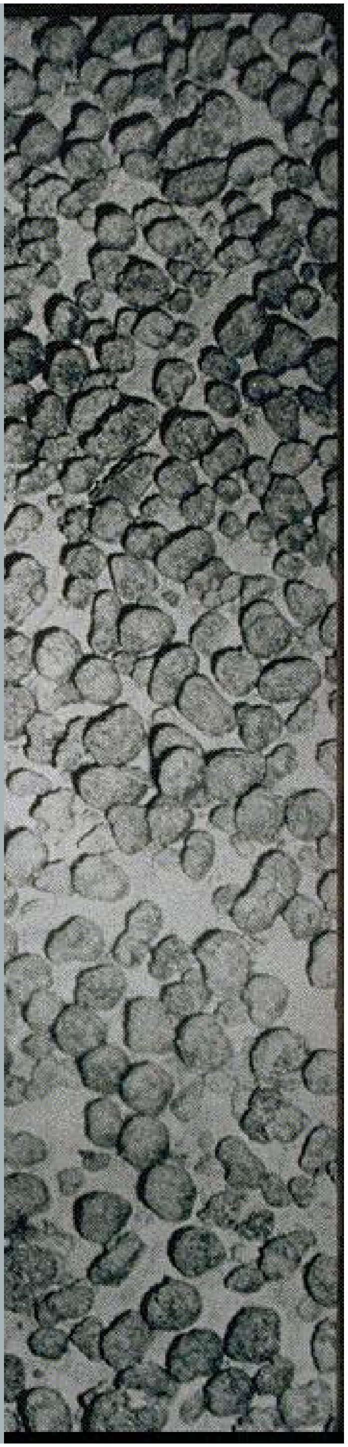
Seamounts and Cobalt-Rich Ferromanganese Crusts

James R. Hein

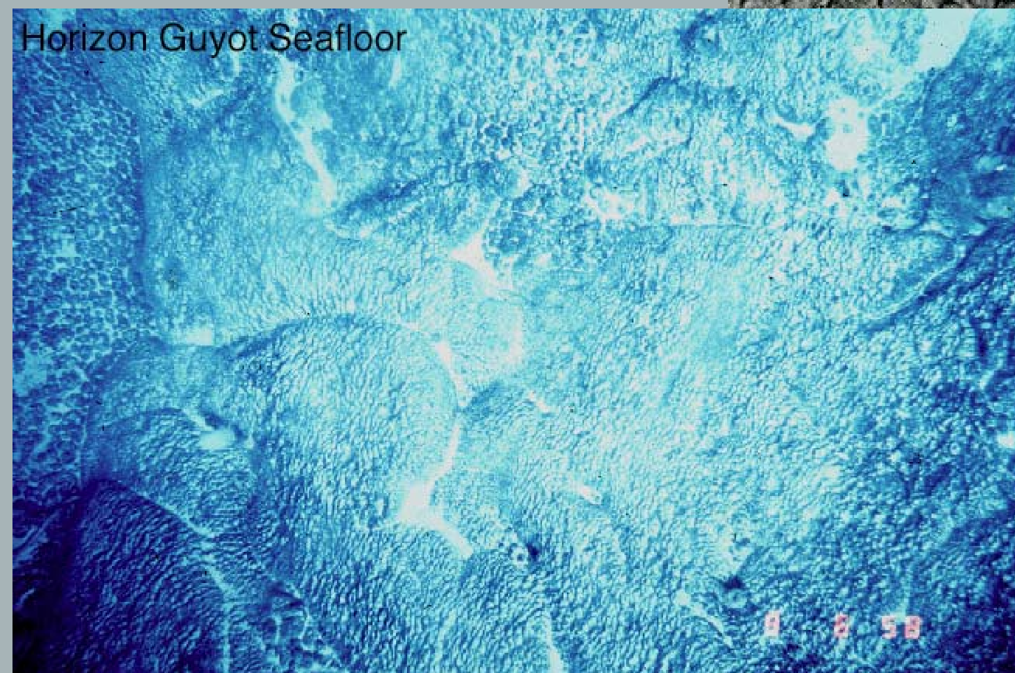
U.S. Geological Survey

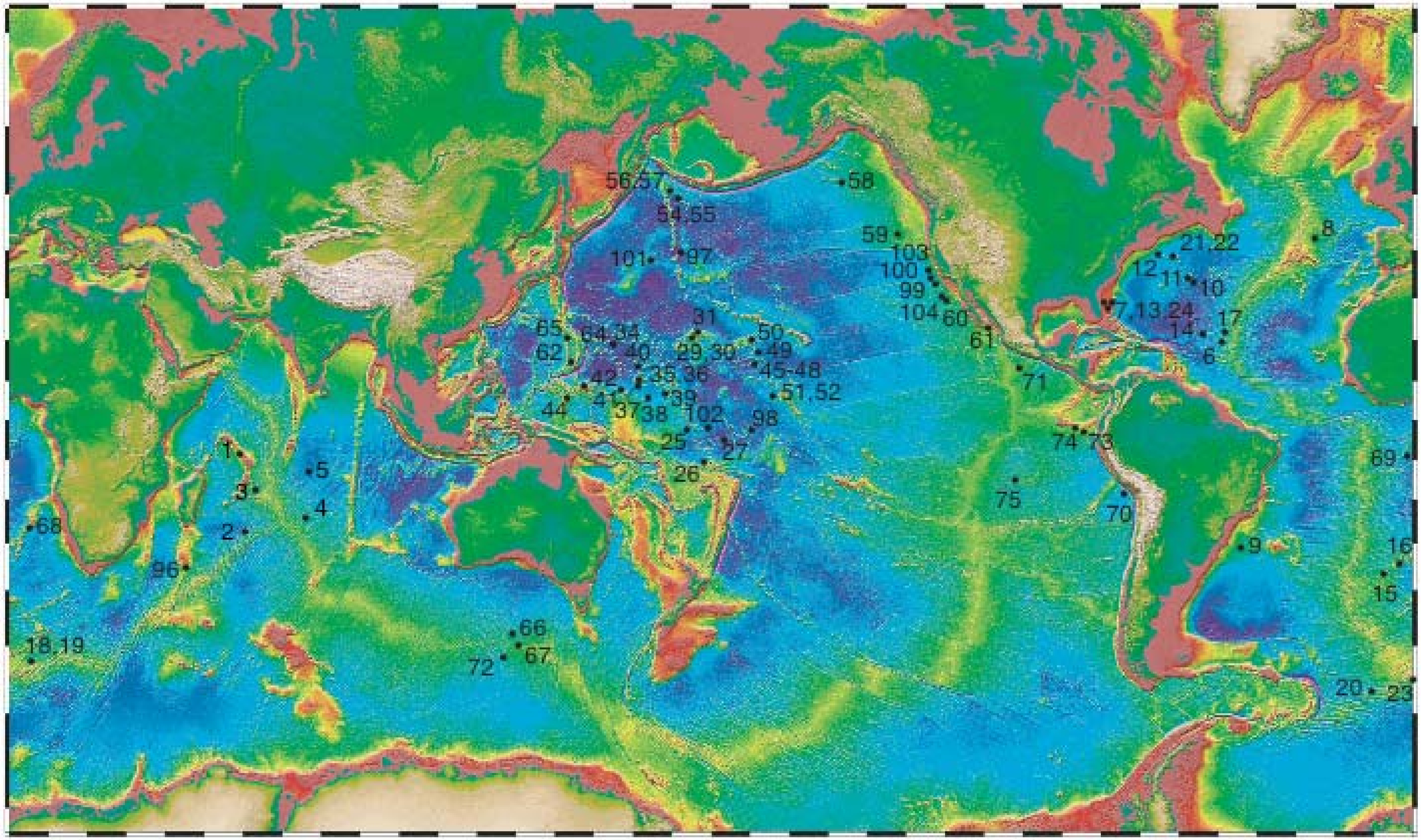
For the ISA



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 ≈1,500-2,500 m, summit outer rim*





56,57
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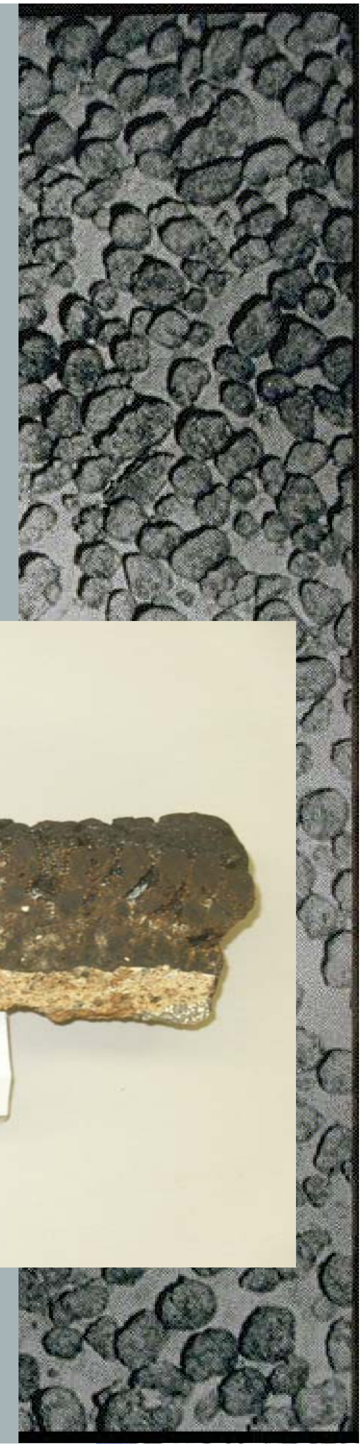
23

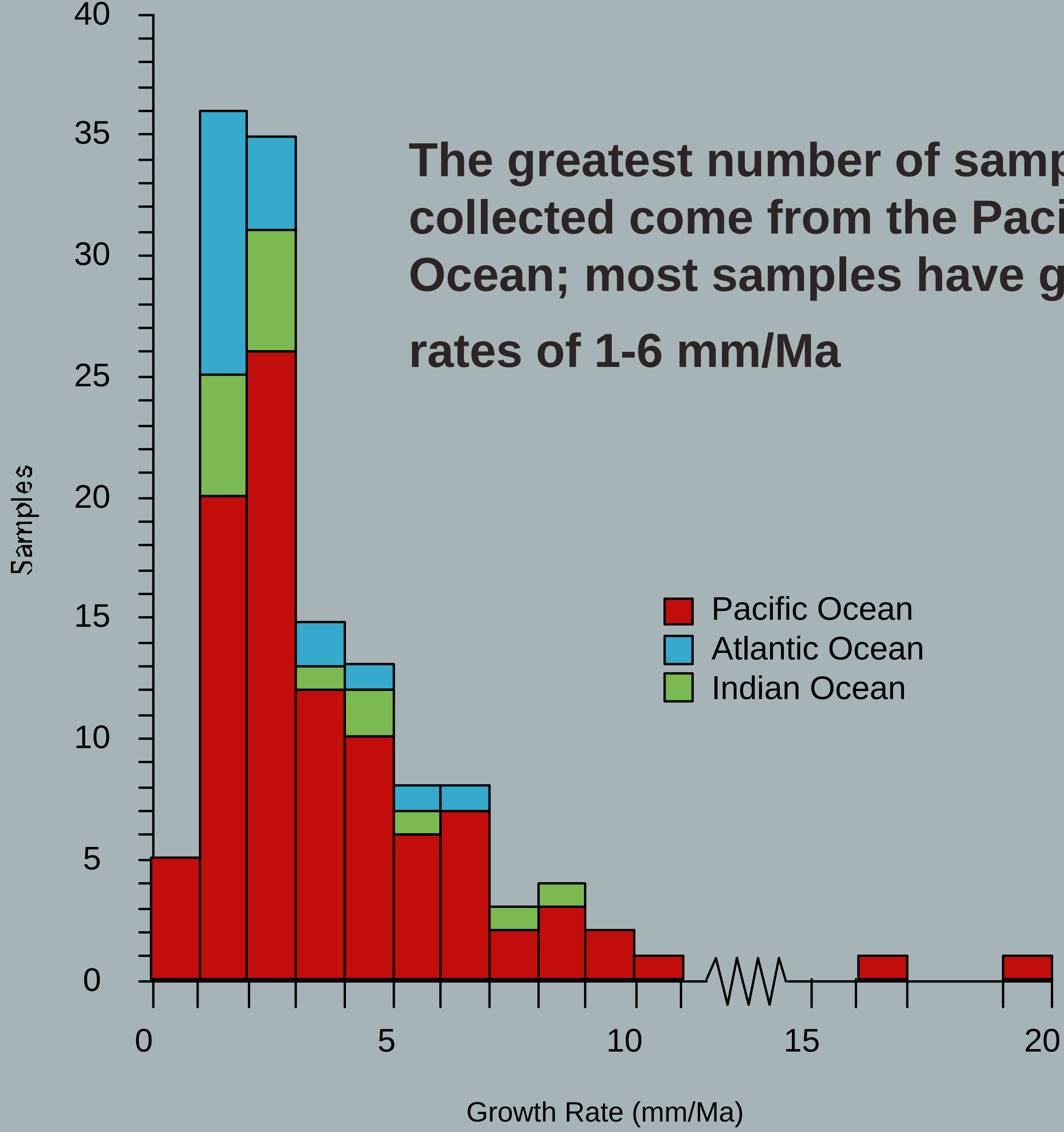
Important Properties of Cobalt-Rich Crusts

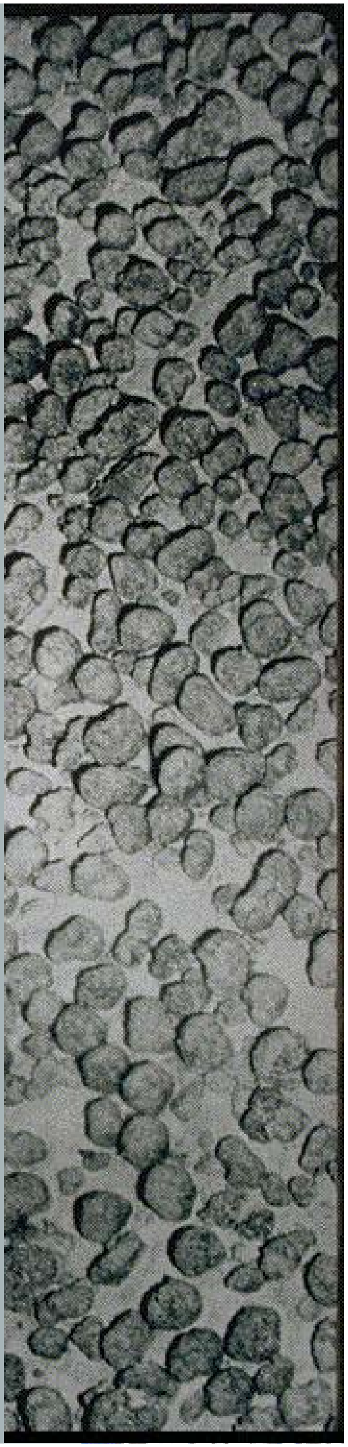
- *Very high porosity (60%)*
- *Extremely high specific surface area (300 m^2/g)*
- *Extremely slow rates of growth (1-6 mm/Ma)*

