Seafloor Massive Sulfide Deposits

Towards an Estimate of Global SMS Potential

uOttawa

SCHOOL OF MINES COLORADO 1874

GEOMAR

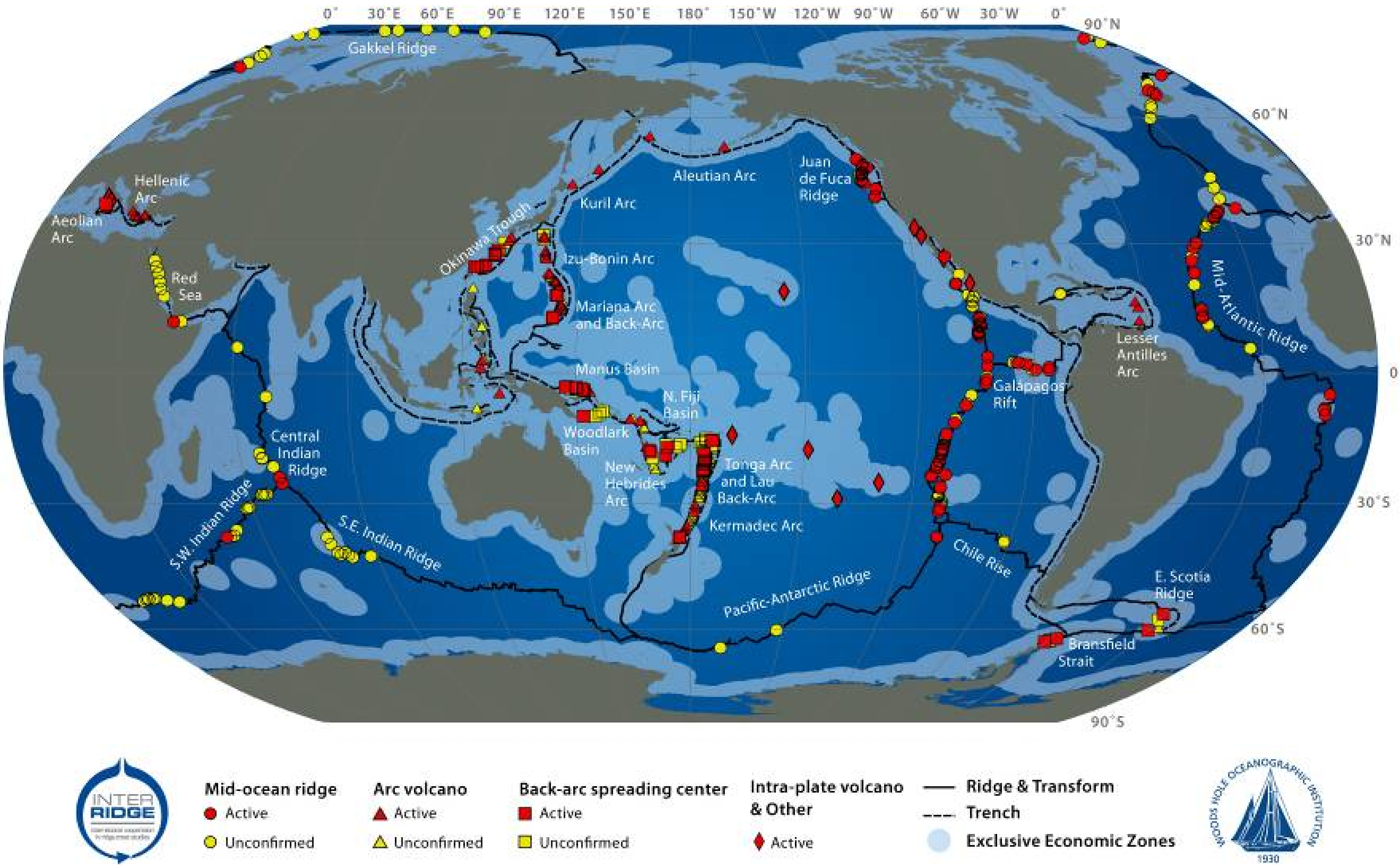
Hannington M.
Jamieson J.
Monecke T.
Petersen S.

January 17, 2011 First Seabed Mining Licence

Report to the European Commission

- Annual increase of about 15% in the price of non-energy raw materials
- A risk of supply shortage for commodities critical to Europe's economy
- Advances in technology are encouraging seafloor exploration
- By 2020, 5% of the world's minerals, including cobalt, copper and zinc, could come from the ocean (10% by 2030)
- Marine mining can be expected to grow to €5 billion in the next 10 years (€10 billion by 2030)

Global Distribution of Hydrothermal Vents



Distribution of Sea-Floor Hydrothermal Vents

- 140 sites of high-temperature venting (black smokers)
- 65% at mid-ocean ridges (64,000 km)
- 22% in back-arc basins (25,000 km including arcs)
- 12% on submarine volcanic arcs (incompletely explored)
- <1% on intraplate volcanoes

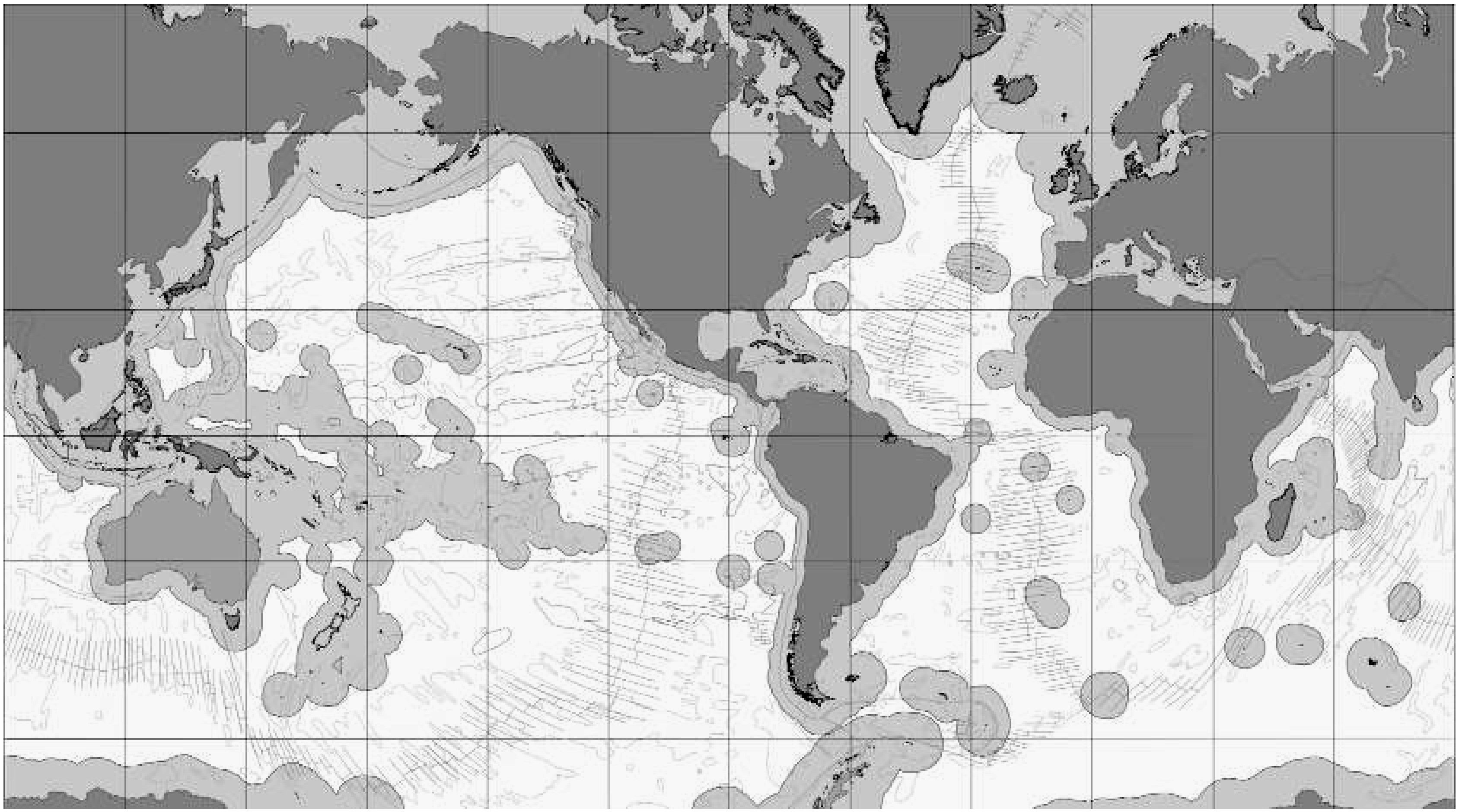
Volcanic & Tectonic Settings

12 different tectonic settings

- mid-ocean ridges (fast, intermediate, slow, ultraslow spreading centers)
- ridge-hotspot intersections
- ridge-transform intersections
- off-axis volcanoes
- intraplate volcanoes
- sediment-covered ridges
- intracontinental rifts, rifted margins
- intraoceanic arcs
- transitional (or island) arcs
- continental margin arcs
- intraoceanic back-arc basins
- intracontinental back-arc basins

Hannington et al. (2005) 100th Anniversary Volume of Economic Geology

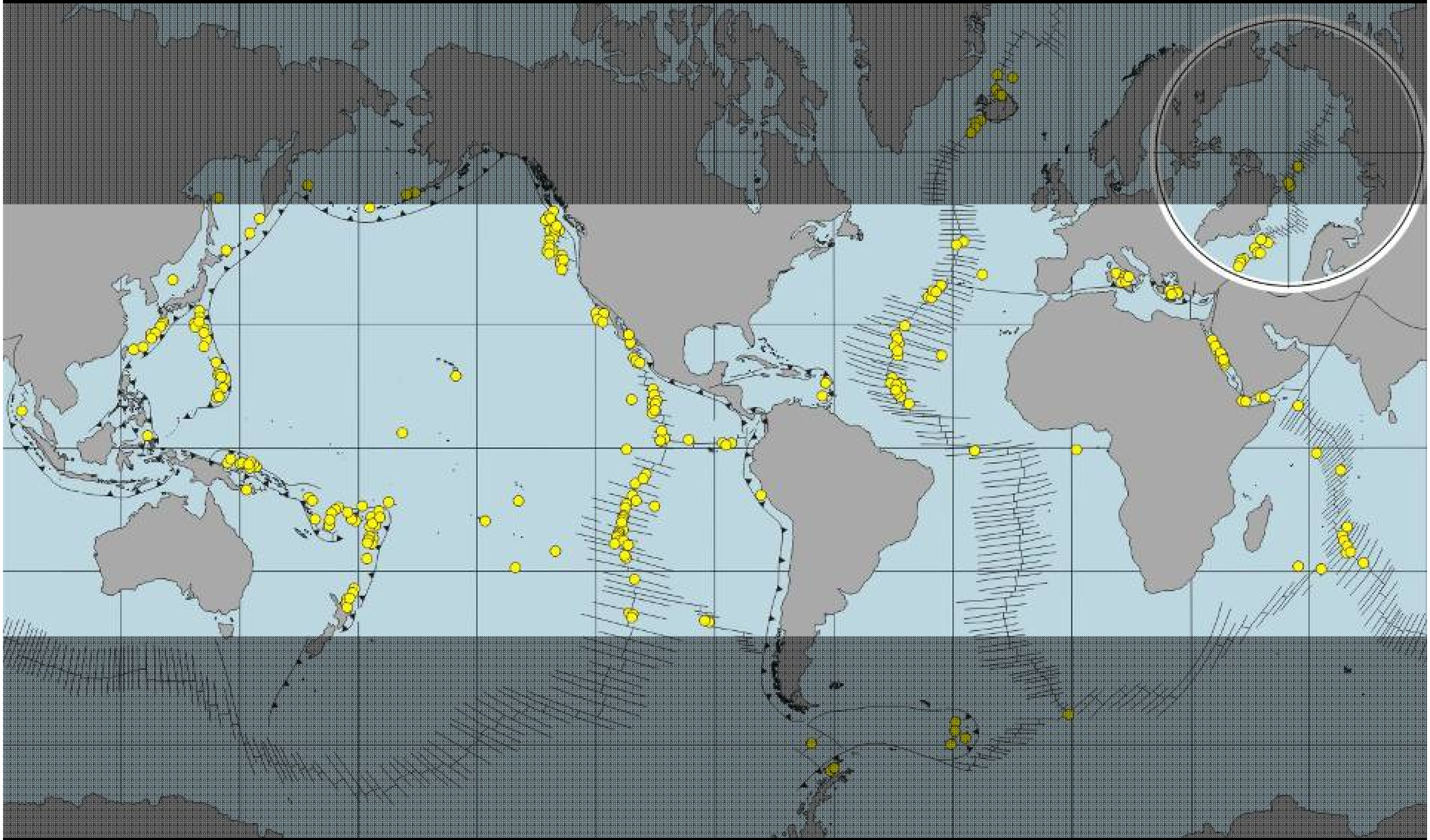
EEZs versus “The Area”



