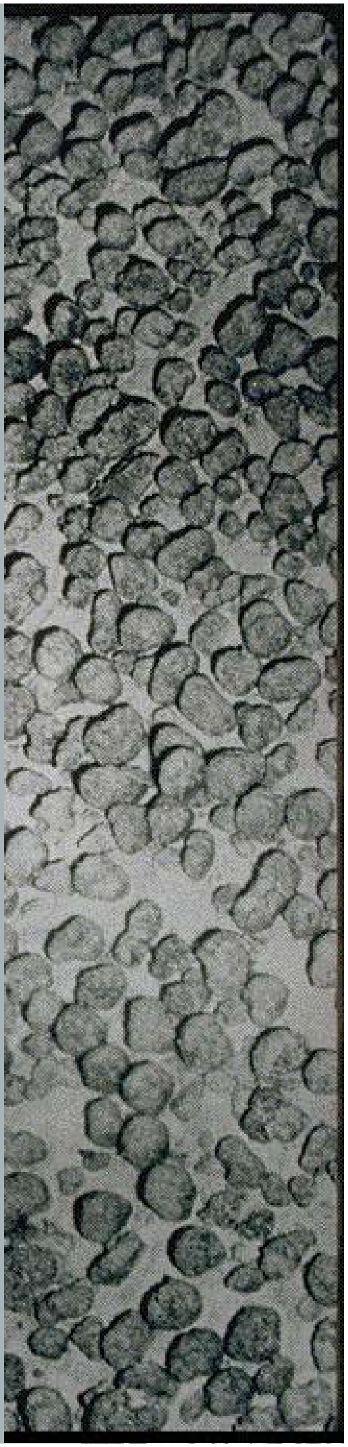
1. Large volcanic edifices as shallow as about 1500 m
2. Volcanic edifices older than about 20 Ma
3. Volcanic edifices not capped by large atolls or reefs
4. Areas of strong and persistent bottom currents
5. A shallow and well-developed oxygen-minimum zone
6. Regions isolated from input of terrigenous & 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 $\geq$40 mm
6. Cobalt contents $\geq$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*