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

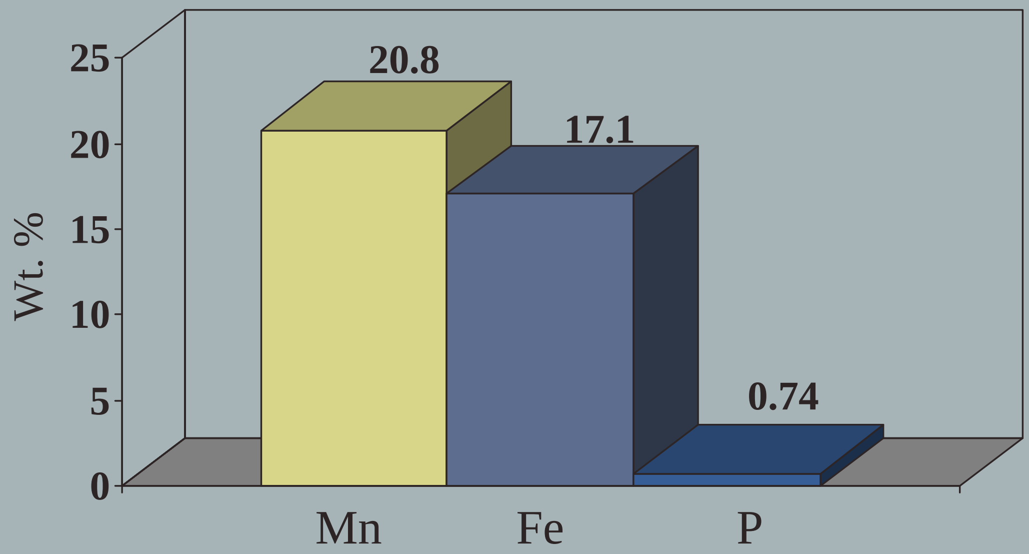


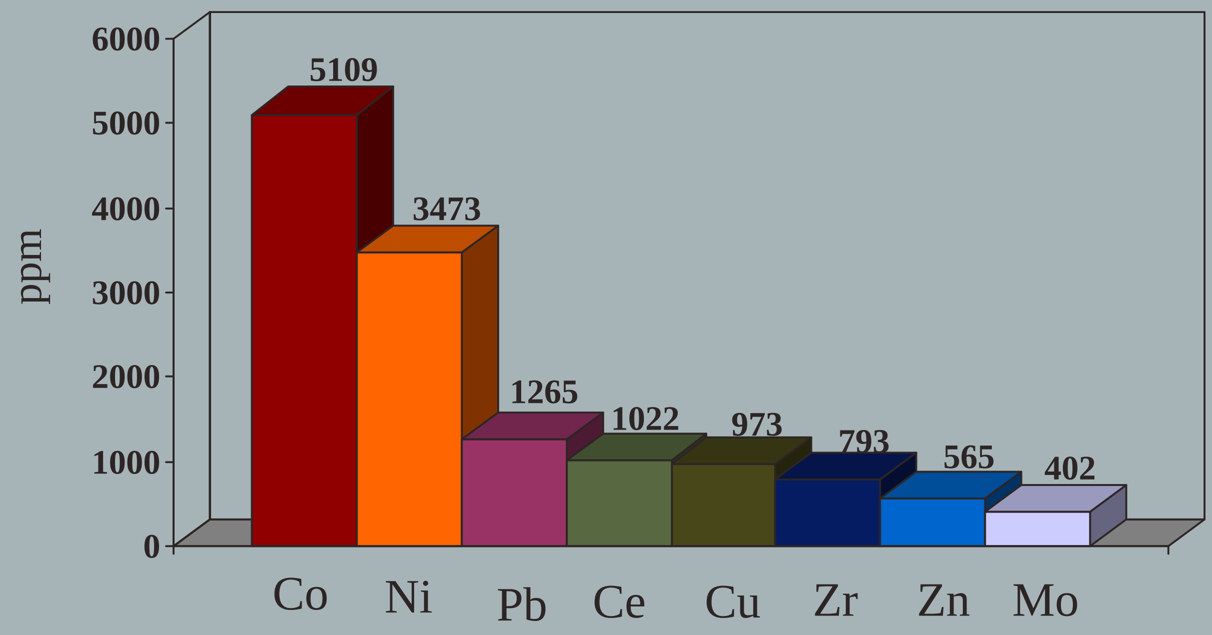
The greatest number of samples collected come from the Pacific Ocean; most samples have growth rates of 1-6 mm/Ma

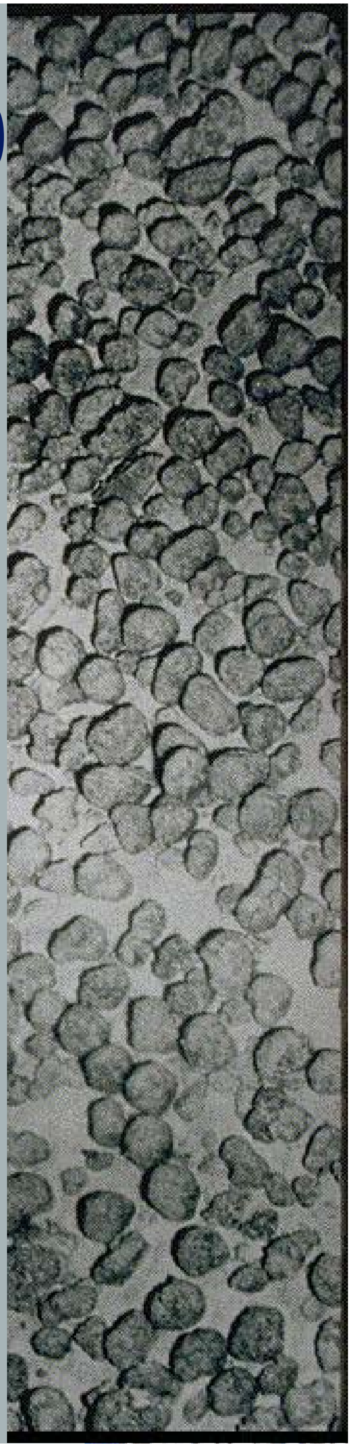




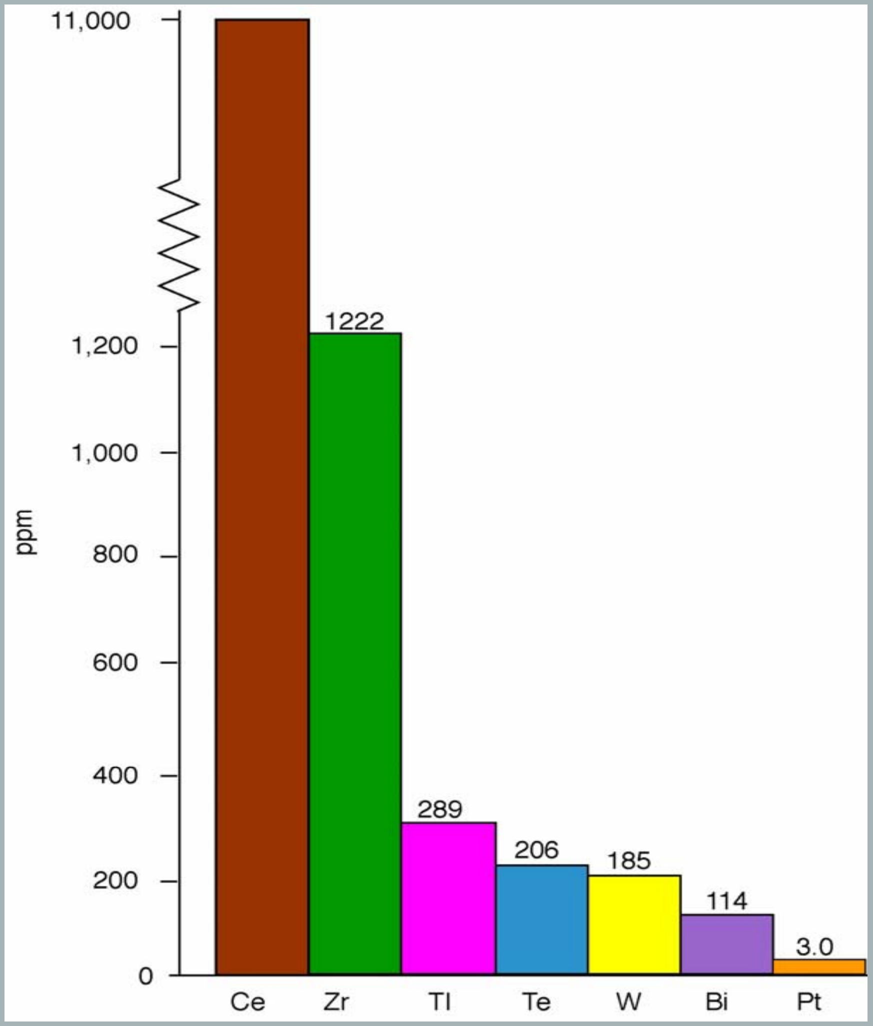
C+W N. Pacific Average (n = 627)