- Submarine volcanic arcs and back-arc basins are almost entirely in EEZs
- Mid-ocean ridges are almost entirely in “The Area”


37ºS East Pacific Rise

Technically Off Limits



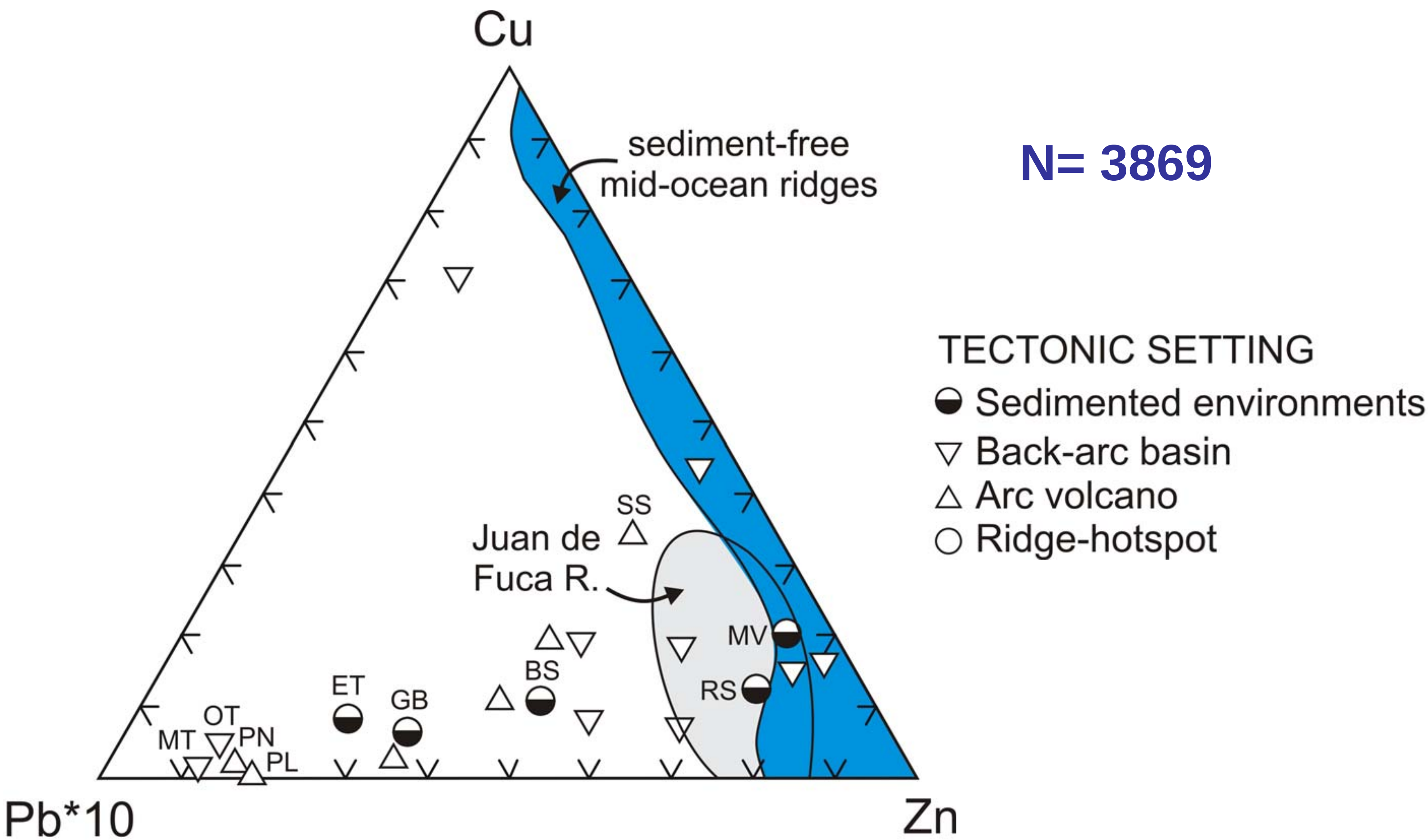
The global database ...

- 327 sites with manifestations of hydrothermal activity
- 140 sites of active venting or polymetallic sulfides
- 187 sites of other hydrothermal manifestations

- 1,250 literature references and other data sources
- 3,800 chemical analyses of polymetallic sulfides (95 sites)
- increasing by about 10% per year

New discoveries are being made ... but are they different from what has already been found?