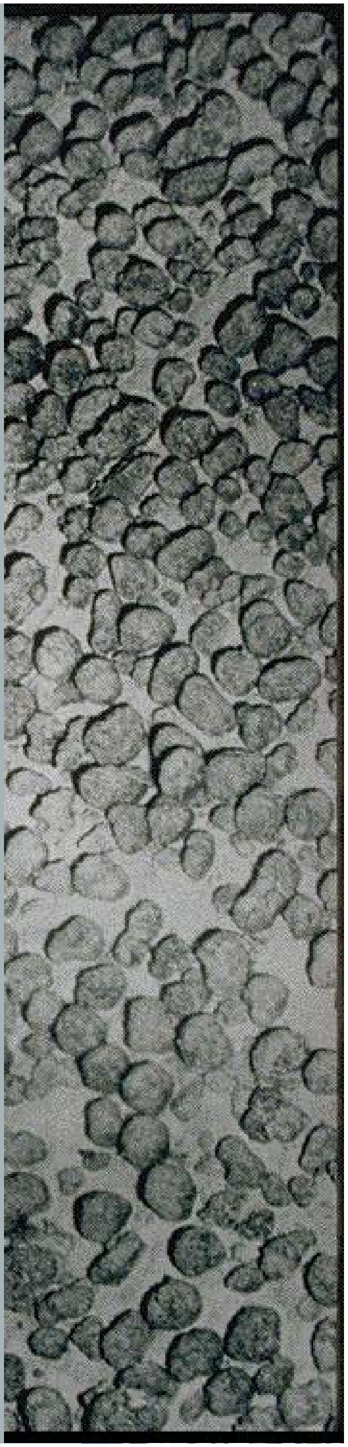




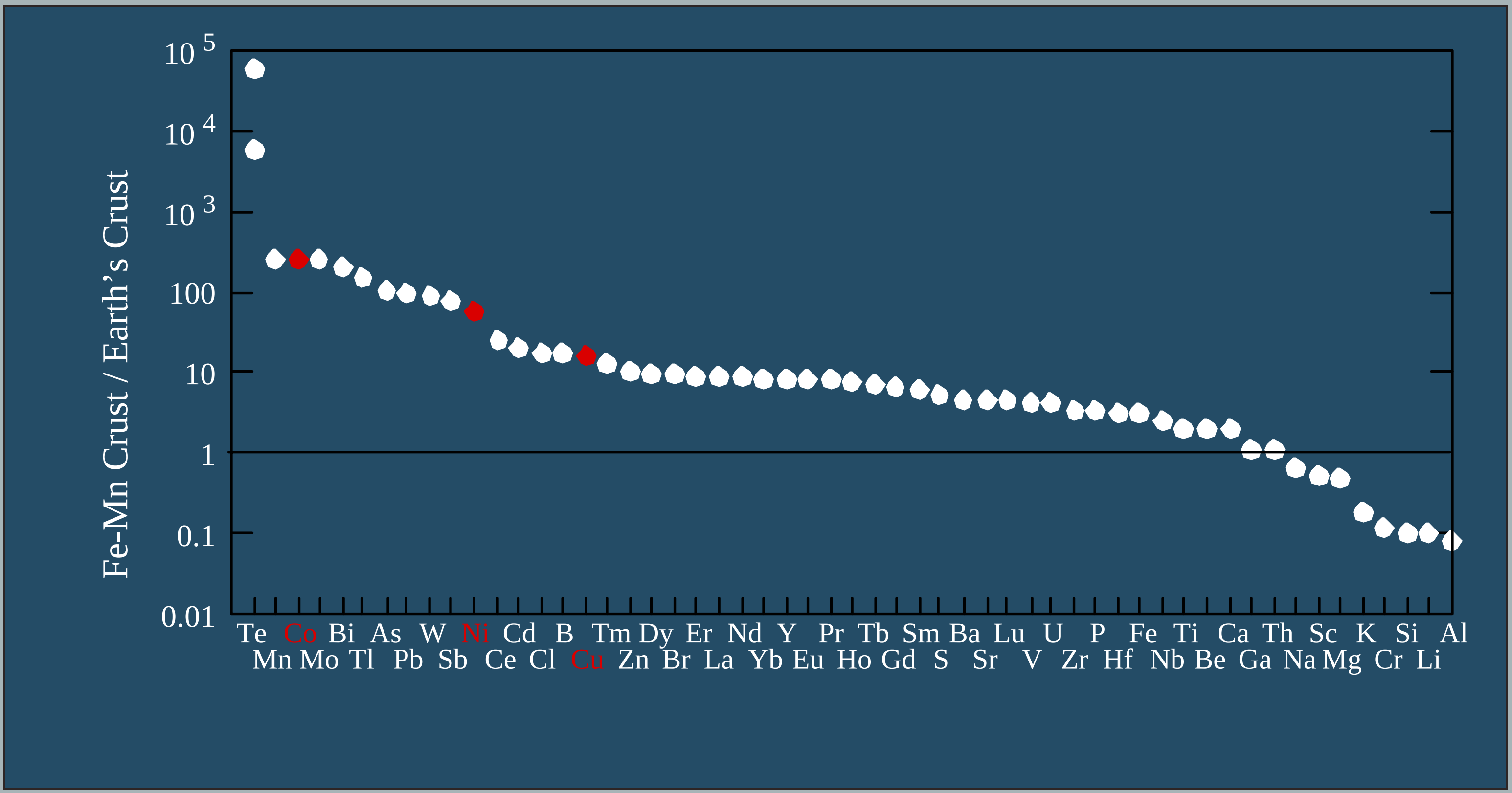


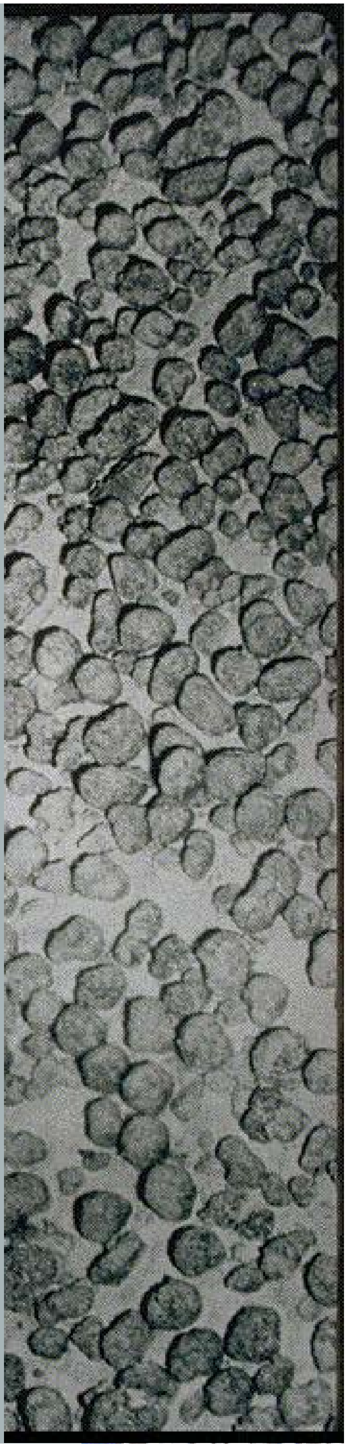
Trace Metal Maxima



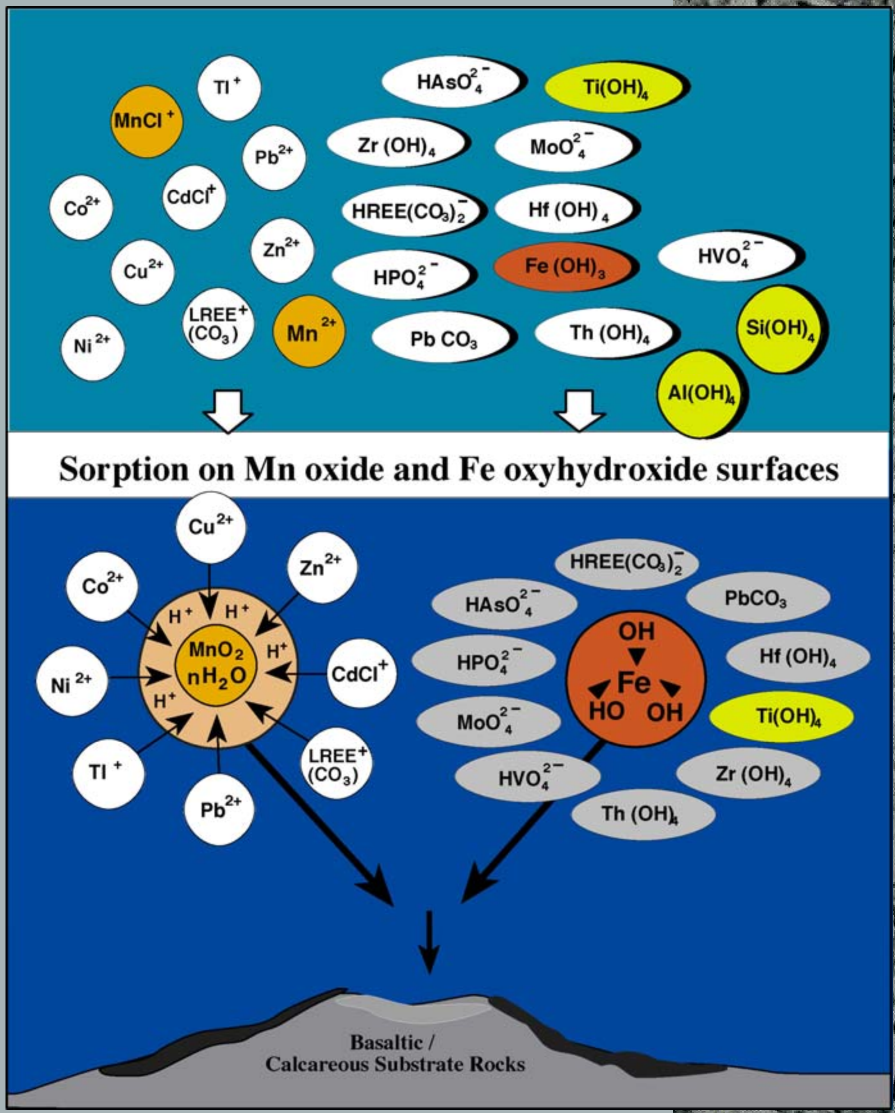


Element Enrichment in Fe-Mn Crusts Relative to the Earth's Crust

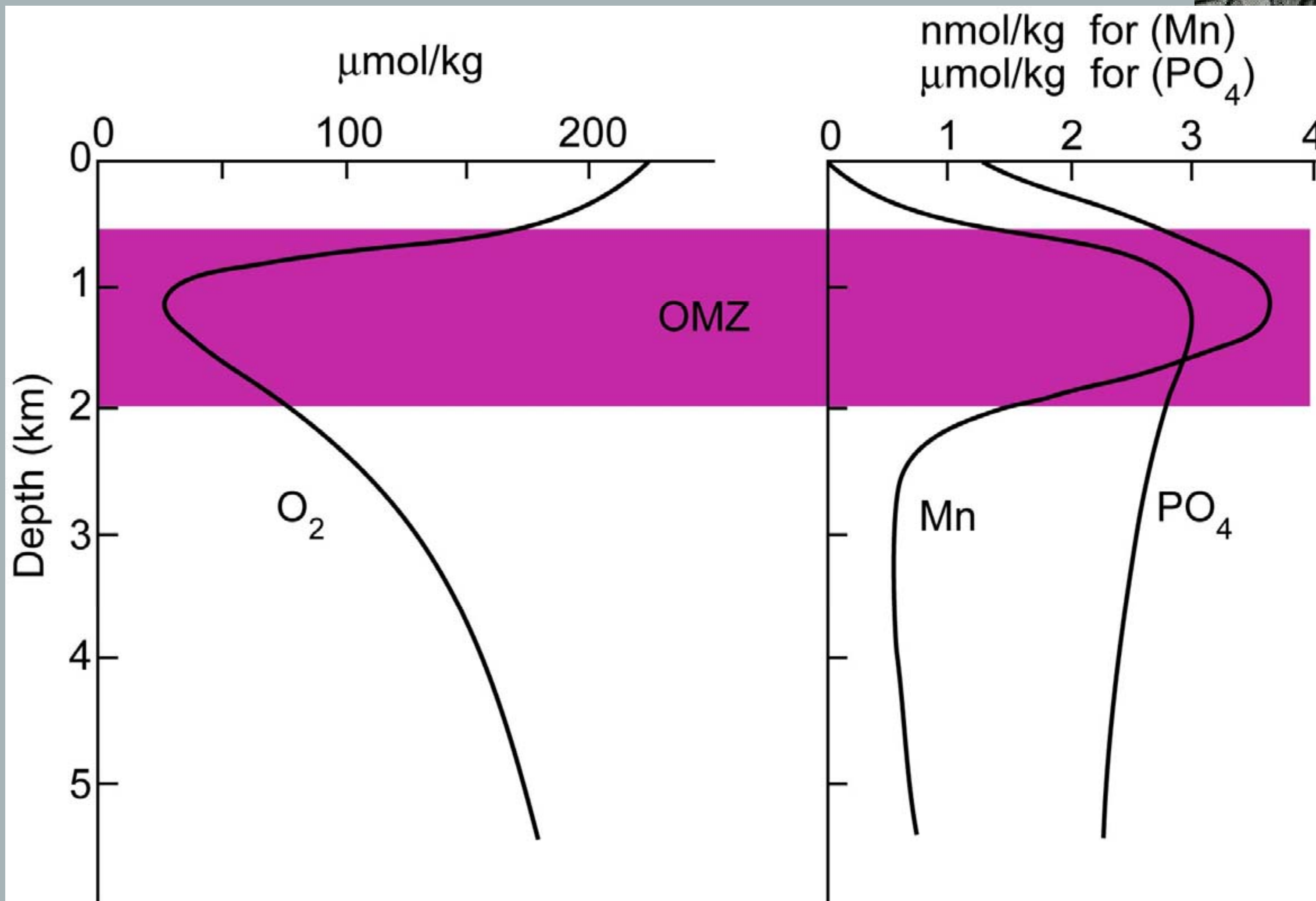


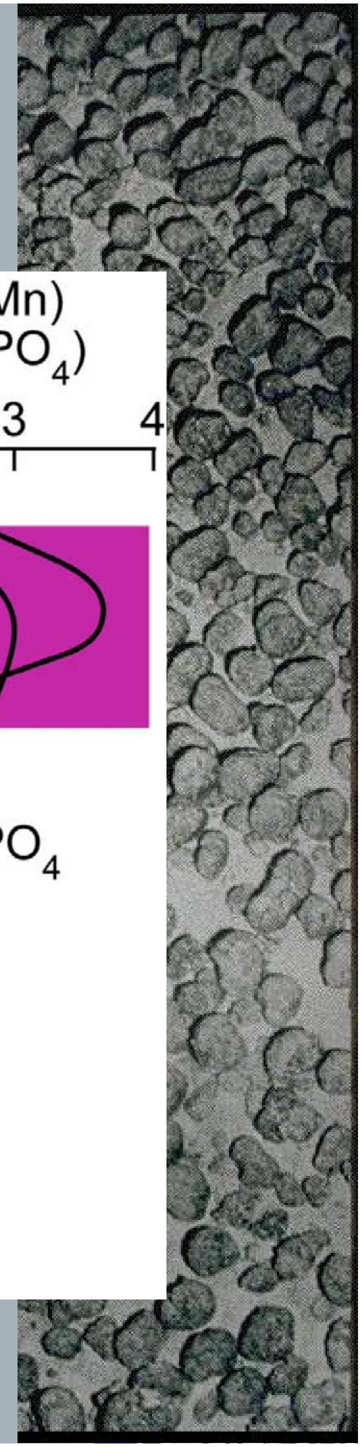


How Do Hydrogenetic Fe-Mn Crusts Form?

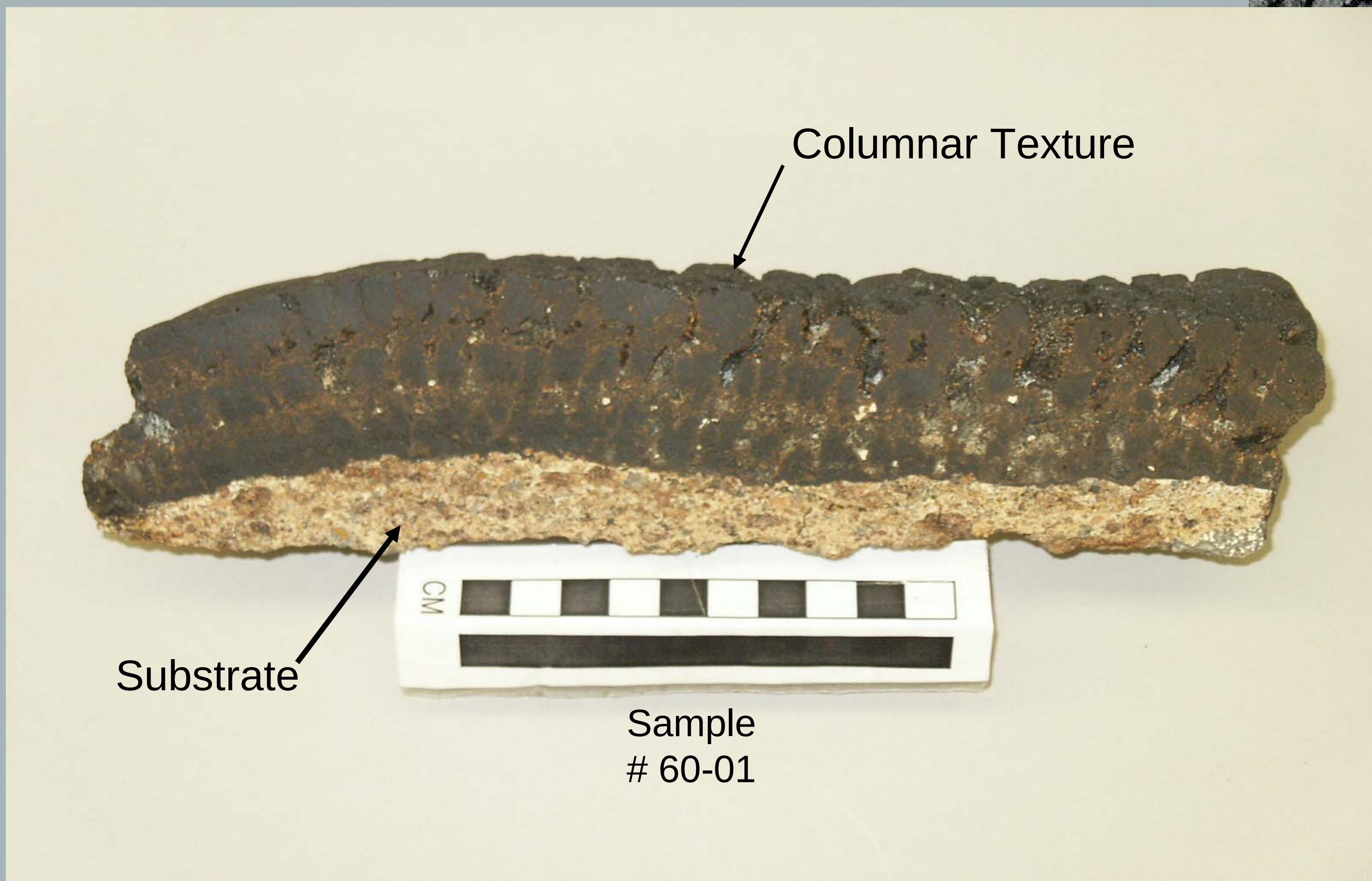


- *Simplified electrochemical model for the formation of Fe-Mn crusts by sorption of trace metal species on colloidal Mn oxide and Fe oxyhydroxide (Koschinsky and Hein, 2003)*

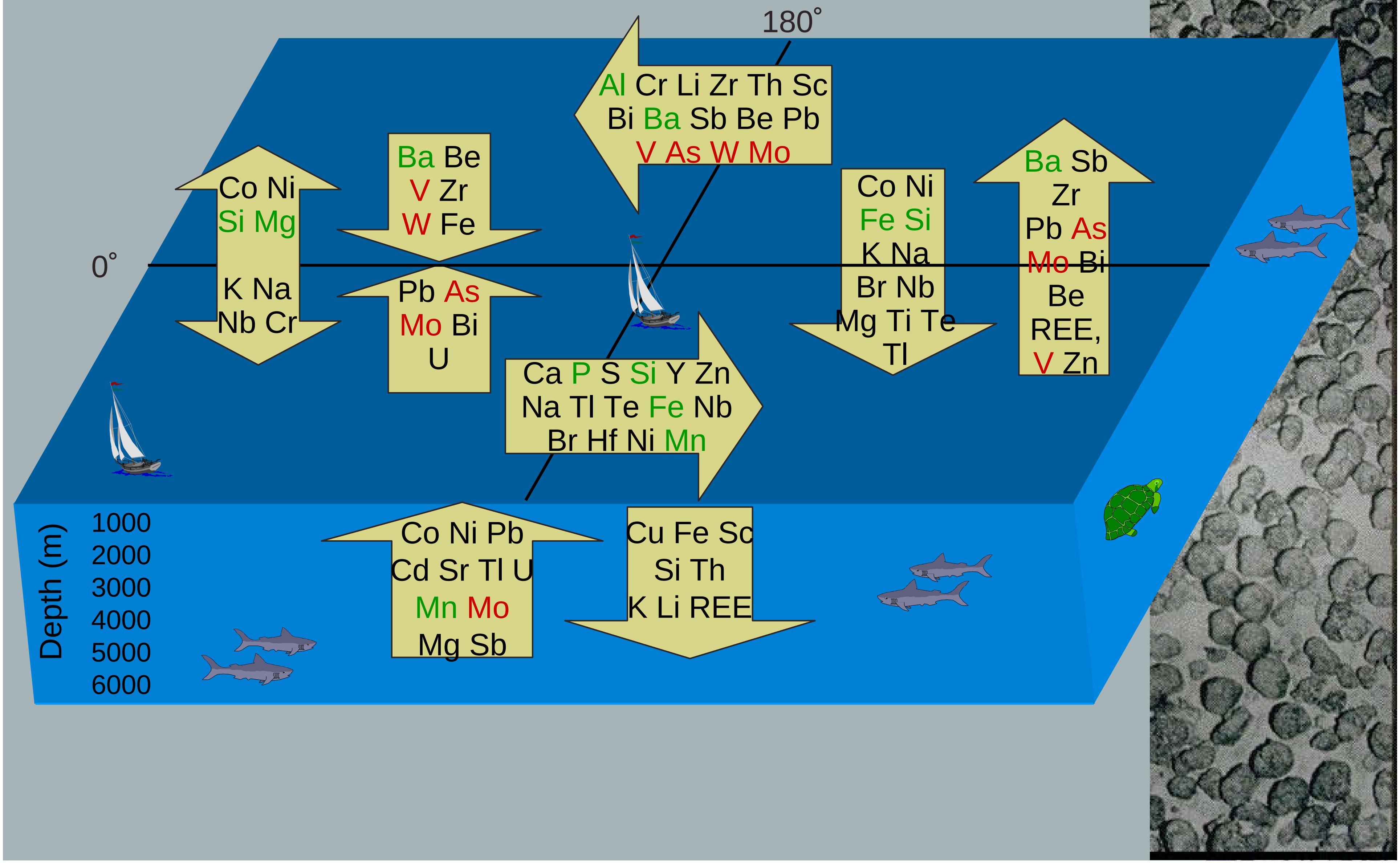

μmol/kg
nmol/kg for (Mn)
μmol/kg for (PO4)
0 100 200
0 1 2 3 4
Depth (km)
0 1 2 3 4 5
OMZ
O2
Mn
PO4