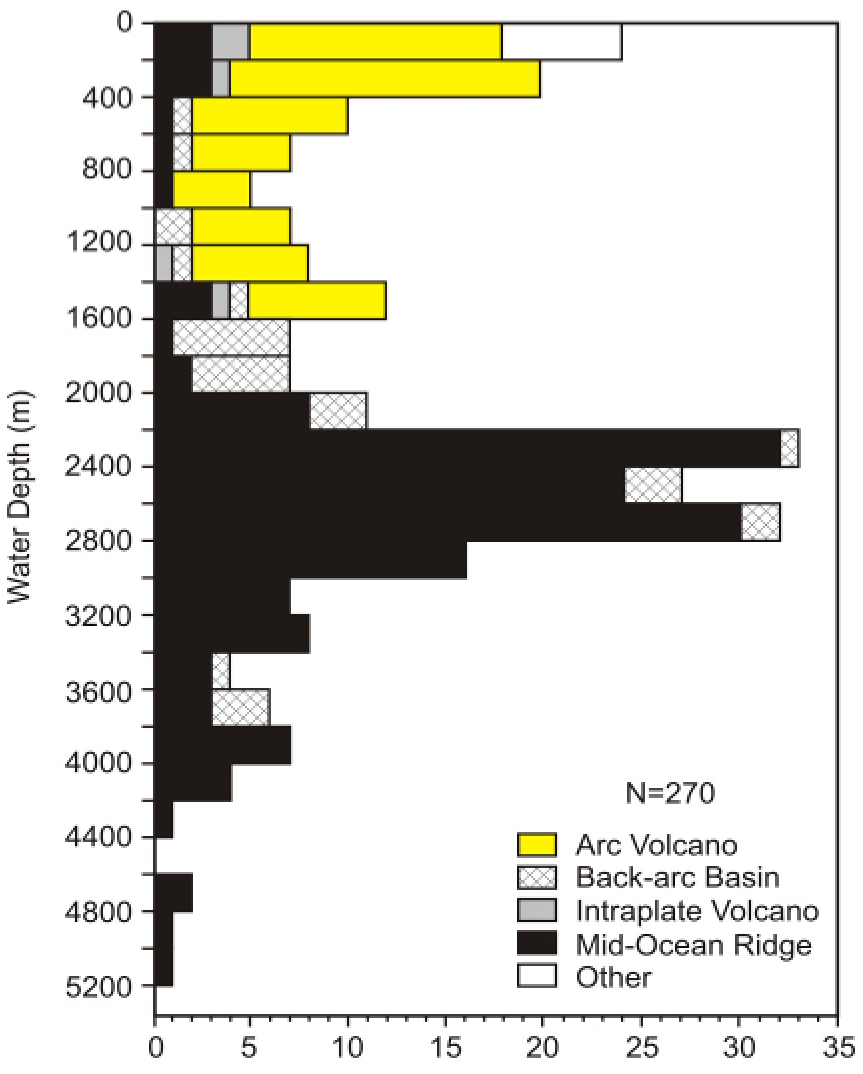
Bulk Compositions

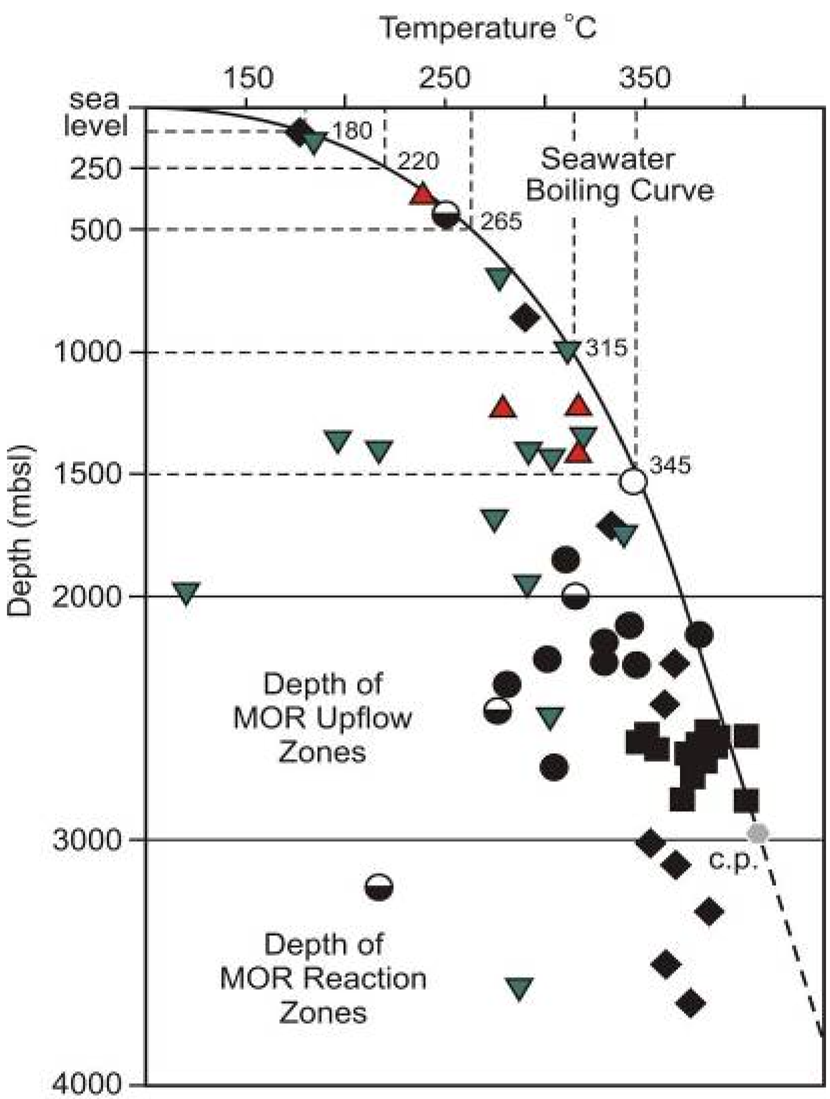


N= 3869

Hannington et al., 2005

Water Depth





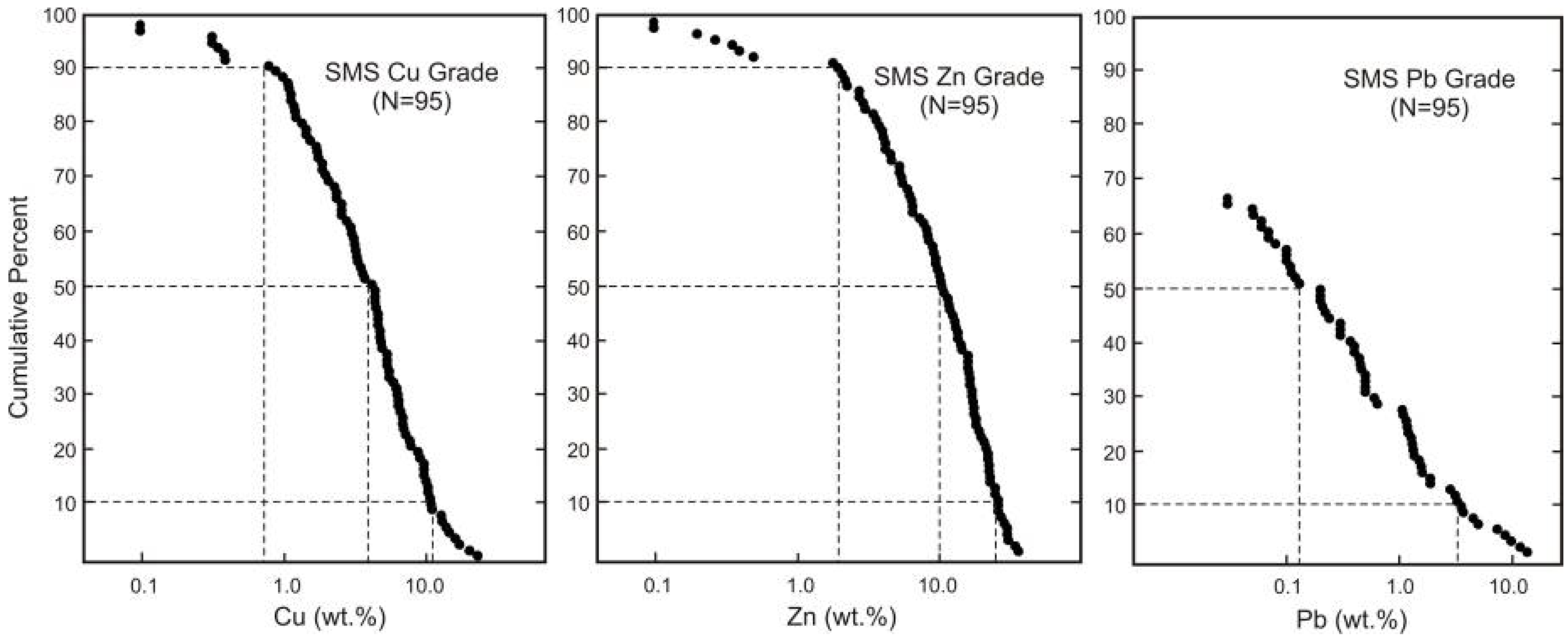
Hannington et al., 2005

Grade Distribution

Average bulk compositions of 95 SMS deposits, 3869 surface samples

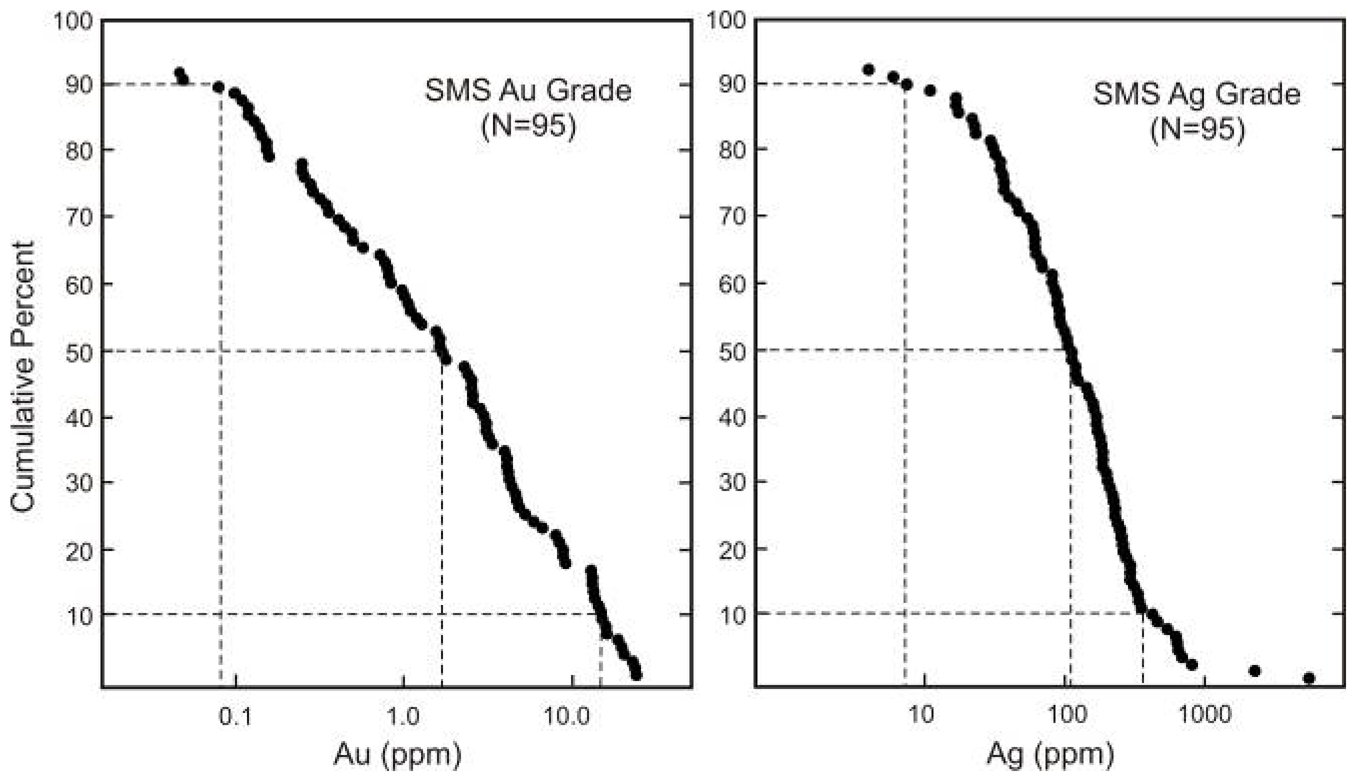
Geological Setting	N	Cu	Zn	Pb	Au	Ag
		wt%			ppm	
Mid-Ocean Ridges	2071	5.9	6.1	<0.1	1.6	89
Sedimented Ridges	173	1.1	3.6	0.5	0.5	84
Intraoceanic Back-arc	668	3.9	16.4	0.9	6.6	210
Intraoceanic Arc	169	5.3	17.7	2.4	9.6	407
Transitional Arc	728	6.4	14.8	2.0	12.2	692
Continental Margin Arc	60	3.1	20.3	10.0	2.3	953
Solwara 1 (Surface)	250	9.7	5.4	1.1	14.9	174

Grade distribution ...



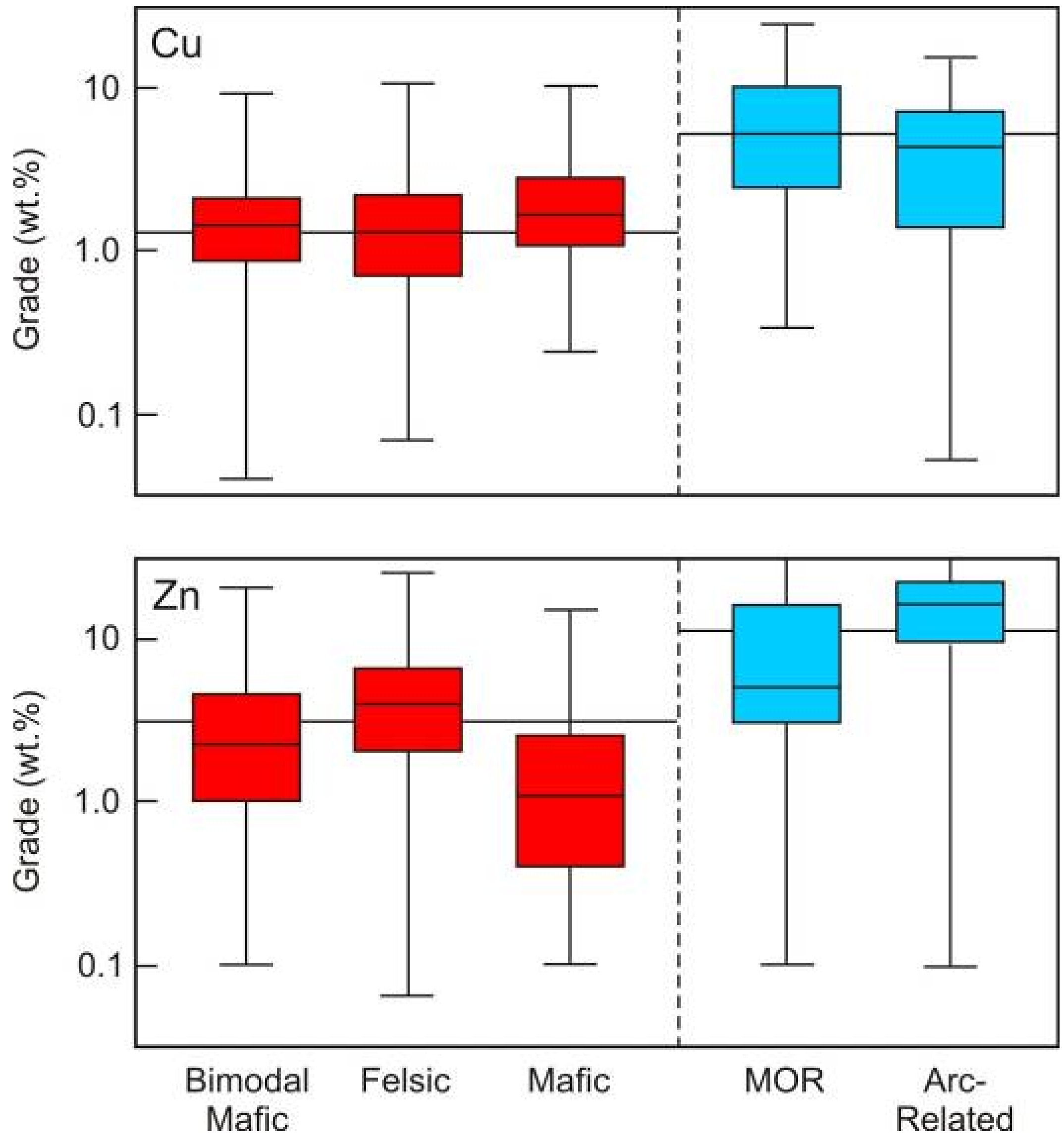
The median deposit has grades of 4.3% Cu, 10.6% Zn, and 0.1 % Pb

Grade distribution ...