Cobalt-Rich Fe-Mn Crust

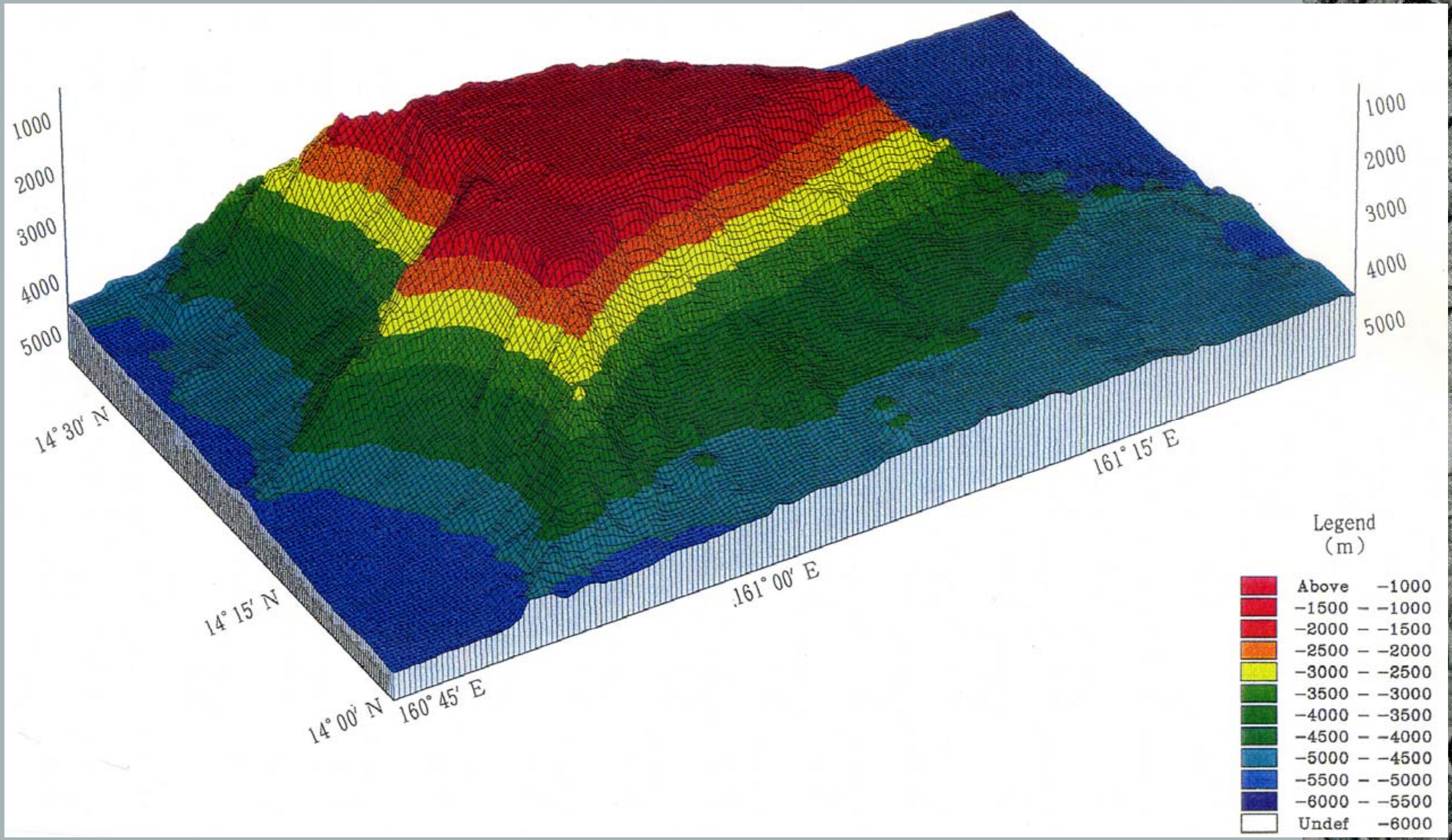


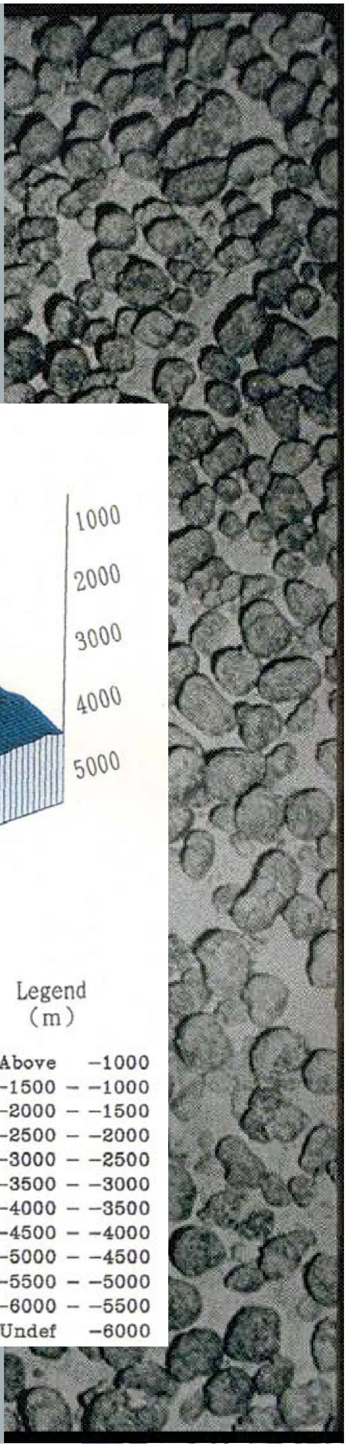
Geographic Control of Fe-Mn Crust Chemistry



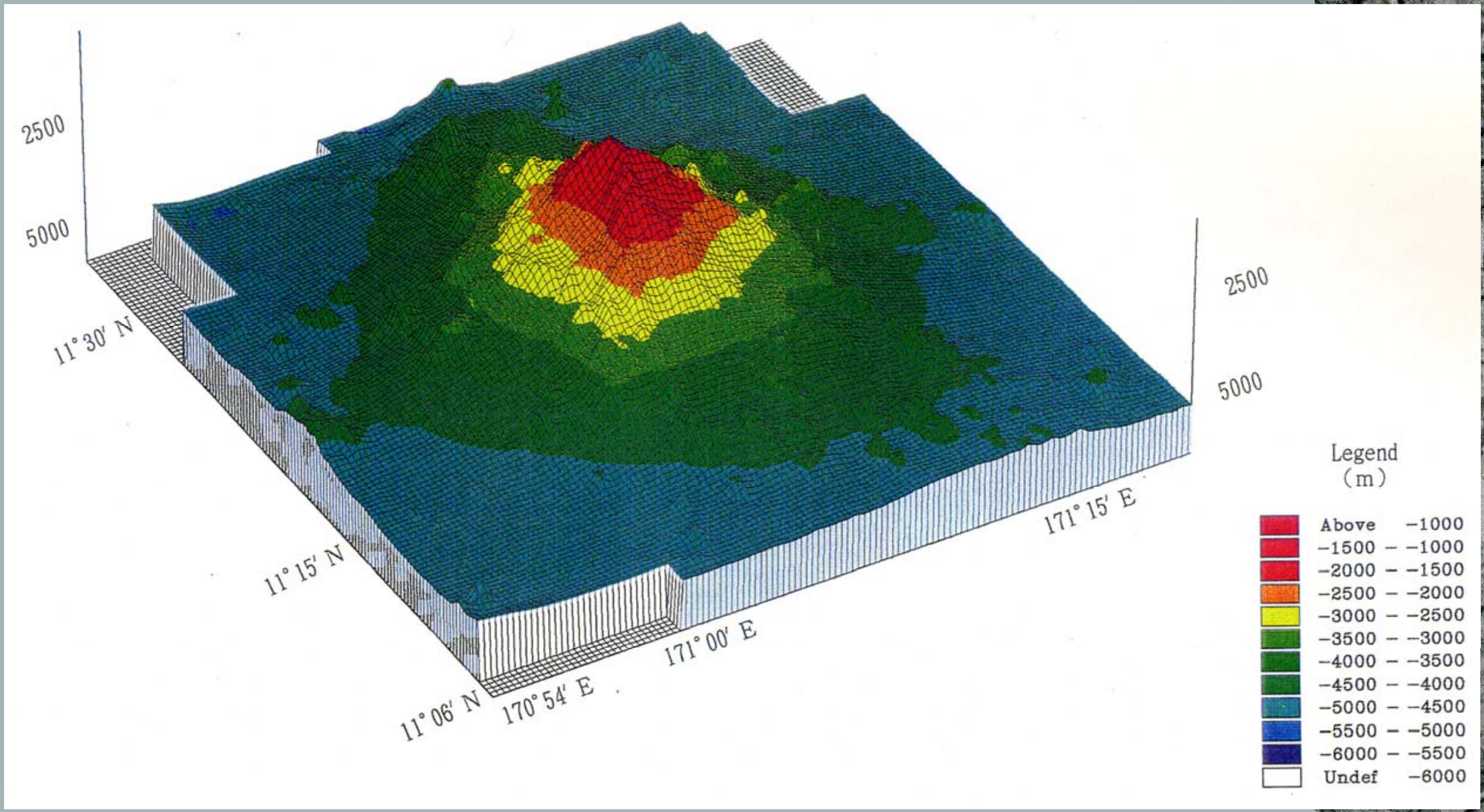
56 kilometers long
Terraces
Debris apron

Typical Guyot

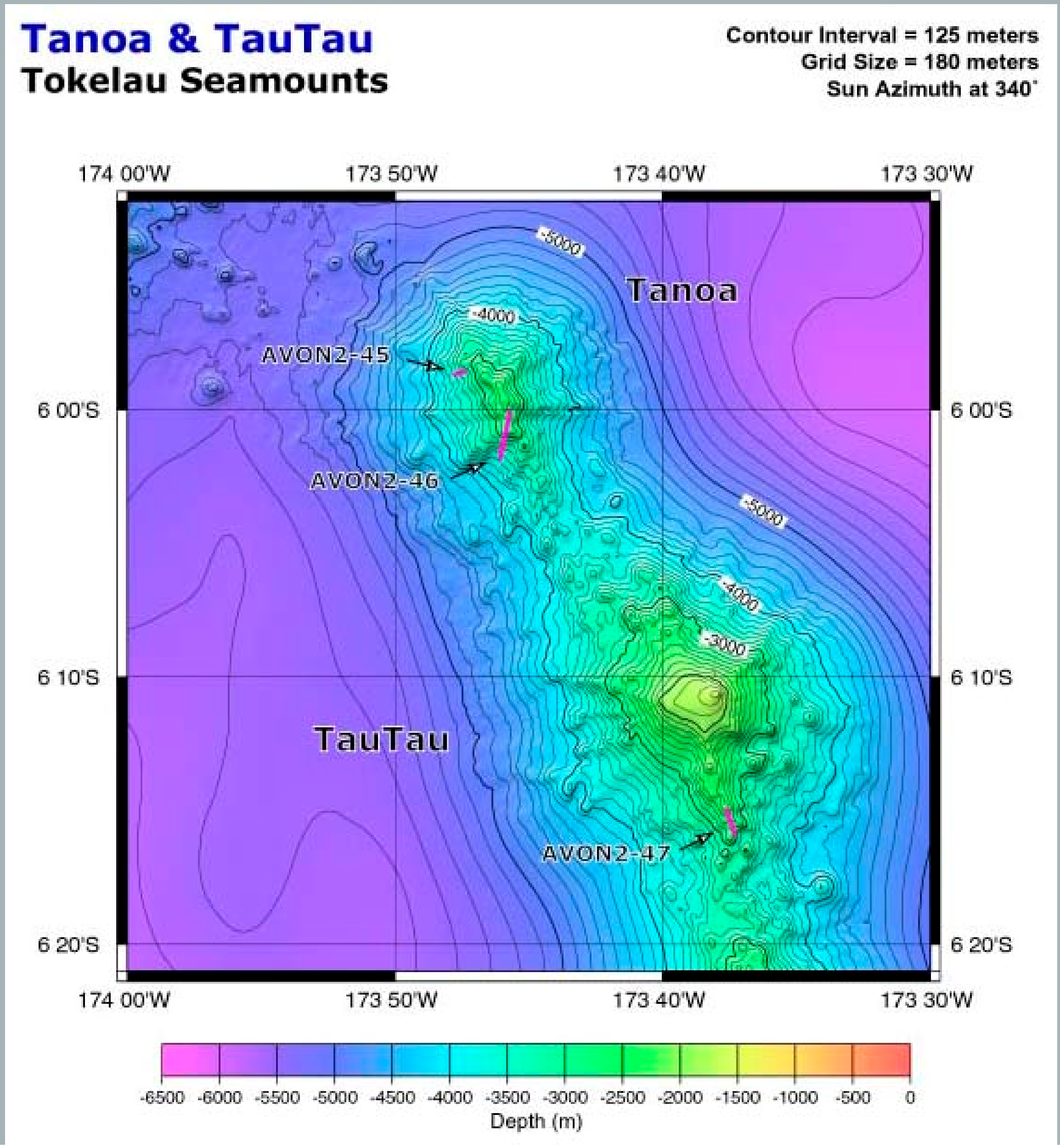


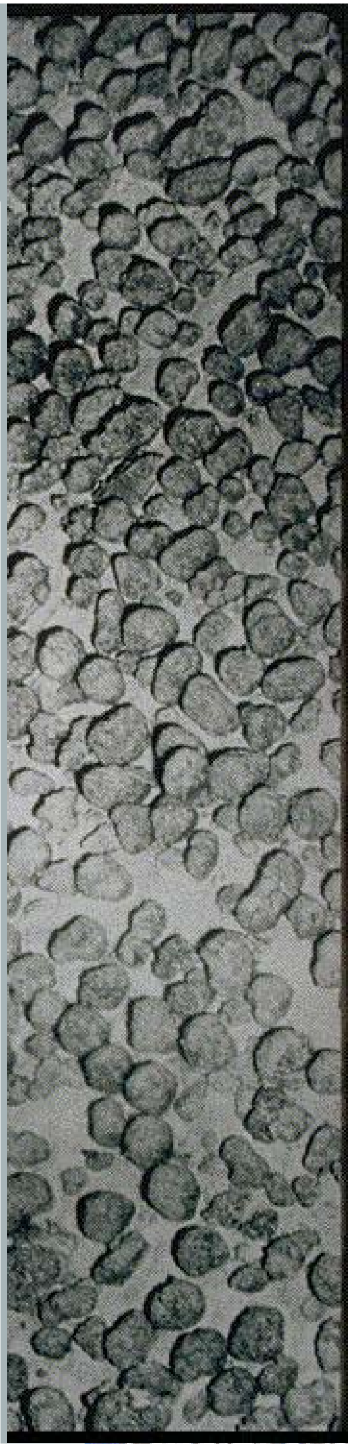


Typical Conical Seamount



Typical Sampling Density



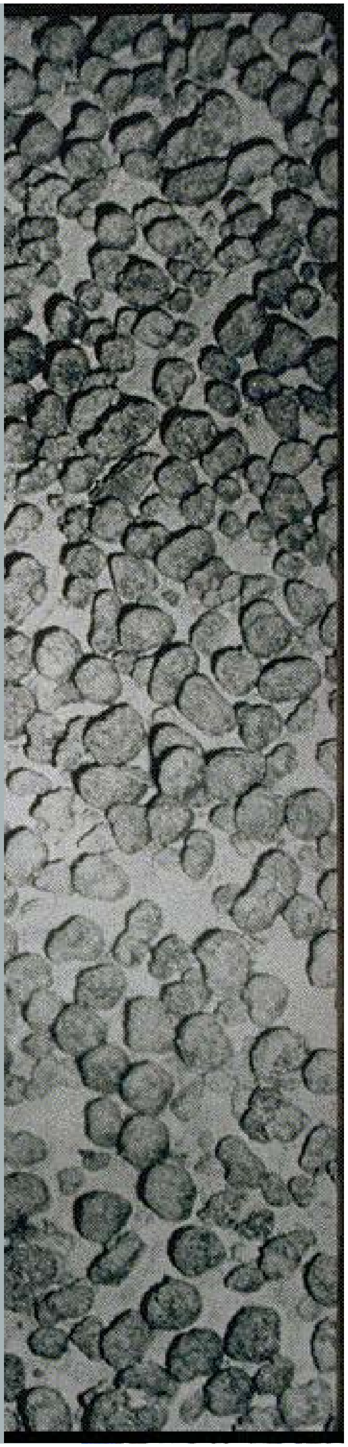


Average Seamount

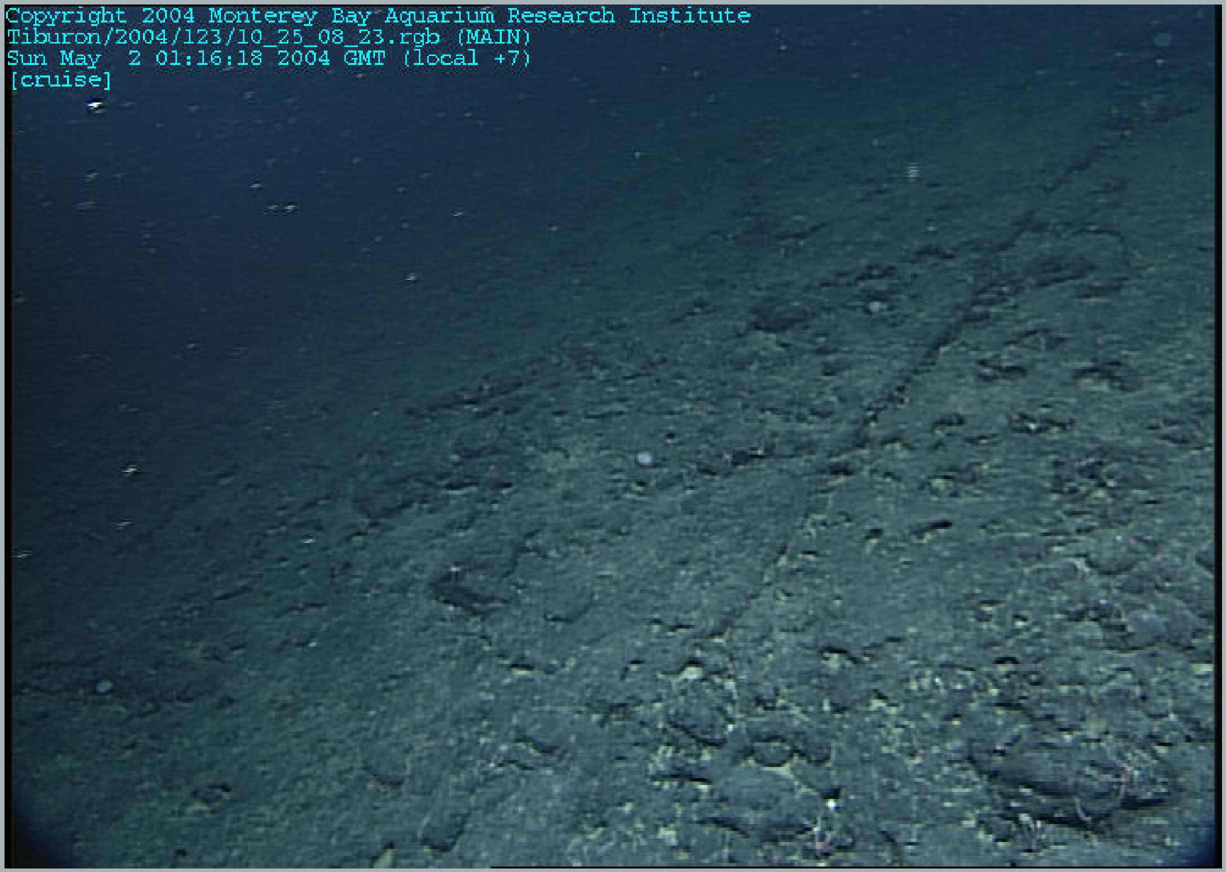
(Surface Area Statistics for 34 Seamounts)