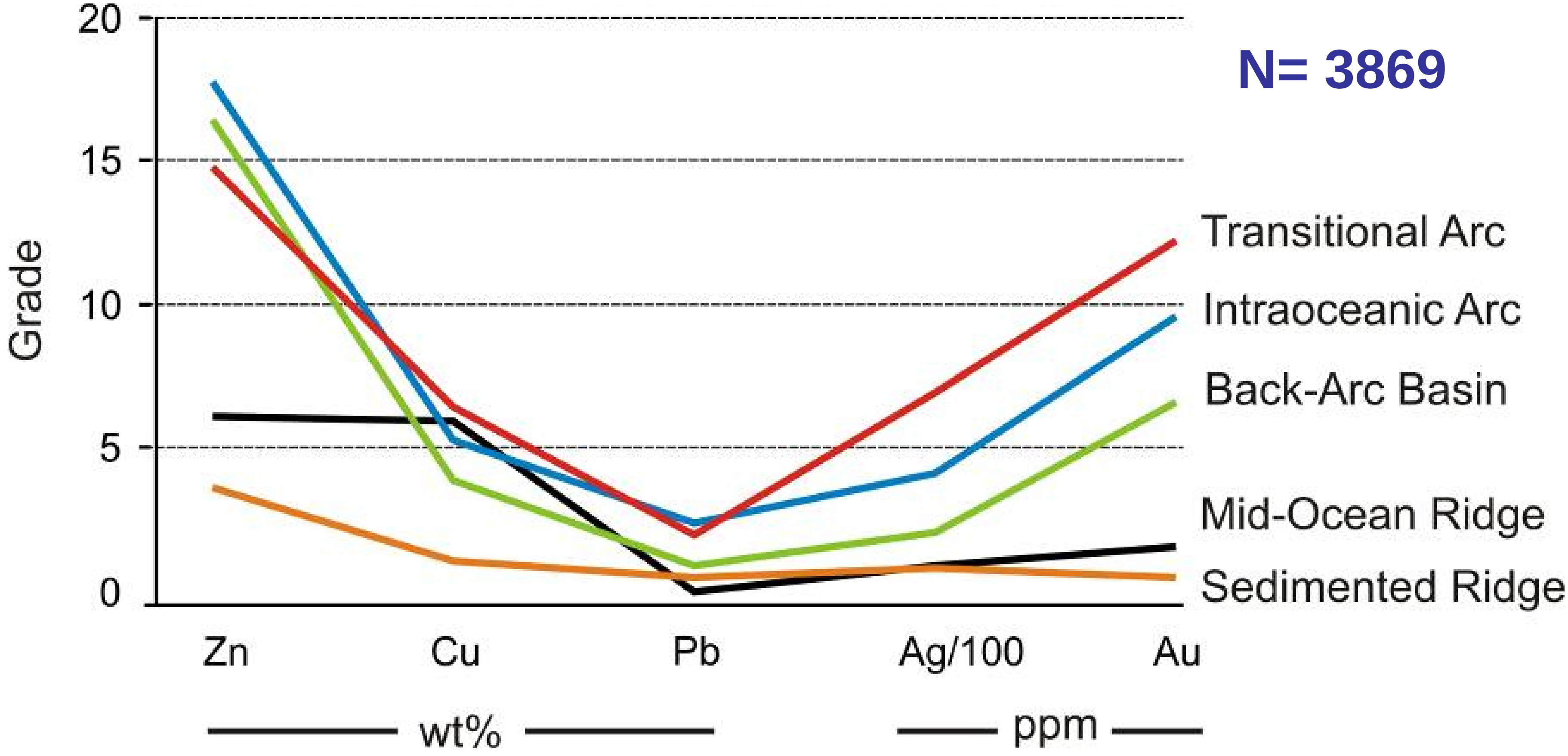


... and precious metal grades of 1.7 g/t Au and 107 g/t Ag

Comparison with Ancient VMS



Average grades of surface samples



Hannington, unpubl.

Trace Element Signatures of the Basement

- Ba enrichment at Axial Seamount, Lucky Strike (E-MORB vs N-MORB)
- Pb enrichment in Juan de Fuca deposits (FeTi basalt)
- Hg enrichment in Endeavour Ridge sulfide deposits (buried sediment)
- Ni enrichment in Logatchev, Rainbow sulfides (ultramafic substrate)

Axial Seamount, Ba-rich basalt

Trace Elements in Ancient VMS

Table 4 Concentration ranges of selected trace elements in VMS

Concentrations	Trace elements
To 10 000 ppm	As, Sb, Cd
To 1000 ppm	Co, Sn, Se
To 500 ppm	Ni, Mo, Bi, In, Te
To 100 ppm	Hg, Tl, W, Ge, Ga

Hannington, in press

Draft Regulations

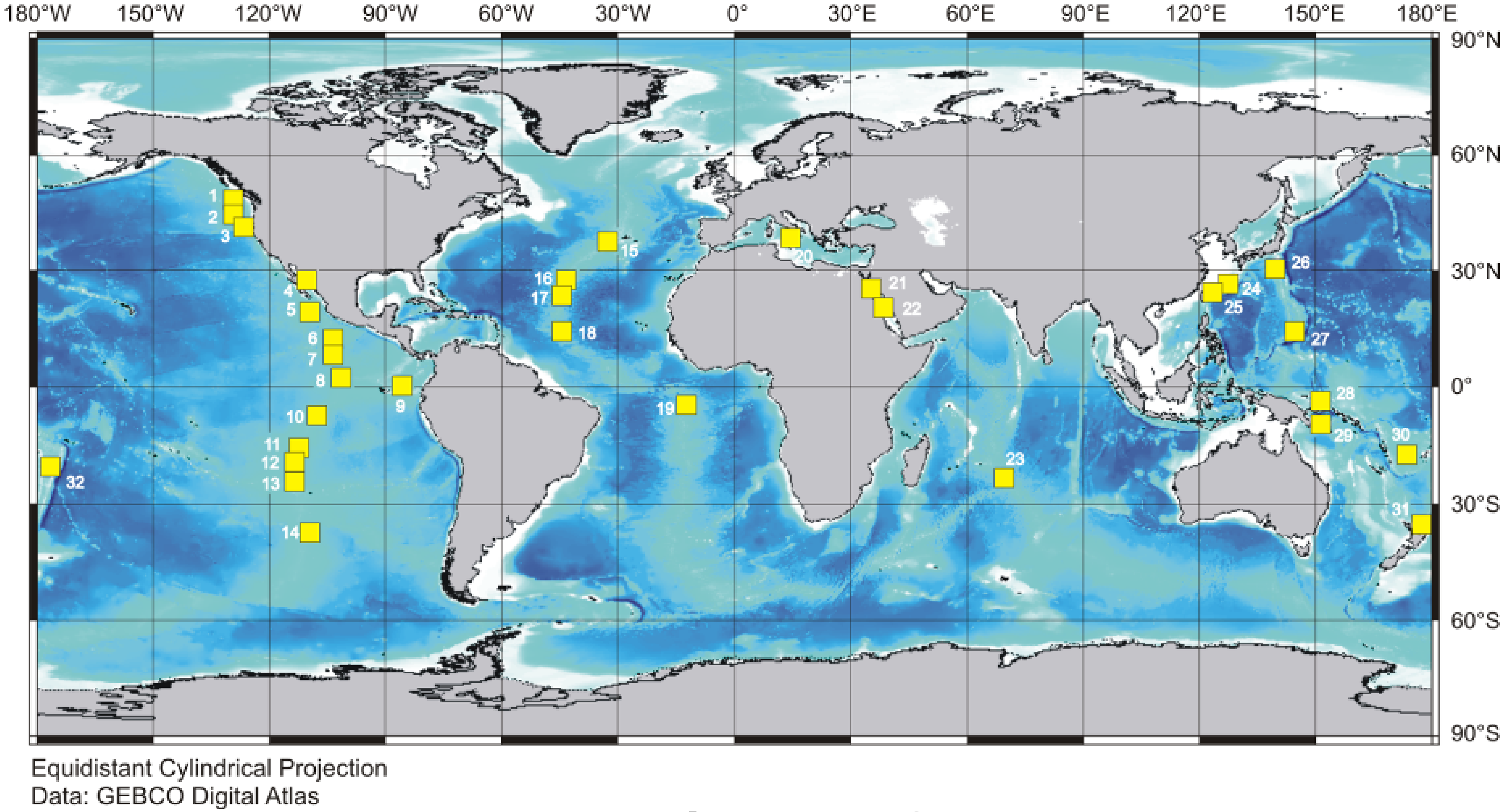
ISBA/12/C/3/Part II

Global Exploration Models for Polymetallic Sulphide Deposits in the Area: Possible Criteria for Lease Block Selection under the Draft Regulations on Prospecting and Exploration for Polymetallic Sulphides

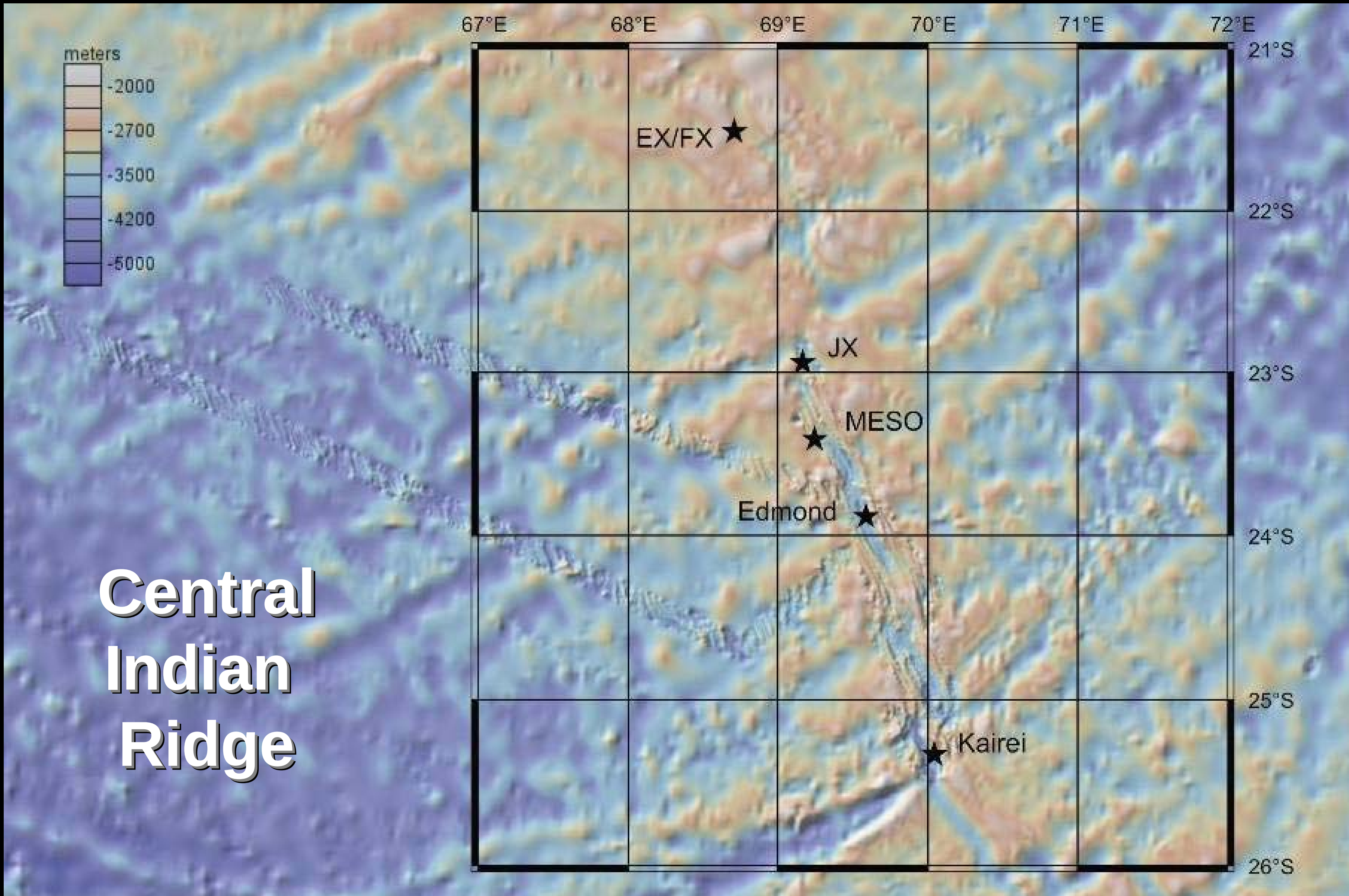
Prepared for the International Seabed Authority by
Mark Hannington and Thomas Monecke
University of Ottawa
June 21, 2006