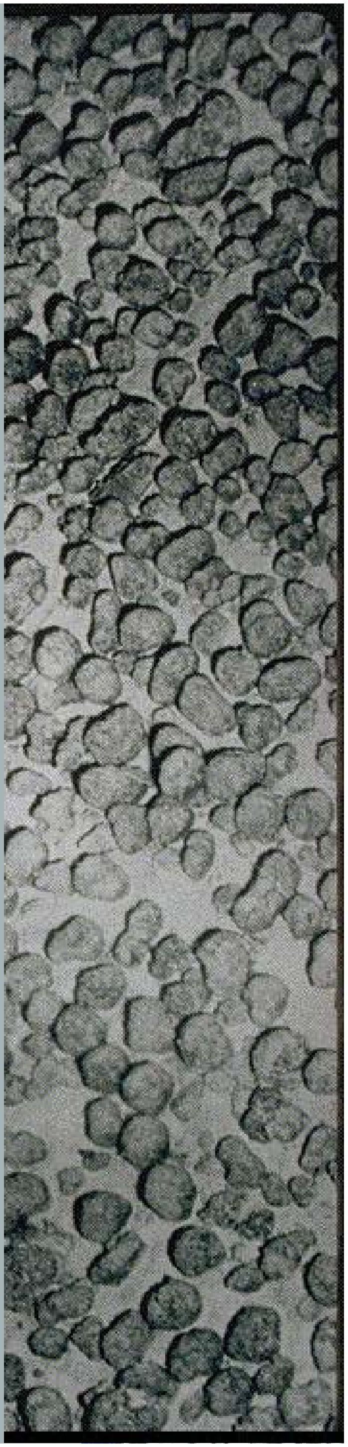
	Total Surface Area (km^2)	*Surface Area above 2500m water depth (km^2)*
Mean	1,850	515
Median	1,450	325
SD[1]	1,150	470
Minimum	310	0
Maximum	4,775	1,843

[1] Standard Deviation

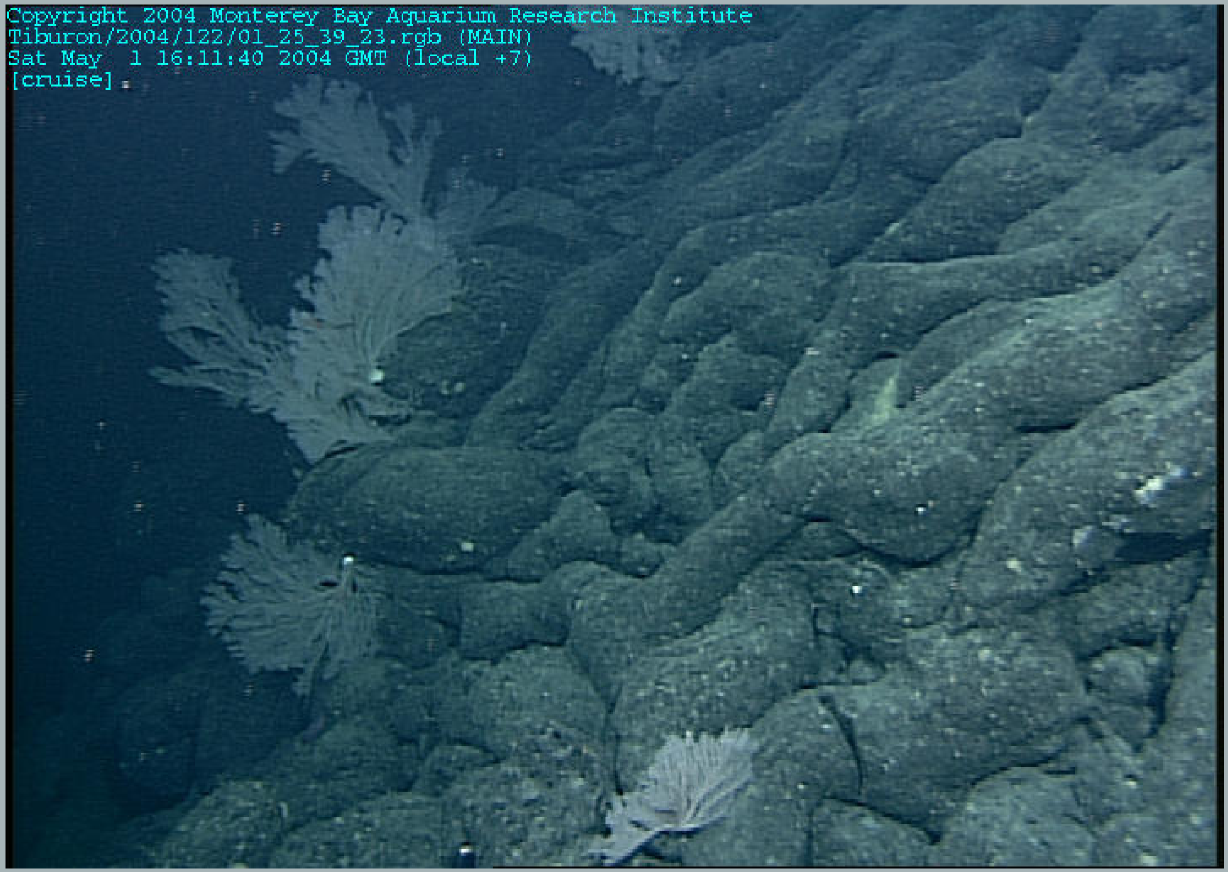


Example of smooth seabed with crust pavement

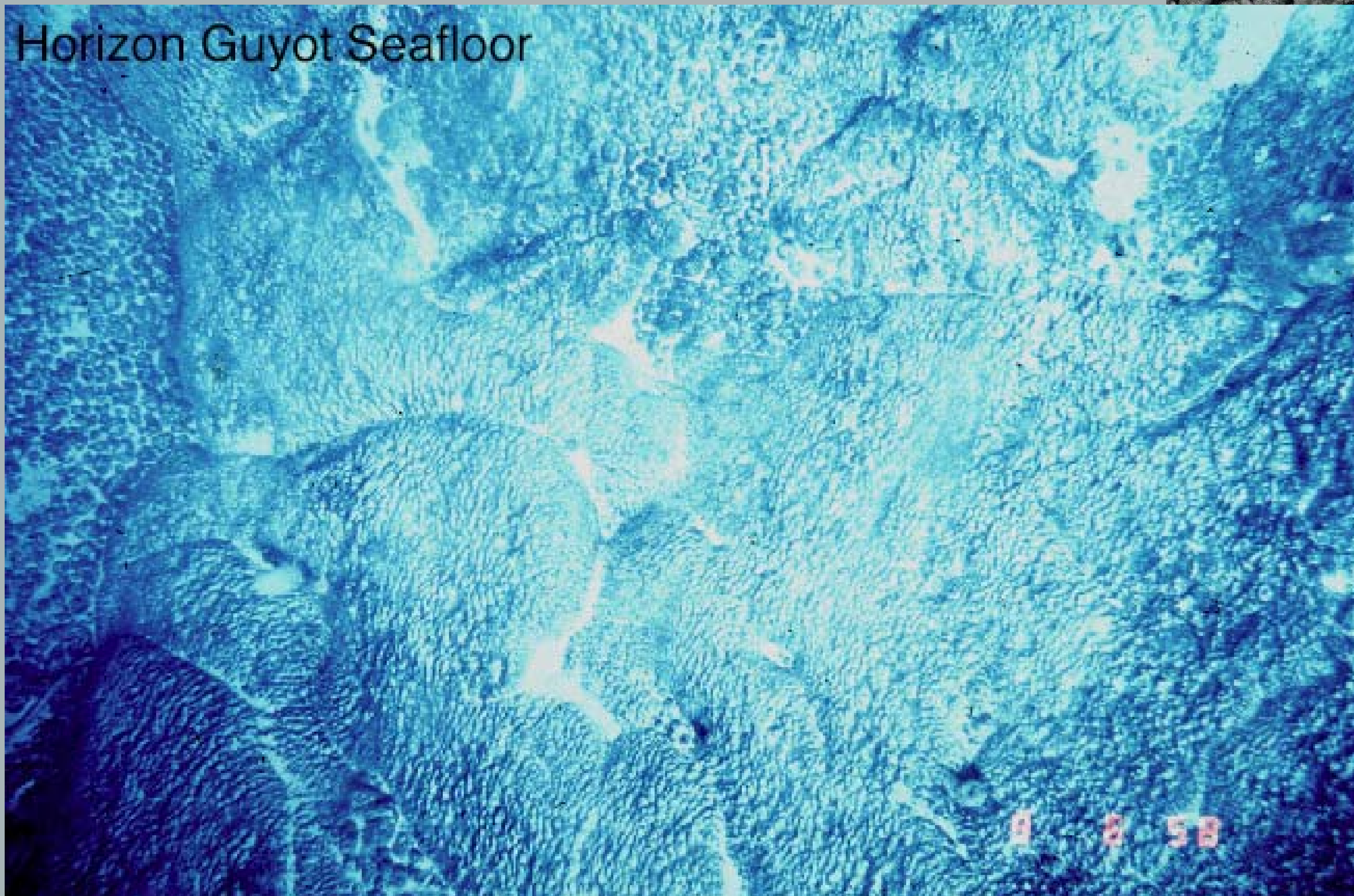


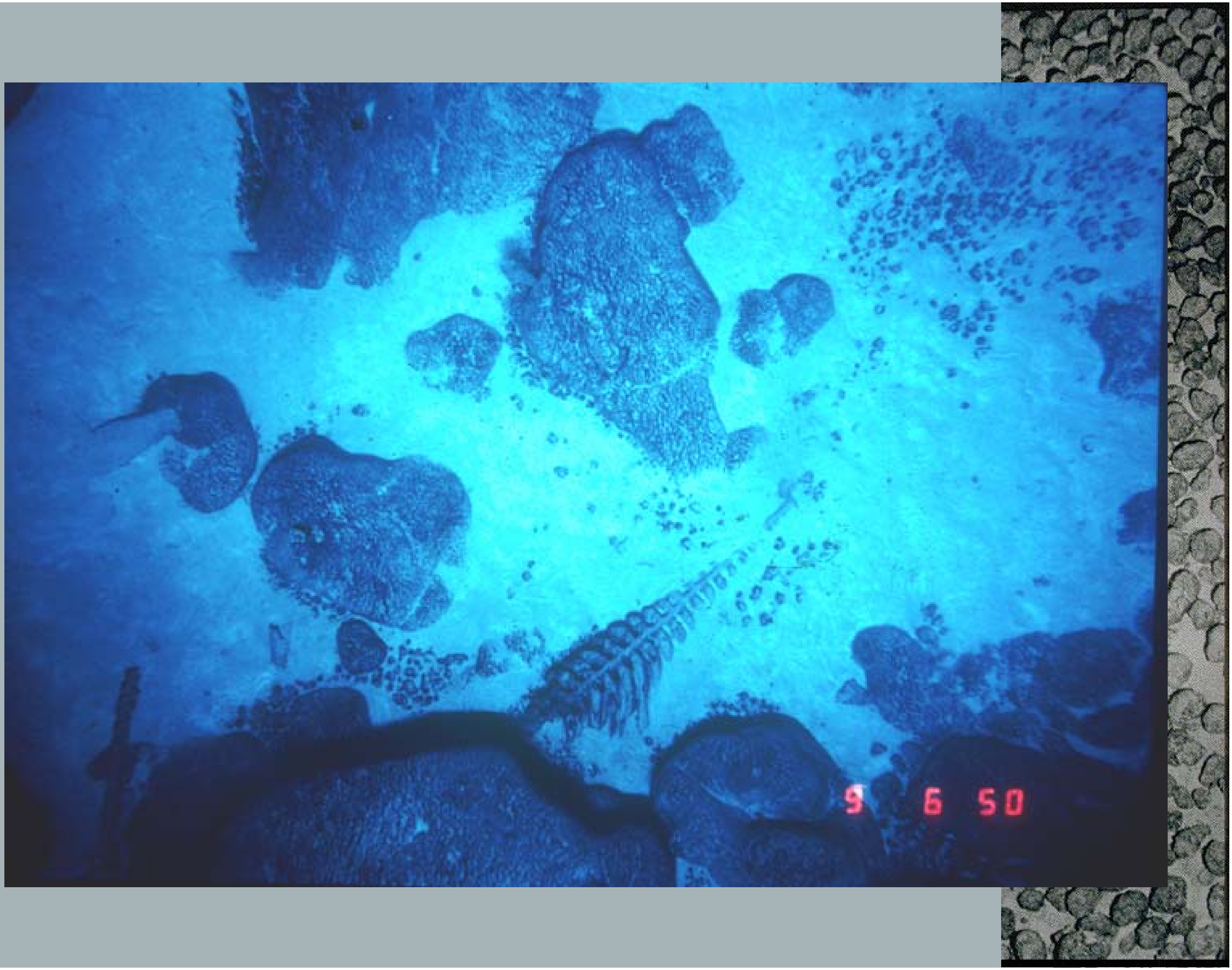


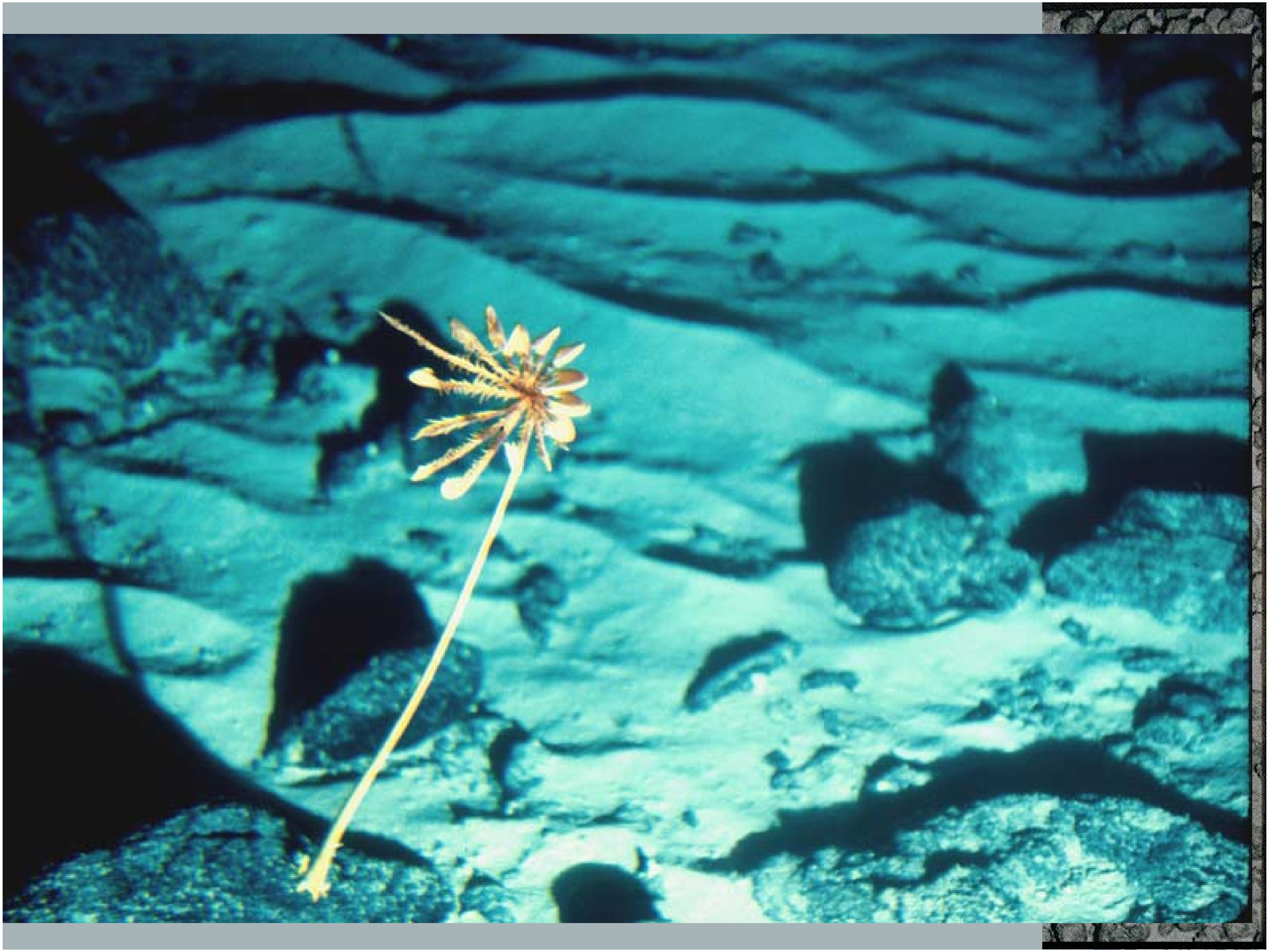
Example of rough seabed with crusts



Horizon Guyot Seafloor




9 6 50



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*

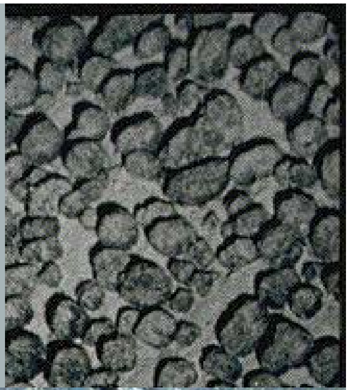
- *Controls*
  - *Seamount height*
  - *Summit size*
  - *Types of ambient currents*
  - *Energy of tidal flow*