Marine Georesources and Geotechnology, 2009, v. 27, no. 2

Deposit Densities

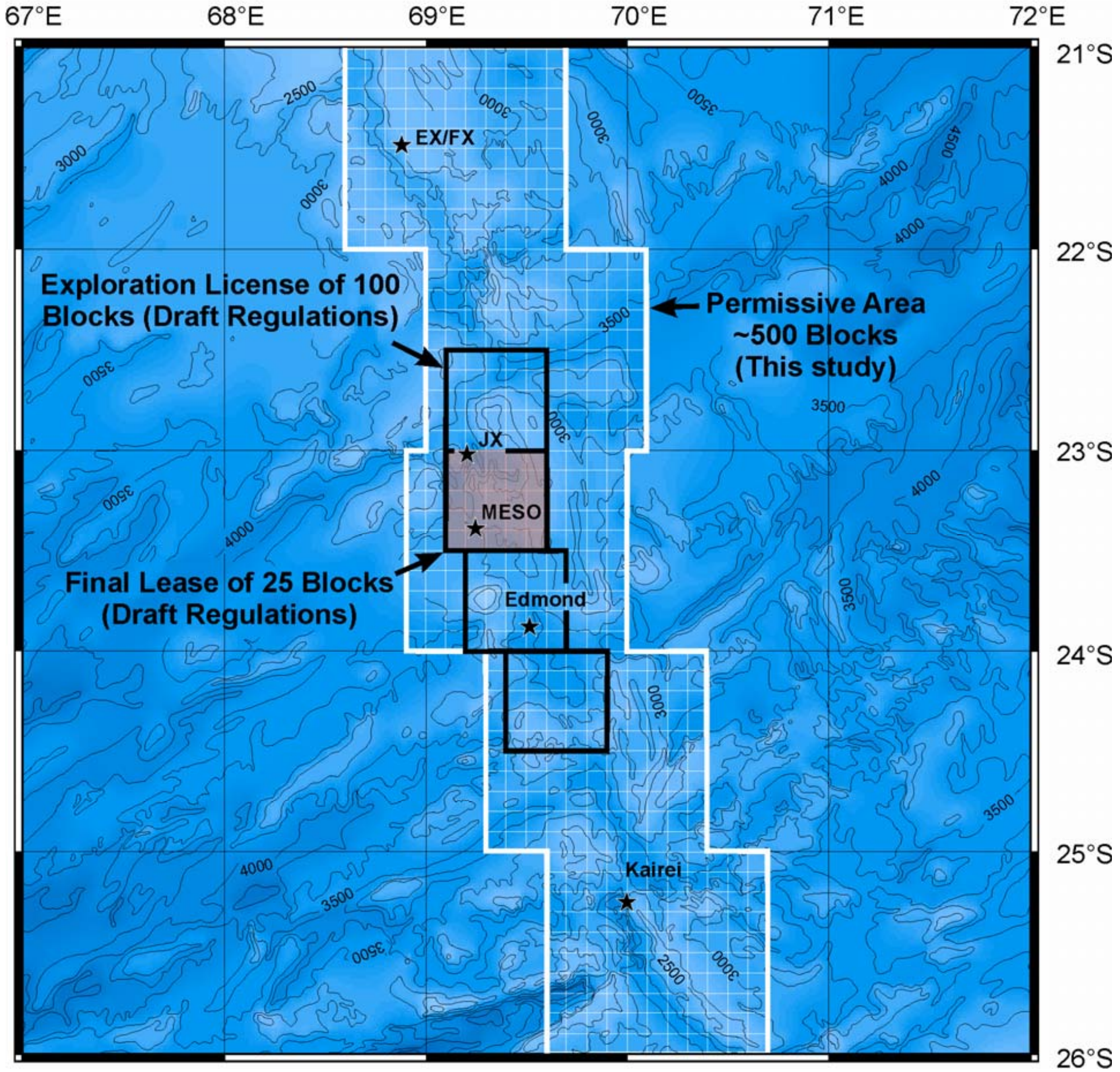


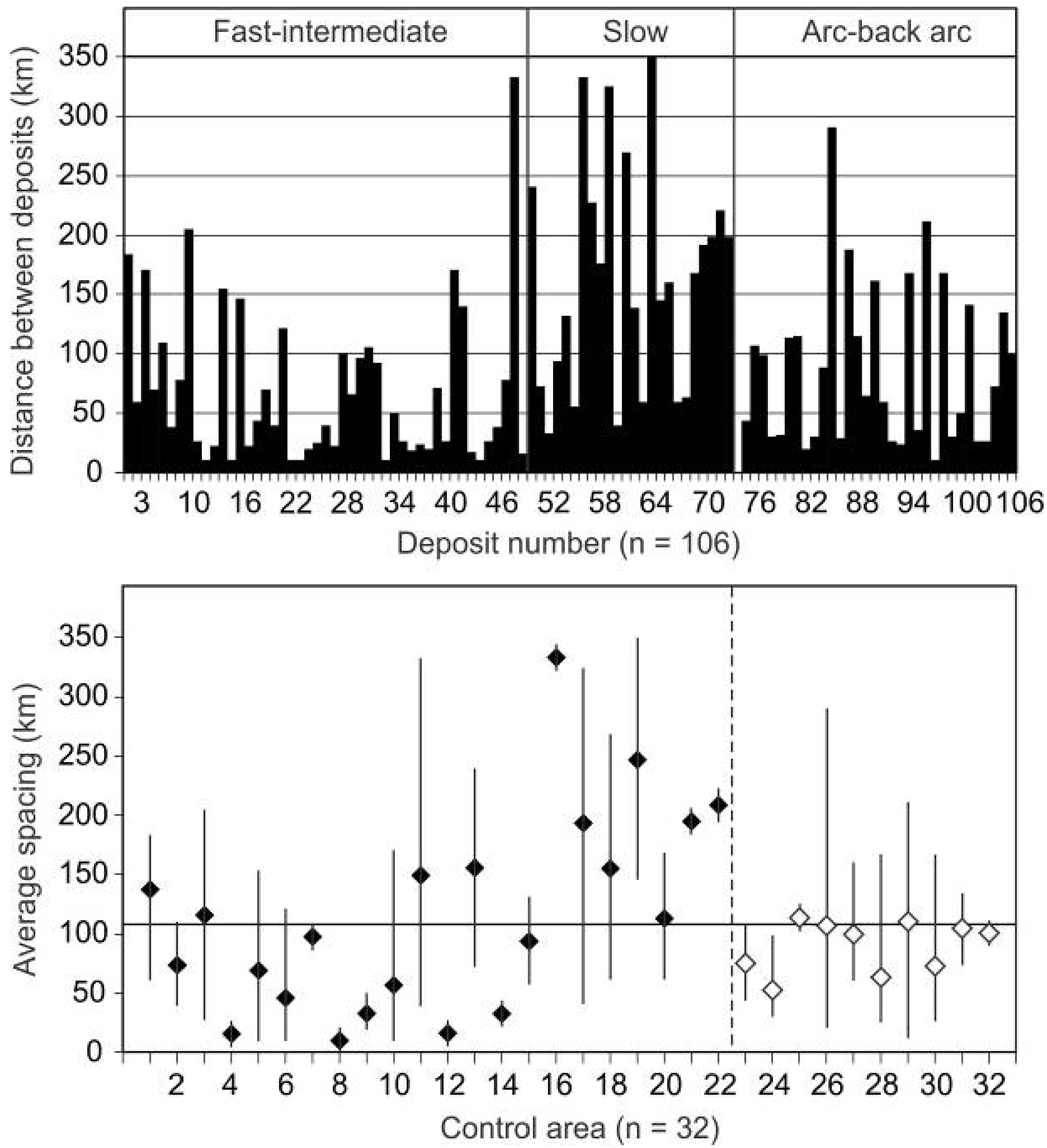
32 Control Areas of 5° X 5°


Central Indian Ridge
meters
-2000
-2700
-3500
-4200
-5000
67°E
68°E
69°E
70°E
71°E
72°E
21°S
22°S
23°S
24°S
25°S
26°S
EX/FX
JX
MESO
Edmond
Kairei

Permissive Areas for SMS Exploration

In each 5 x 5 deg map, the areas considered to be “permissive” for deposits ranged from 25,000 to 100,000 km^2





Hannington et al., 2011

Number and Spacing of Deposits

The average permissive area contains 3.4 deposits

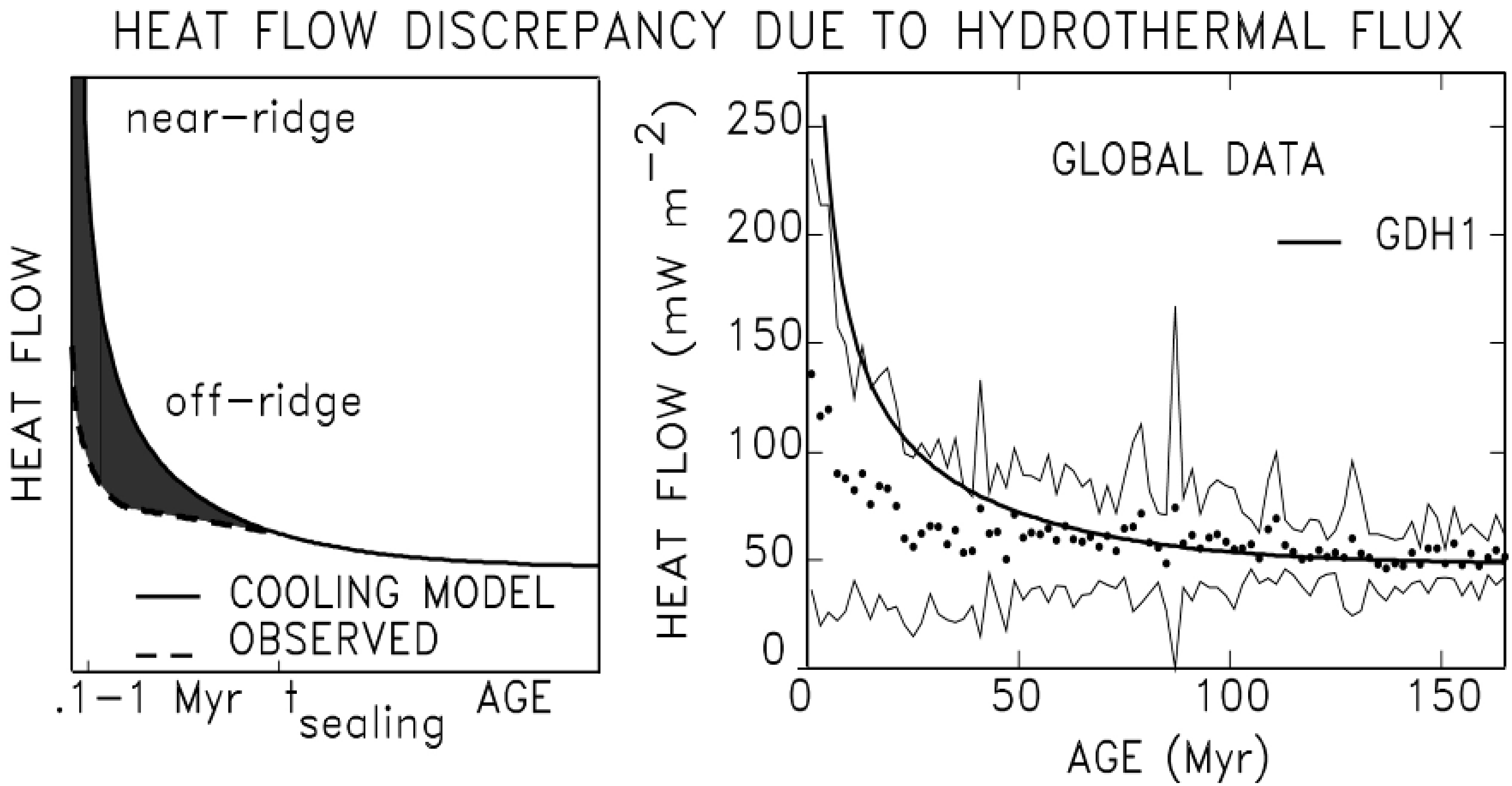
The average spacing between deposits is 98 km