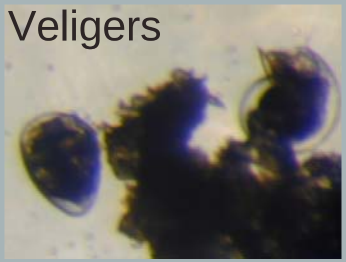
Seamount Biology

- *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.

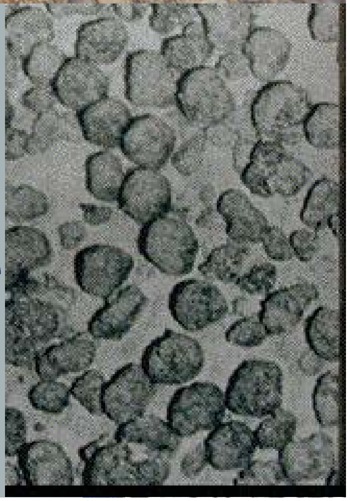




Veligers

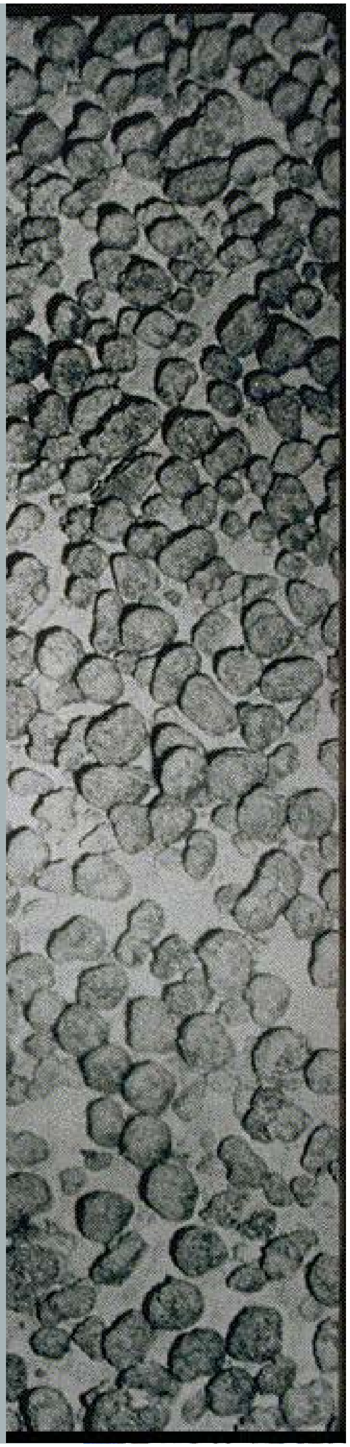
Protoconch

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*



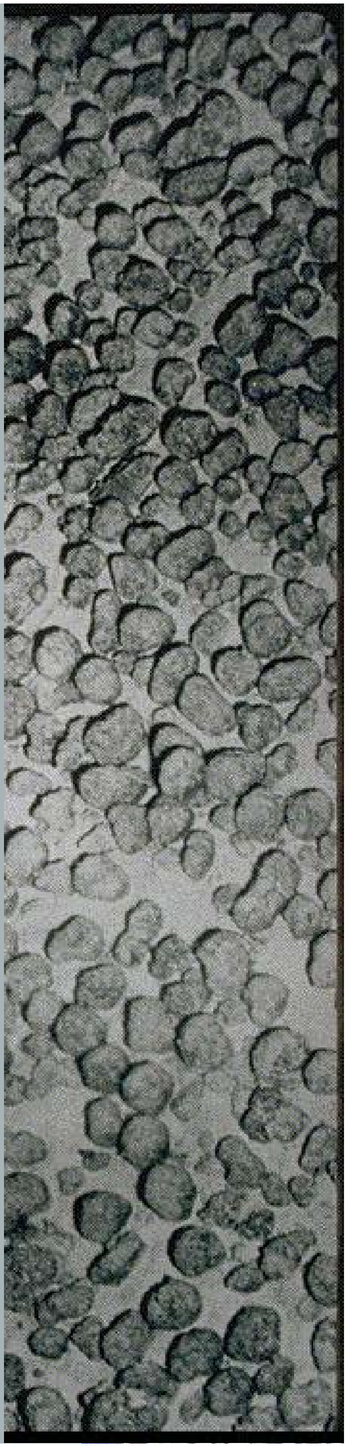
NEW RESOURCES FOR COORDINATION OF SEAMOUNT BIOLOGY:

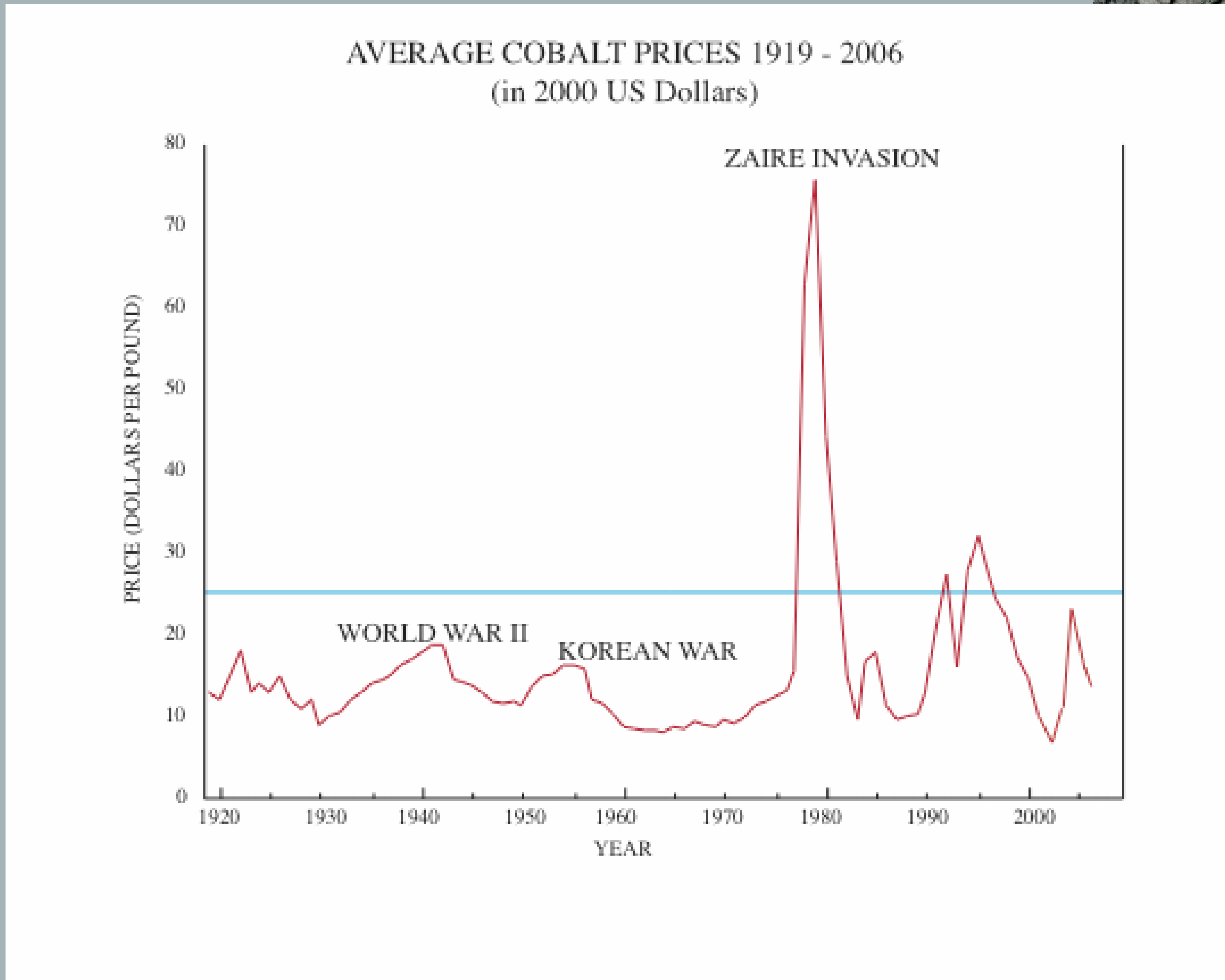
Census of Marine Life (CoML) (www.coml.org)

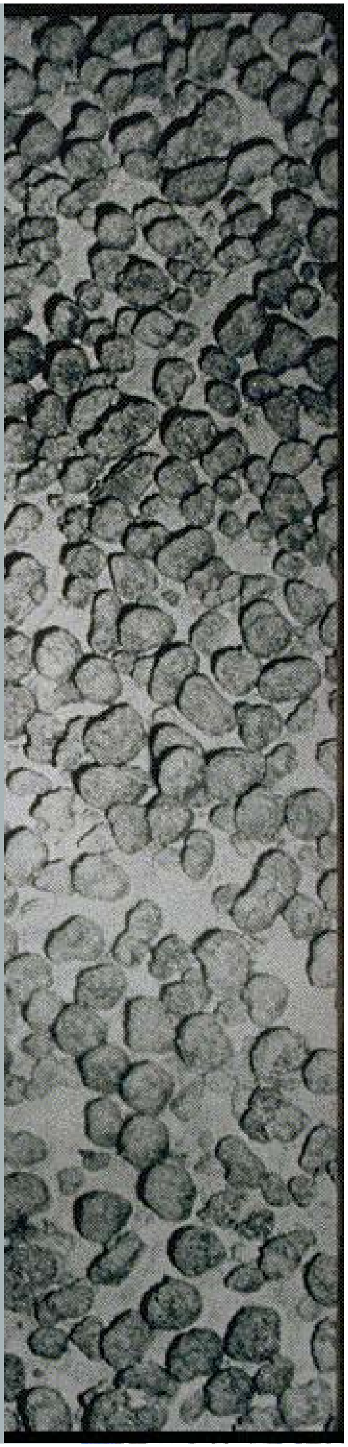
Global census of marine life on seamounts (CenSeam) (http://censeam.niwa.co.nz)

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

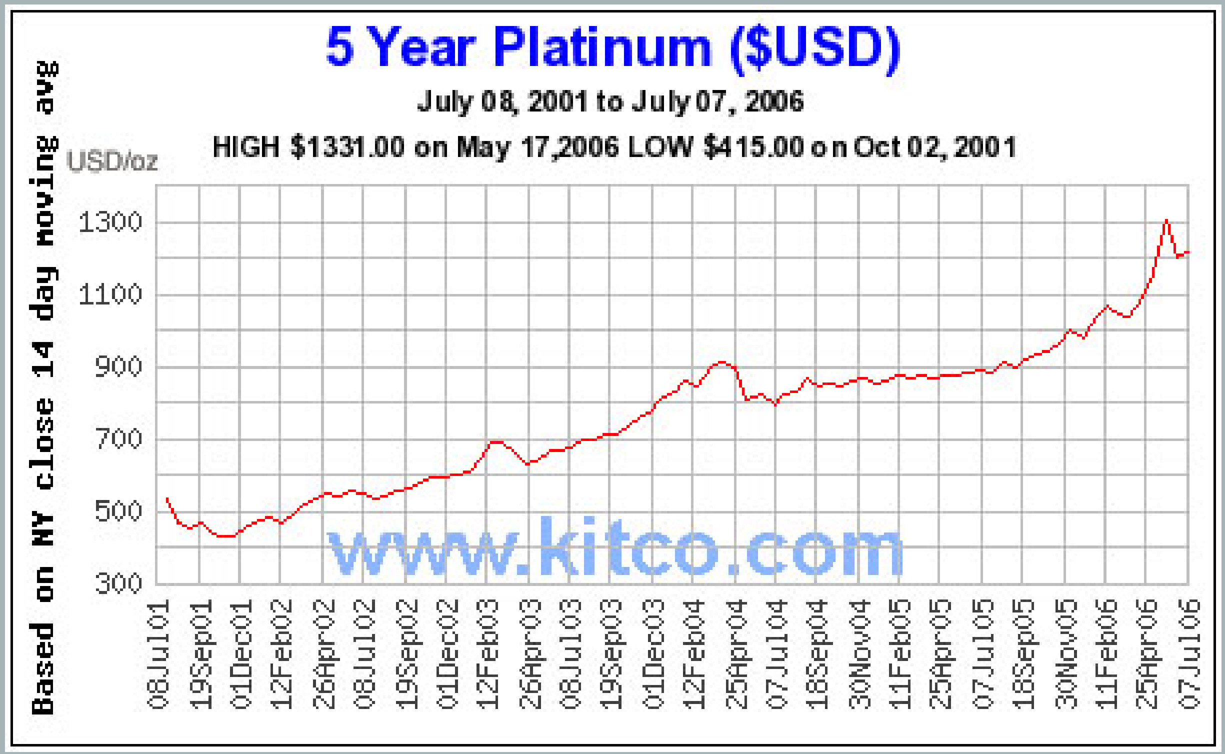
Biogeosciences Network (SBN) (http://earthref.org/events/SBN/2006/index.html)




AVERAGE COBALT PRICES 1919 - 2006
(in 2000 US Dollars)
ZAIRE INVASION
WORLD WAR II
KOREAN WAR
PRICE (DOLLARS PER POUND)
0
10
20
30
40
50
60
70
80
1920
1930
1940
1950
1960
1970
1980
1990
2000
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
USD/oz
Based on NY close 14 day moving avg
1300
1100
900
700
500
300
08Jul01
19Sep01
01Dec01
12Feb02
26Apr02
08Jul02
19Sep02
01Dec02
12Feb03
26Apr03
08Jul03
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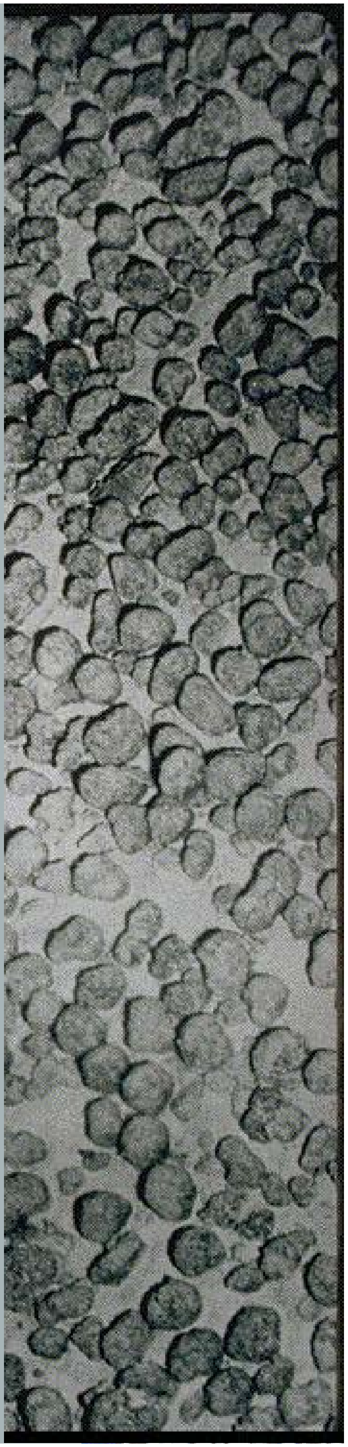
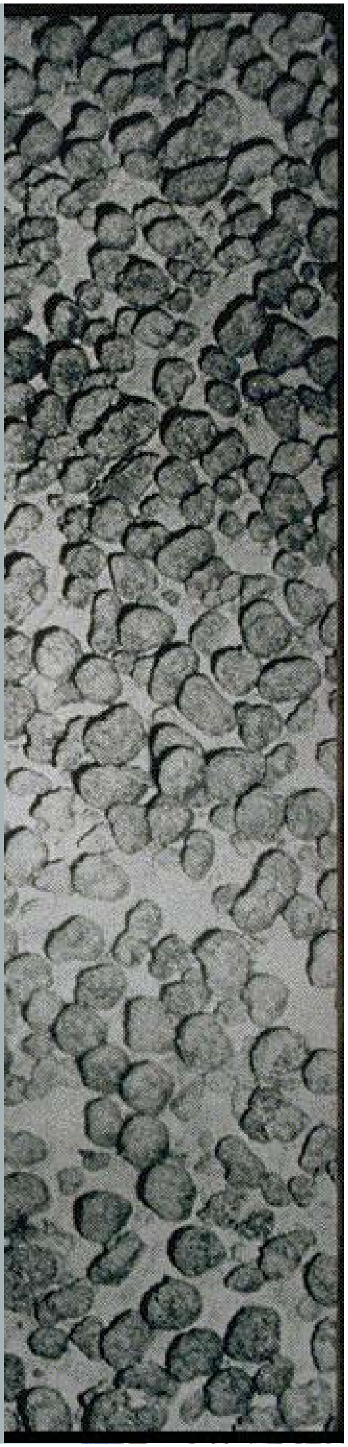
www.kitco.com



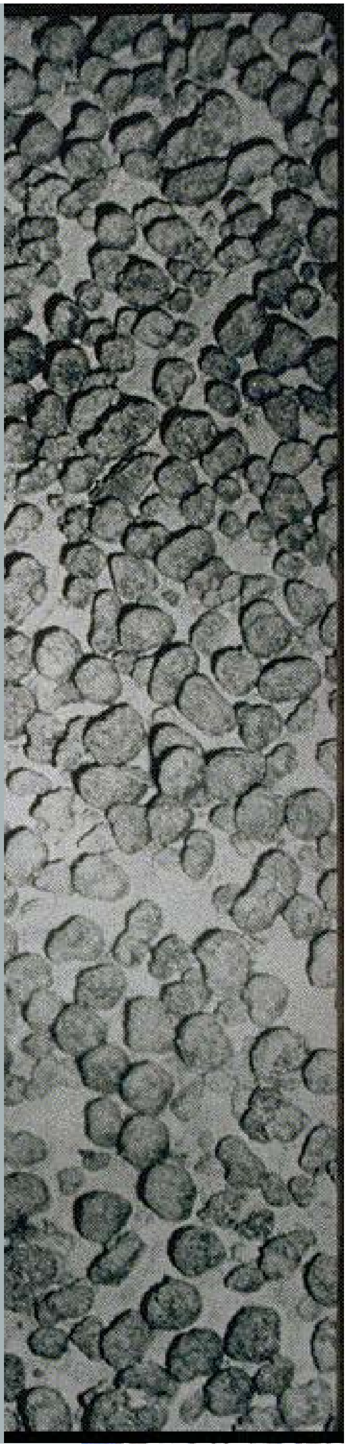
Fe-Mn crusts provide the richest source of tellurium (Te) known (Hein et al., 2003)

- 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).



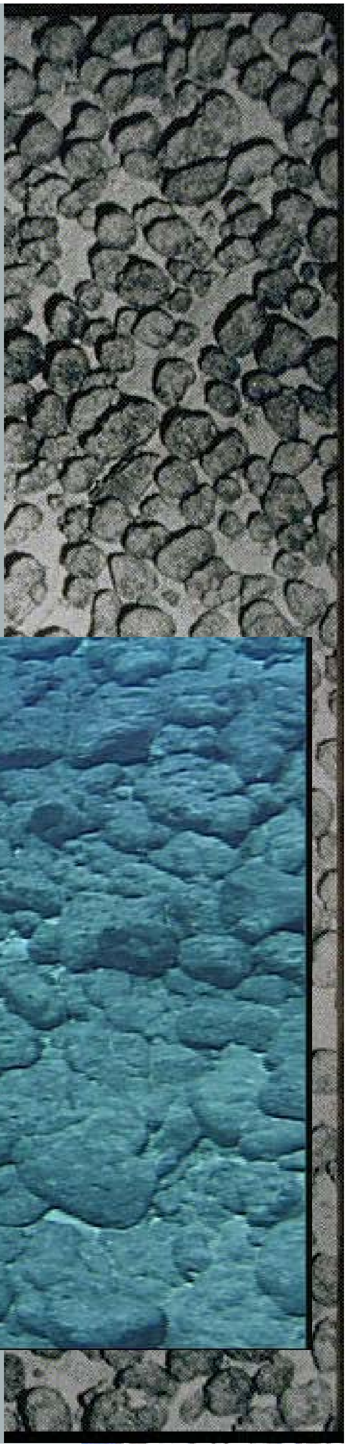
Value of Metals in 1 Metric Ton of Fe-Mn Crust from the Central-Equatorial Pacific

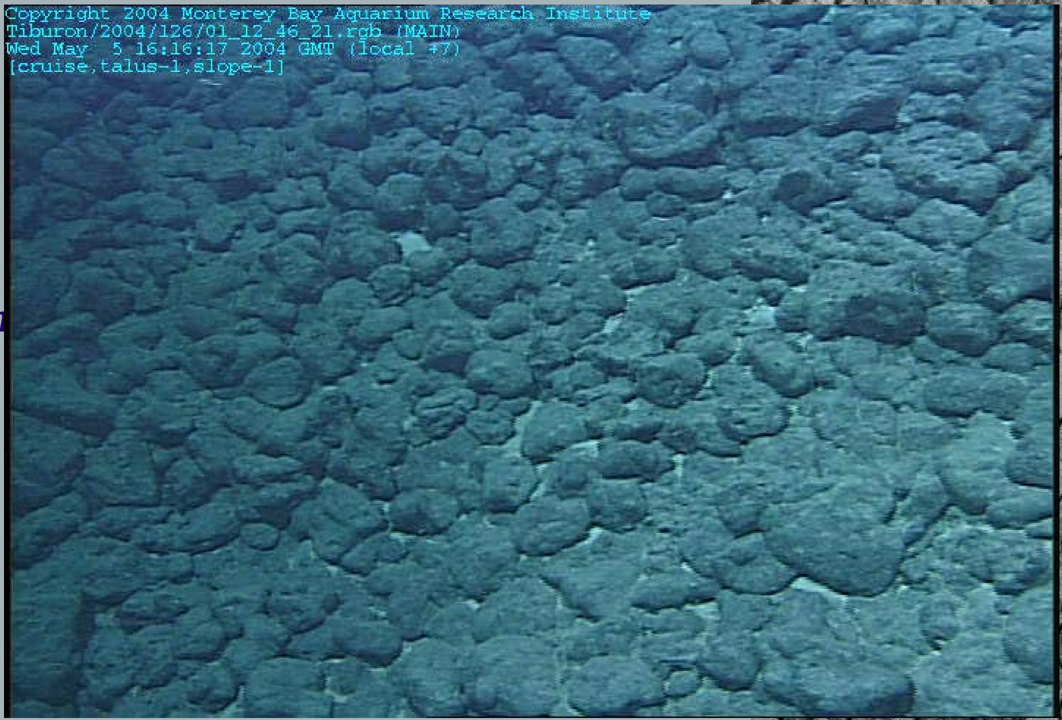
	Mean Price of Metal (2006 $/kg)	Mean Content in Crusts (g/ton)	Value per Metric Ton of Ore ($)
Cobalt	$32.41	6899	$223.60
Titanium	$18.03	12,035	$216.99
Cerium	$85.00	1605	$136.43
Zirconium	$22.00	618	$13.60
Nickel	$17.36	4125	$71.61
Platinum	$33,919.41	0.5	$16.96
Molybdenum	$51.47	445	$22.90
Tellurium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



Global Tonnage and Area of Ferromanganese Crusts

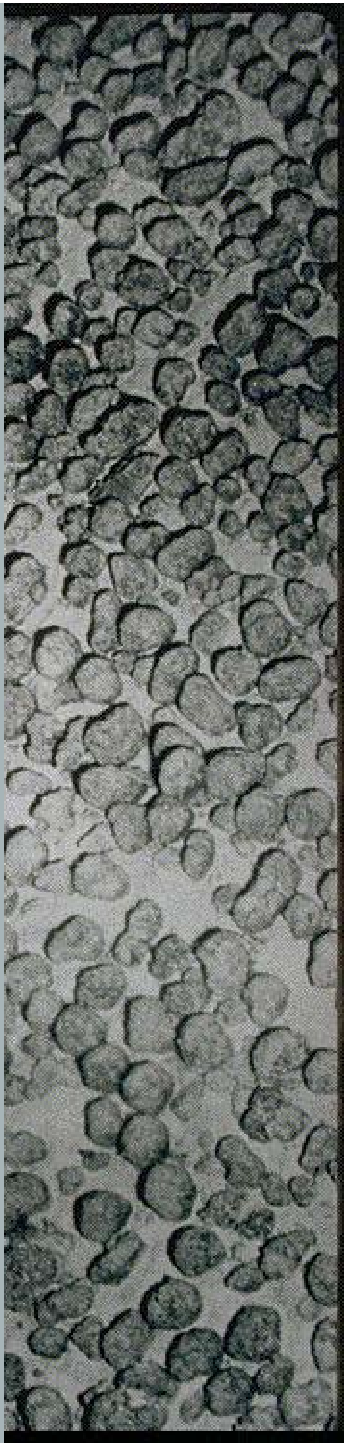
- ***Area of seafloor with crusts: 6.35 million km^2***
- ***Total dry bulk mass of crusts: 200 billion tonnes (2 x 10^{11} tonnes)***
- ***Total amount of cobalt metal: 1 billion (10^9) tonnes***