89,000 km of ridge, arc, and back-arc basin should contain ~900 deposits

	Five Degree Map Area	Estimated Permissive Area (km^2)	Number of Occurrences In the Area (N=106)	Average Spacing (km) Between Occurrences
	In "the Area"			
1.	EPR, 13°N	80,000	8	54
2.	EPR, 9°N	50,000	4	23
3.	EPR, AHA Field	50,000	1	--
4.	EPR, 7°S	40,000	2	10
5.	EPR, 17°S	60,000	4	120
6.	EPR, 18°S	60,000	9	55
7.	EPR, 37°S	50,000	2	15
8.	MAR, TAG and Broken Spur	50,000	2	300
9.	MAR, 24°N and Snakepit	45,000	2	175
10.	MAR, 14°N and Logatchev	60,000	3	87
11.	MAR, 5°S	60,000	2	--
12.	Central Indian Ridge	50,000	5	108
	National EEZs			
1.	N. Juan de Fuca Ridge	56,000	3	86
2.	S. Juan de Fuca Ridge	40,000	4	40
3.	Gorda Ridge	50,000	4	67
4.	Guaymas Basin	40,000	1	--
5.	Galapagos Rift	50,000	1	--
6.	EPR, 21°N	50,000	3	10
7.	EPR, 23°S	110,000	4	250
8.	MAR, Lucky Strike, Menez	75,000	4	100
9.	Tyrrhenian Sea	35,000	3	70
10.	N. Red Sea	50,000	3	180
11.	S. Red Sea	52,000	1	--
12.	N. Okinawa Trough	60,000	4	53
13.	S. Okinawa Trough	45,000	3	75
14.	Izu-Bonin Arc	65,000	4	123
15.	Mariana Trough and Arc	75,000	3	165
16.	Eastern Manus Basin	25,000	6	48
17.	Woodlark Basin	40,000	1	--
18.	N. Fiji Basin	40,000	3	95
19.	S. Lau Basin	50,000	4	133
20.	Southern Kermadec Arc	70,000	4	110
	Average	55,000	3.4	98

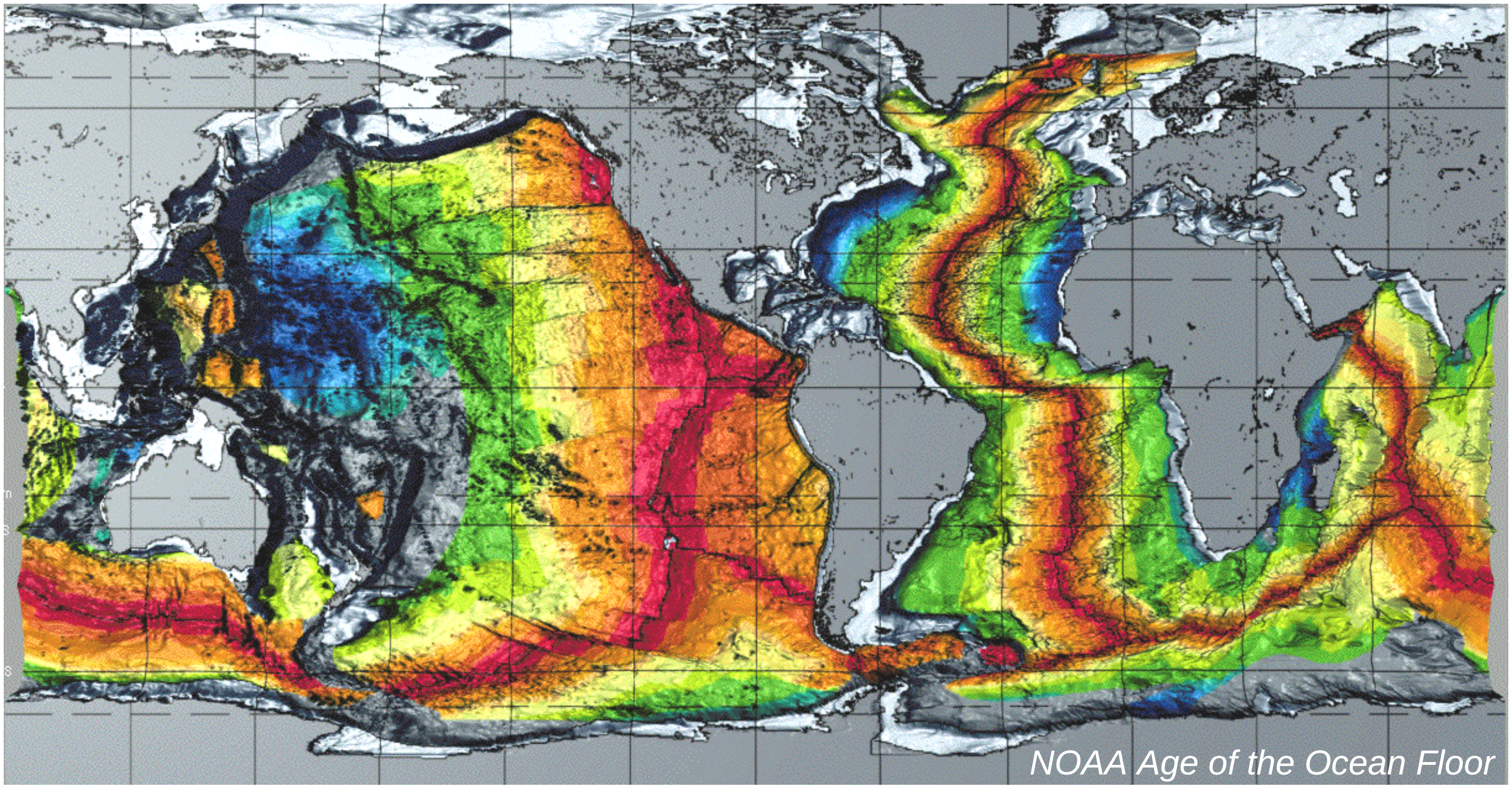
Comparison with Heat Flow Data

Lister, 1972



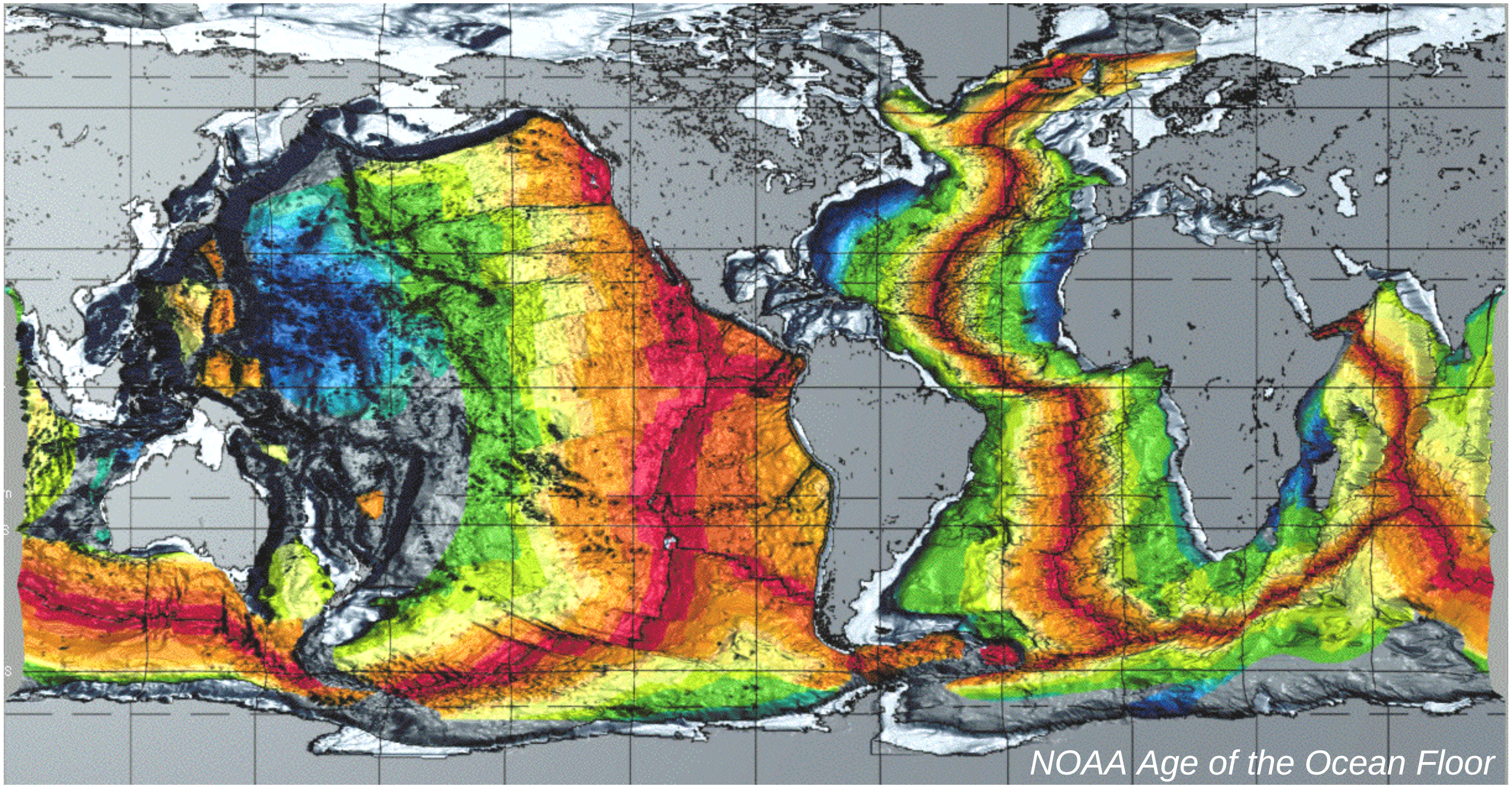
The missing heat = 1.8 x 10^{12} W (Mottl, 2003)

How many black smokers are there?