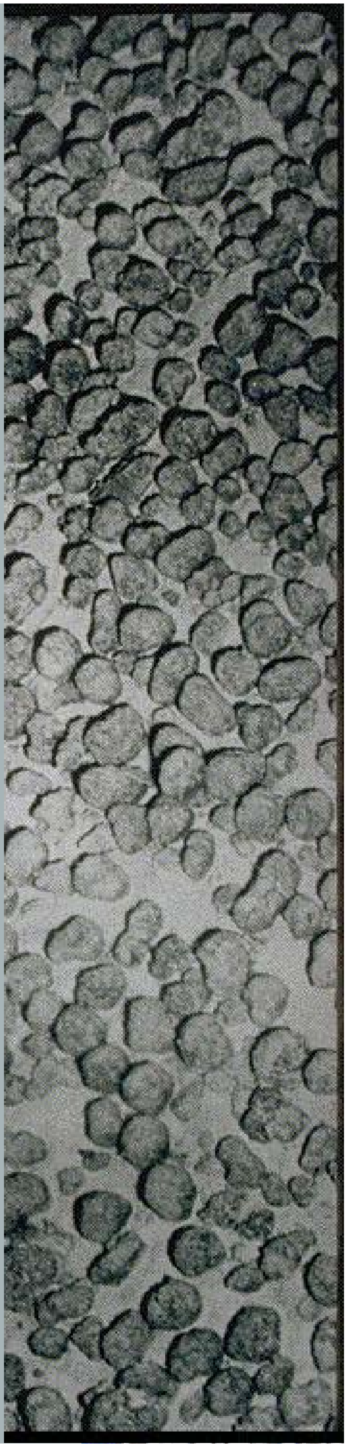
Mining Systems

- *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*



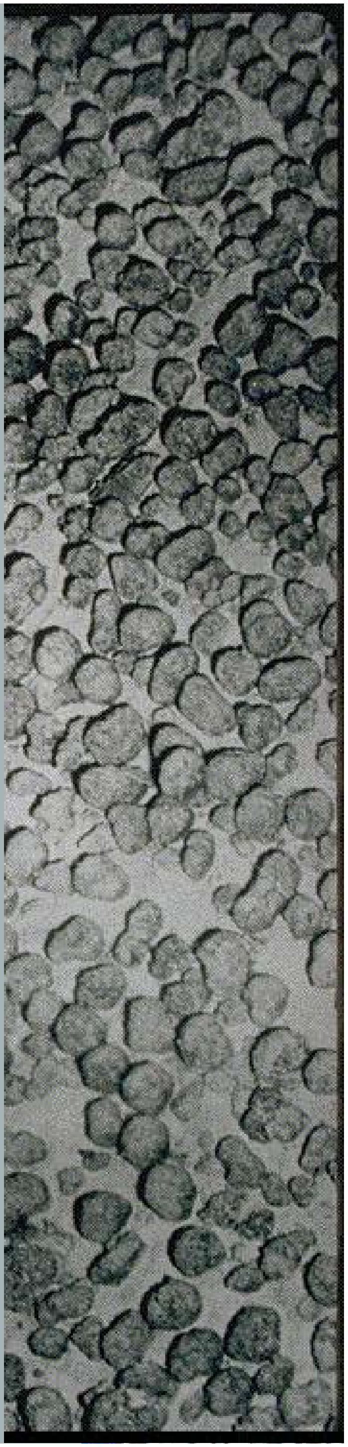
Future Research I

- 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



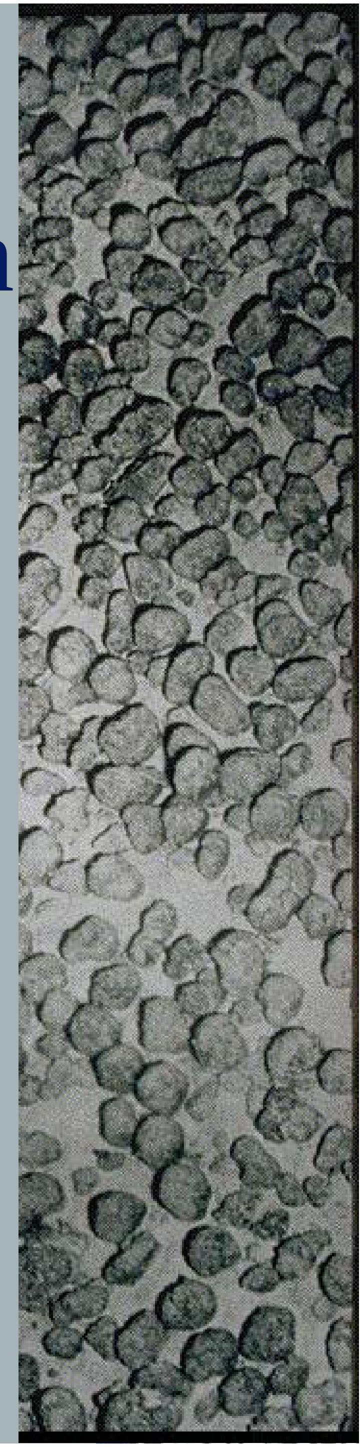
Future Research II

- 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



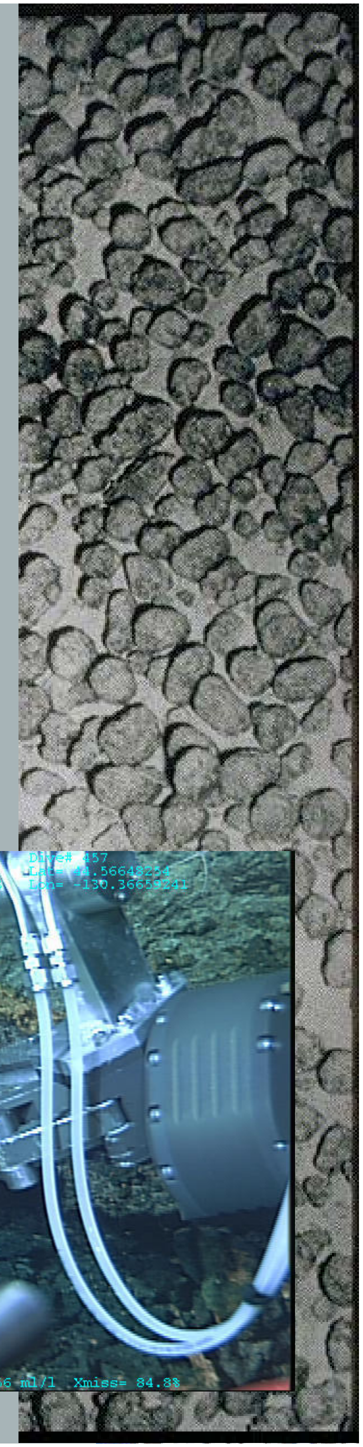
Largest Impediment to Exploration

- *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

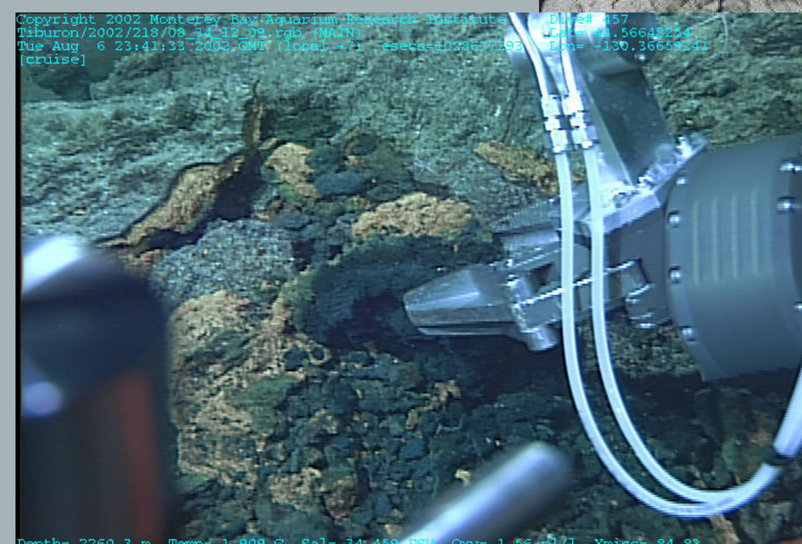


Six Regional Criteria

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

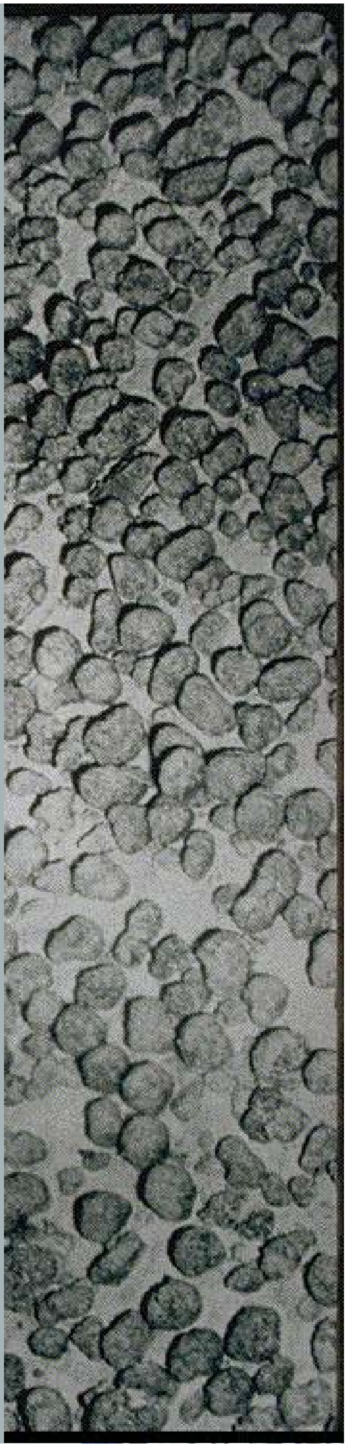
Six Site-Specific Criteria

1. Summit terraces, saddles, and passes
2. Slope stability
3. Subdued small-scale topography
4. Absence of local volcanism
5. Crust thicknesses $\geq$40 mm
6. Cobalt contents $\geq$0.8%



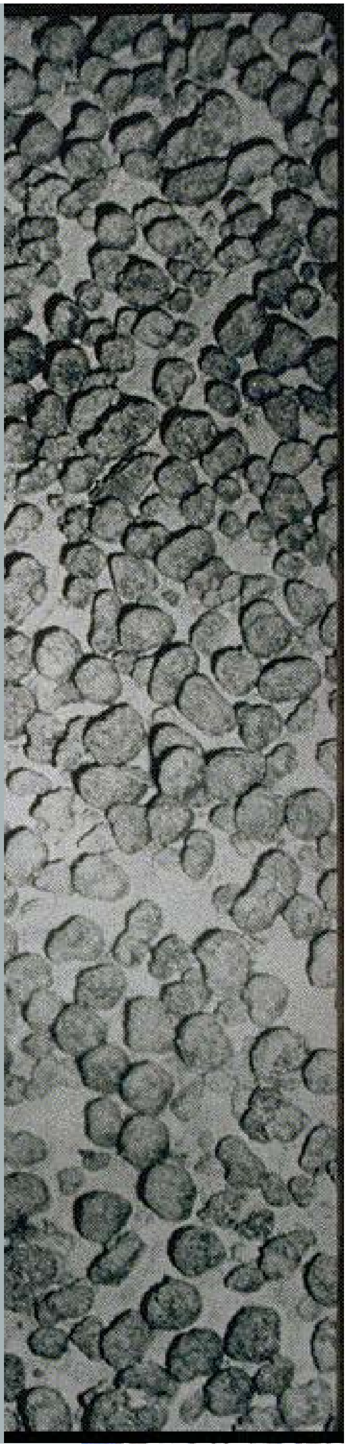
Reconnaissance Exploration Technique

- *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*

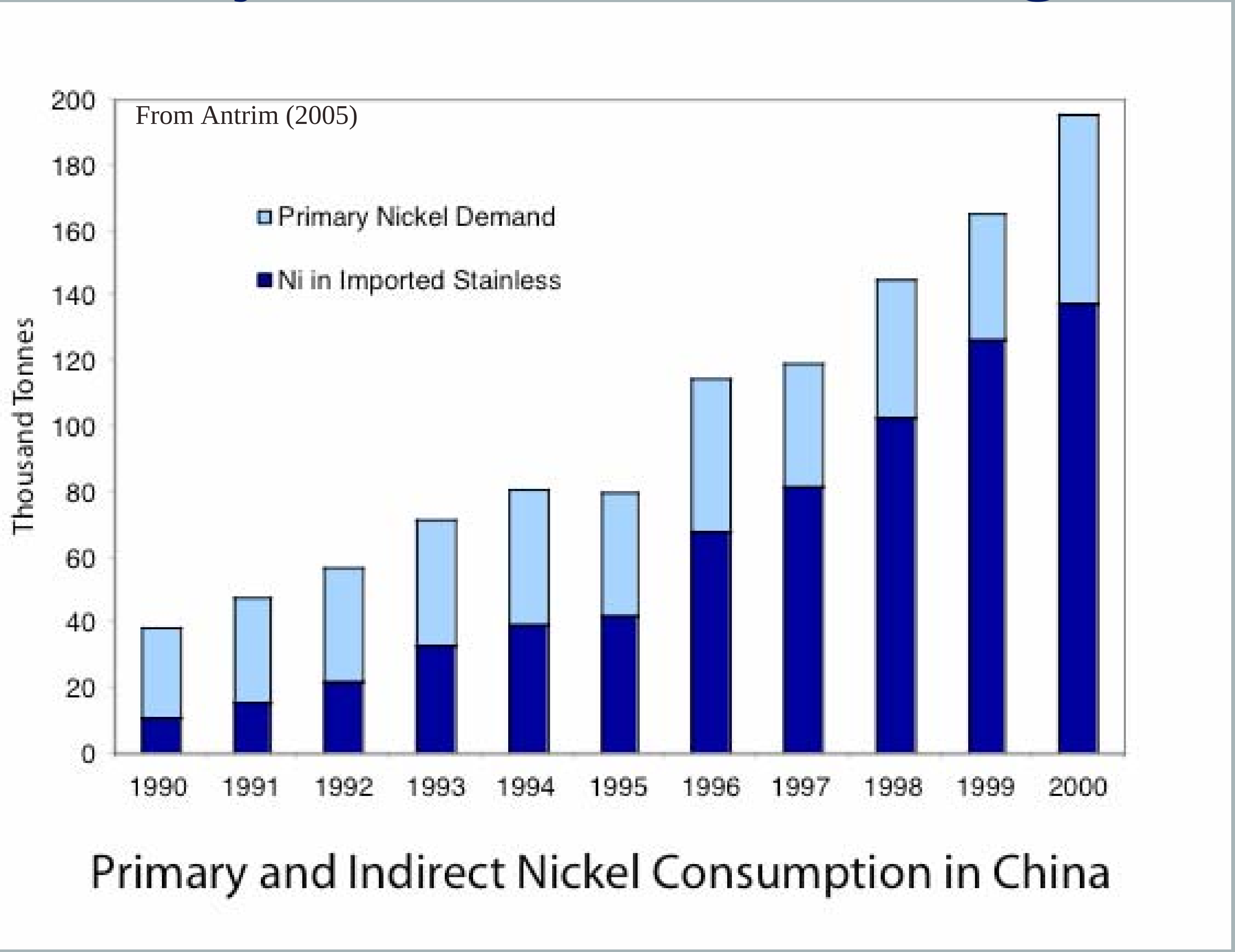


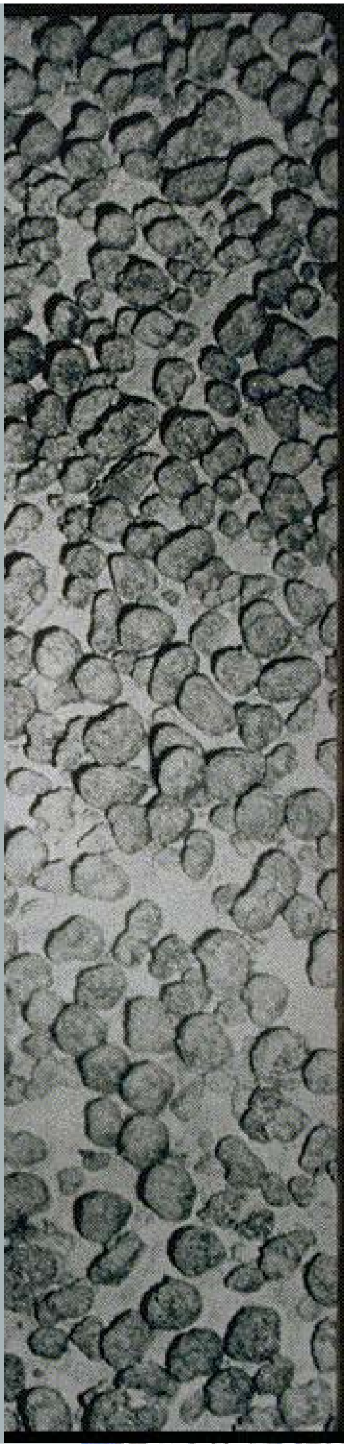
Suggested Site-Specific Techniques

- *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*

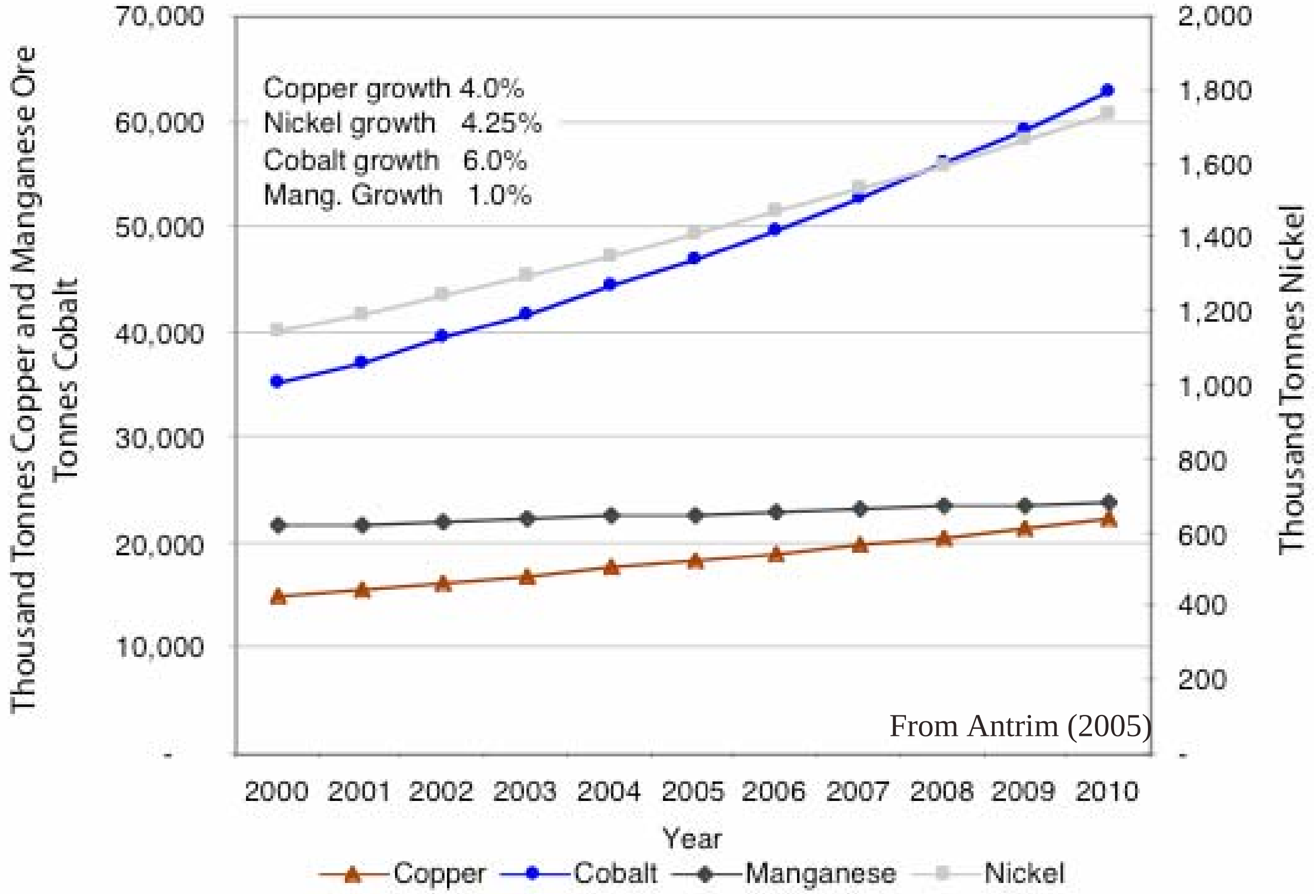


Ni consumption increased five fold in 10 years and continues to grow

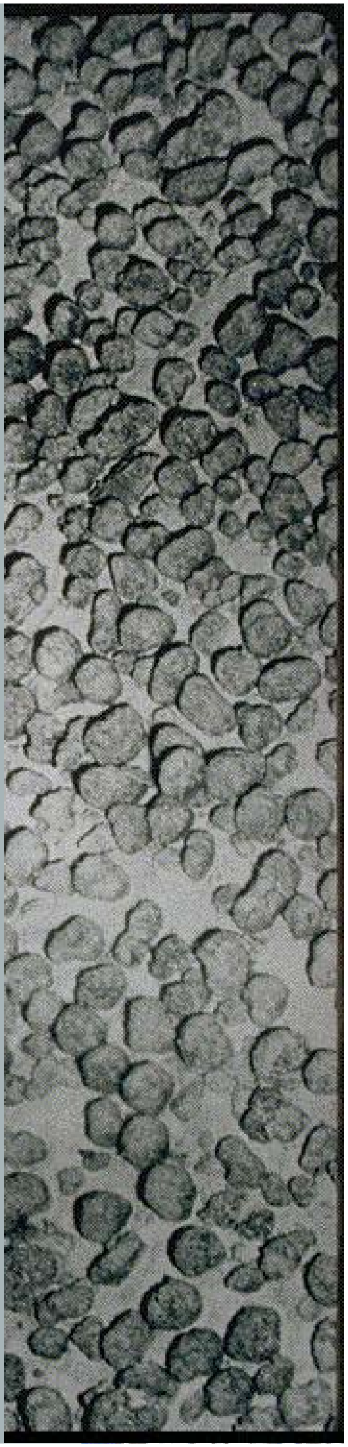




Projected world consumption of select metals



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 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*