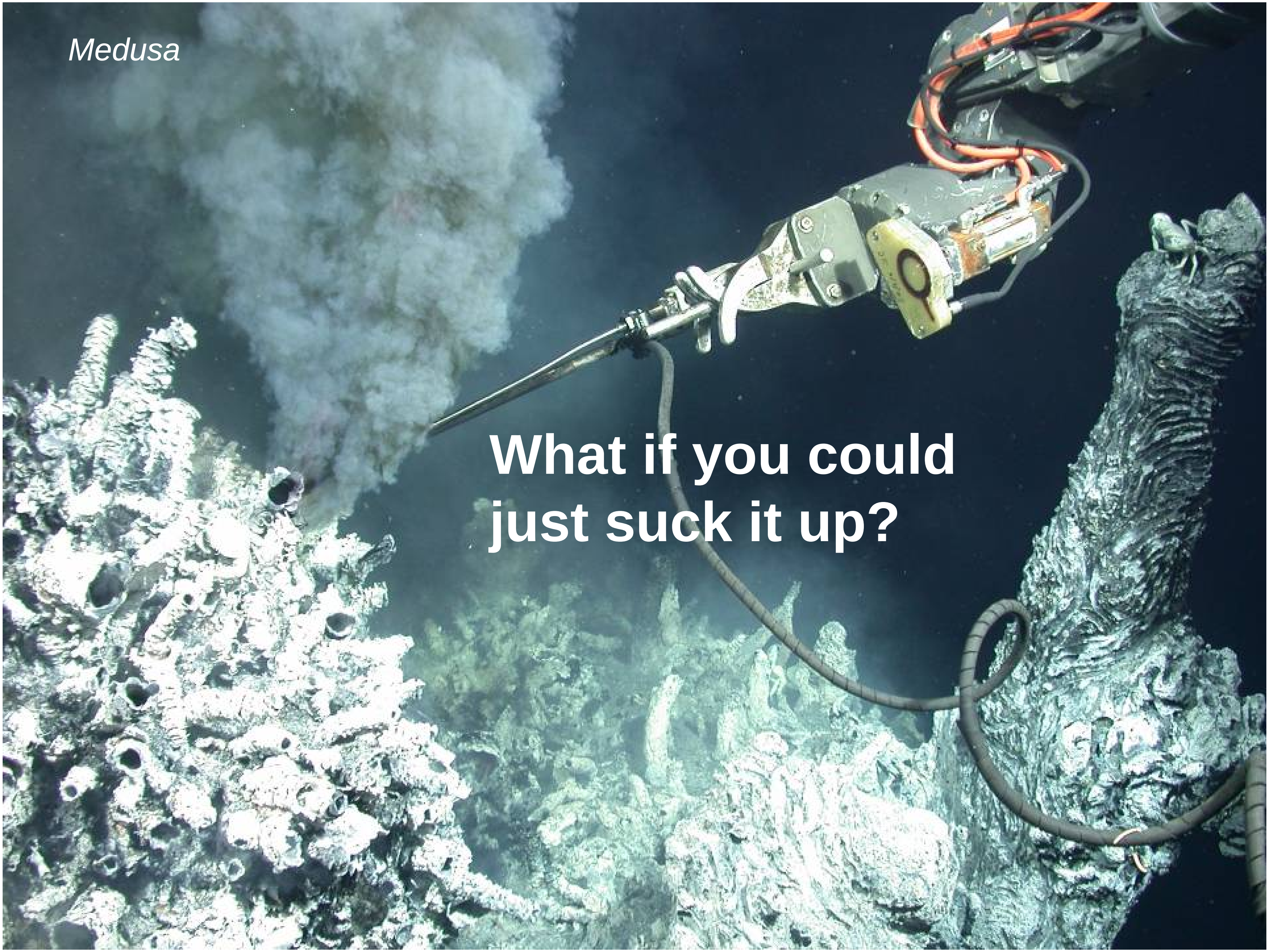


- 1.8×10^{12} W (Mottl, 2003)
- 10% at black smoker temperatures; the rest is diffuse
- 2 to 5 MW for a single black smoker (Converse et al, 1984)
- 50,000 to 100,000 black smokers (at least 1 every km of ridge axis)

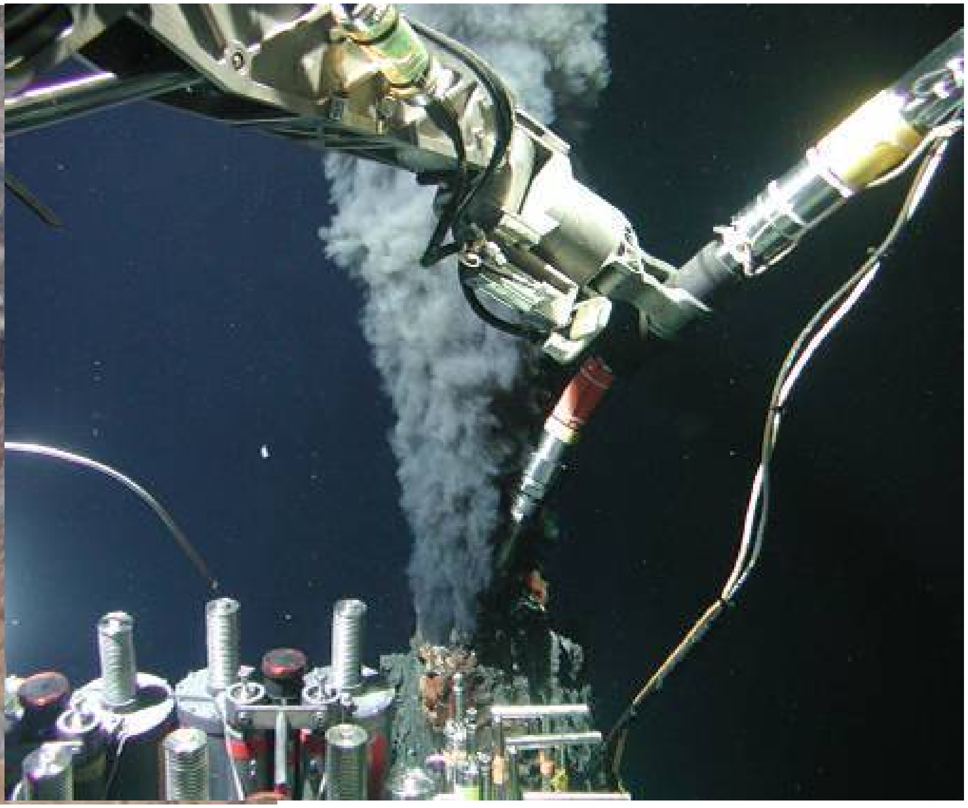
How many vent fields are there?



- 1.8 x 10^{12} W (10% at black smoker temperatures)
- 200 to 500 MW for a large field (100 black smokers)
- 1 large field every 50 to 100 km of ridge axis
- 500 to 1,000 deposits in the neovolcanic zones


Medusa
What if you could
just suck it up?

What if you could just suck it up ...?

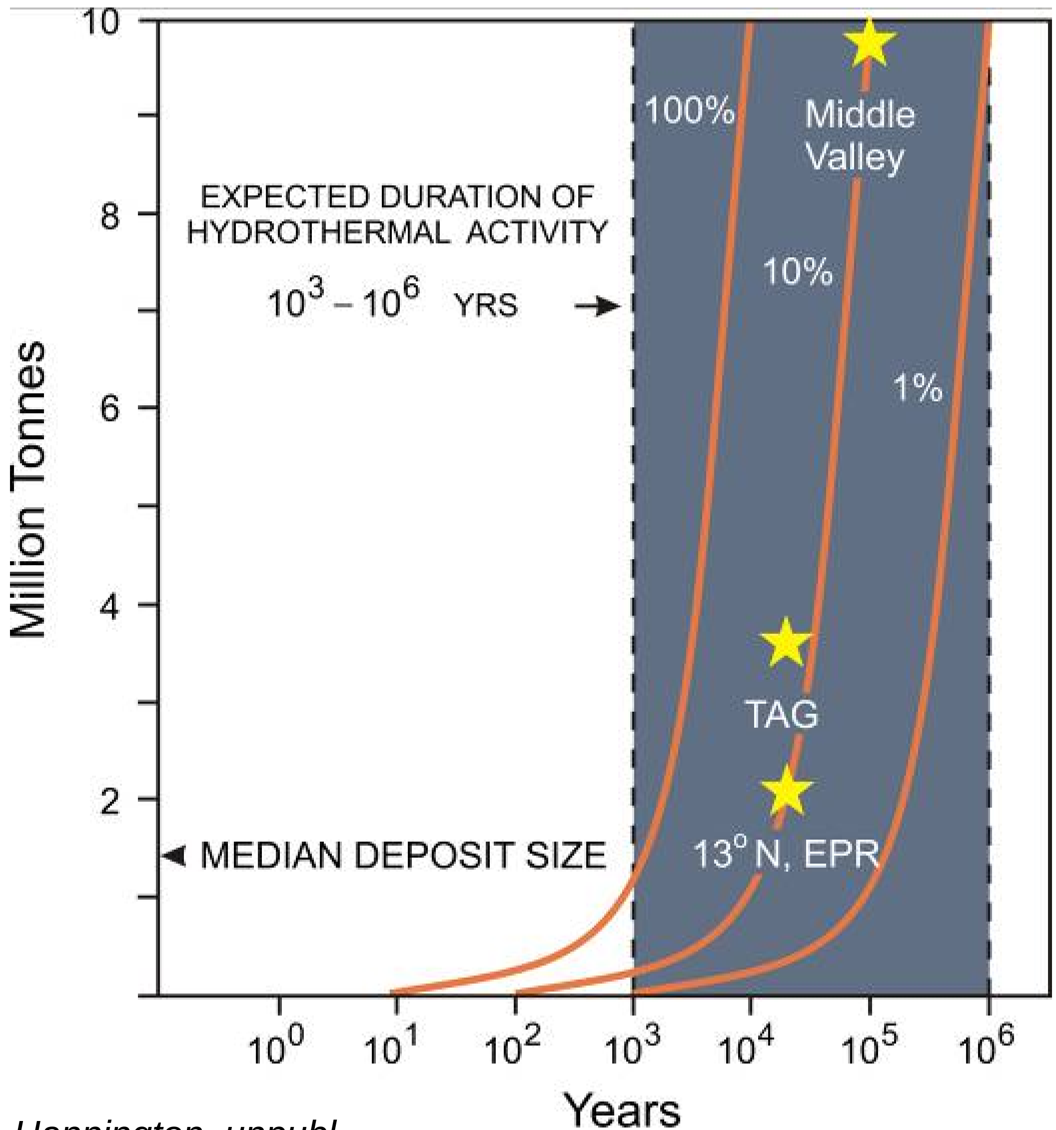


▪ Single Black Smoker	500 kg Cu metal/yr
▪ Large Vent Field	50,000 kg Cu metal/yr
▪ Kidd Creek Mine	75,000,000 kg Cu metal /yr

Deposit Sizes

- EPR-type <0.01 Mt
  meters to 10s of meters in diameter
- Galapagos-Type (TAG, MAR) 1-2 Mt
  150 m in diameter, 40 m high
- Sunrise, Solwara (Manus) 2-5 Mt
  300 m in diameter
- Middle Valley (JFR) 10 Mt
  massive sulfide and subseafloor replacement
- Atlantis II Deep (Red Sea) 90 Mt
  metalliferous sediment

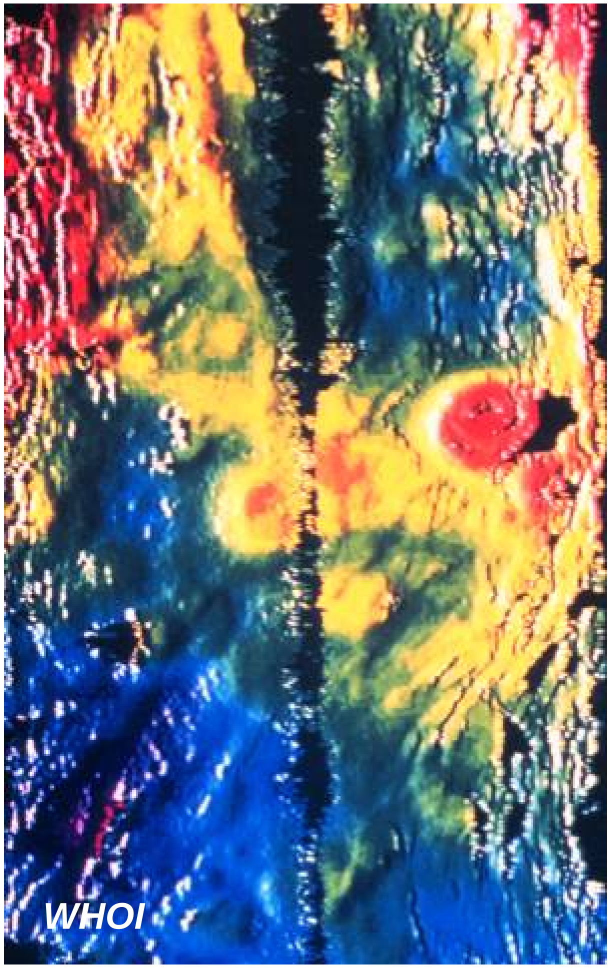
Mass Accumulation Rates



Hannington, unpubl.

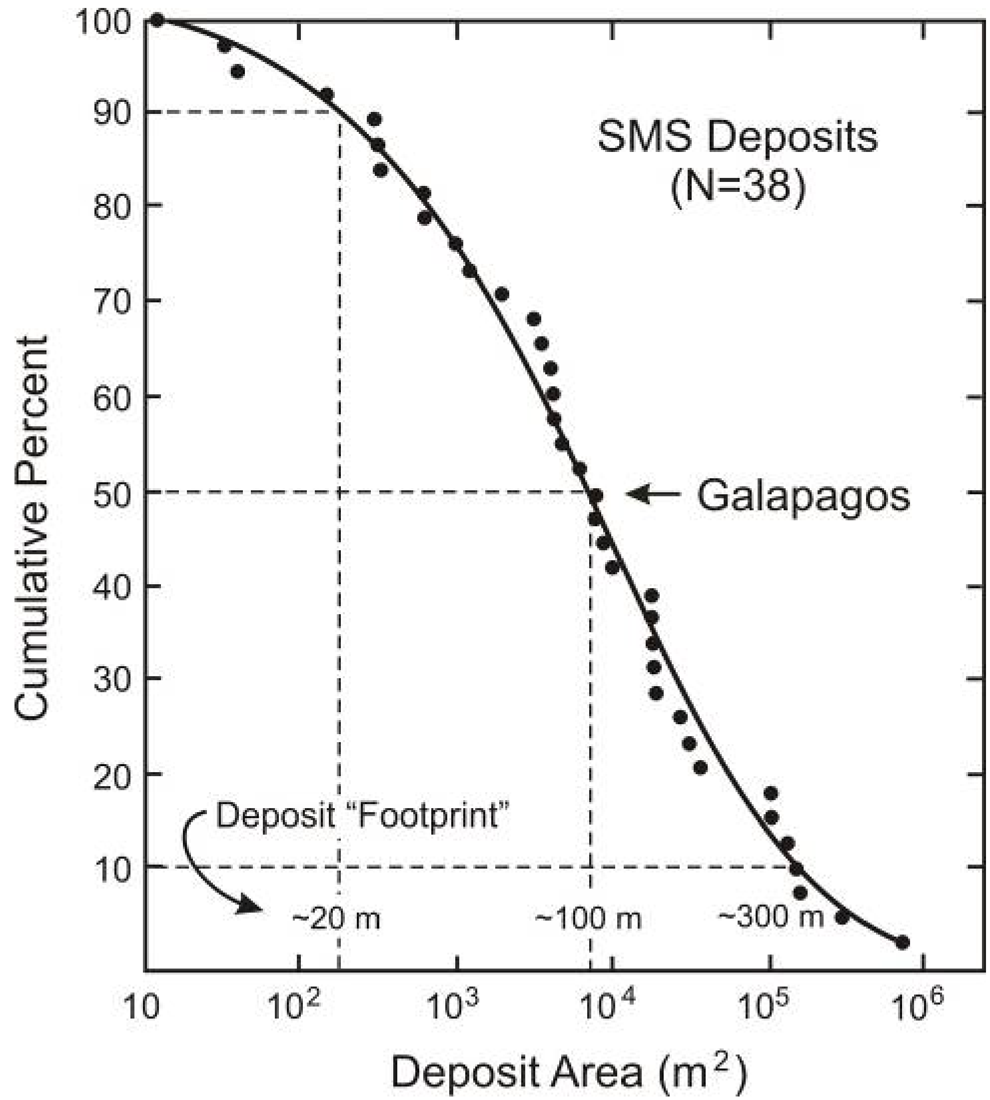
*(100 black smokers at 350°C)

“Footprints” on the Seafloor

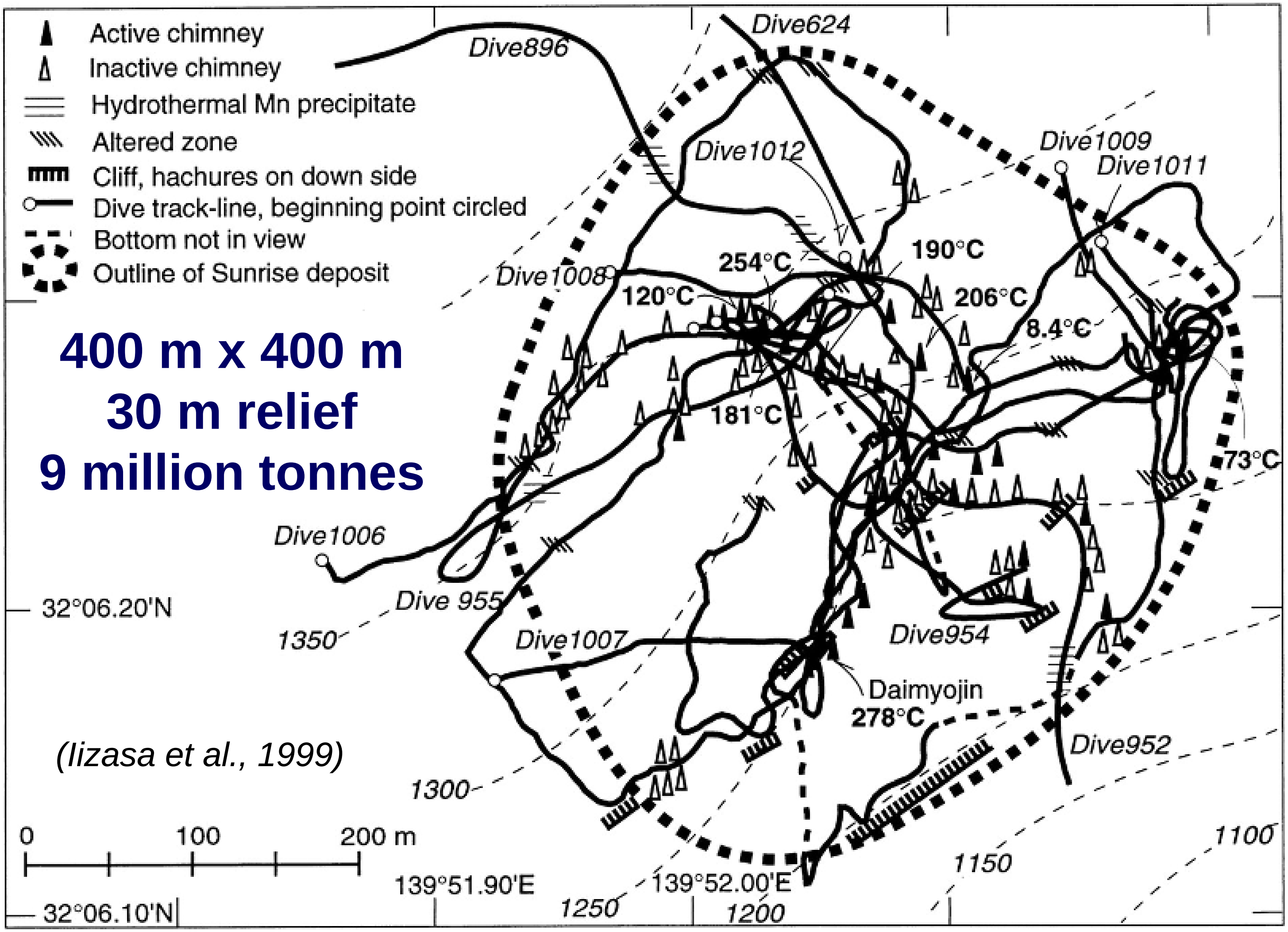


1 km

Jamieson and Hannington, 2010



Difficulties in Measuring the Sizes of Deposits



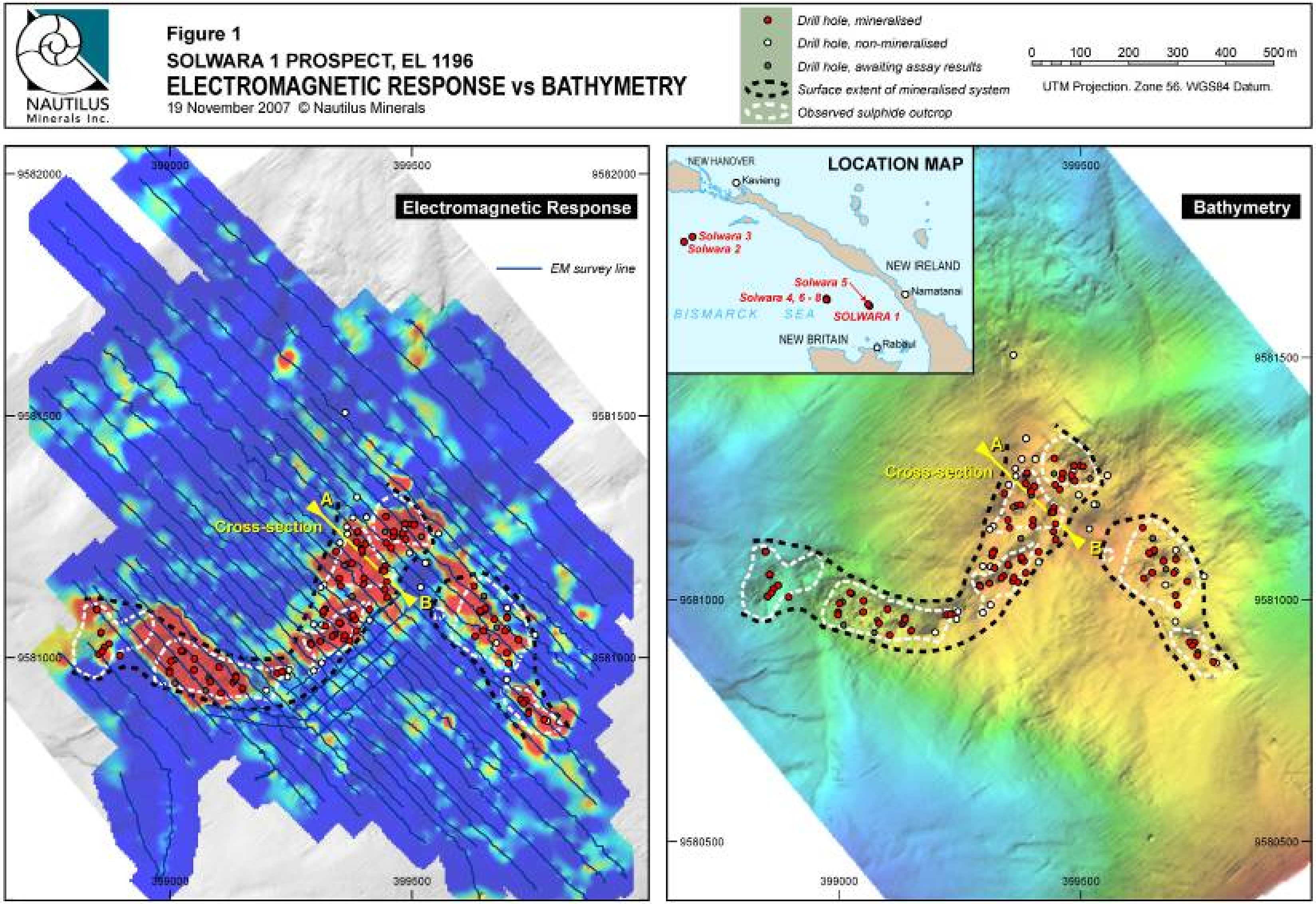
400 m x 400 m

30 m relief

9 million tonnes

(Iizasa et al., 1999)

Reliable Estimates Require Extensive Drilling



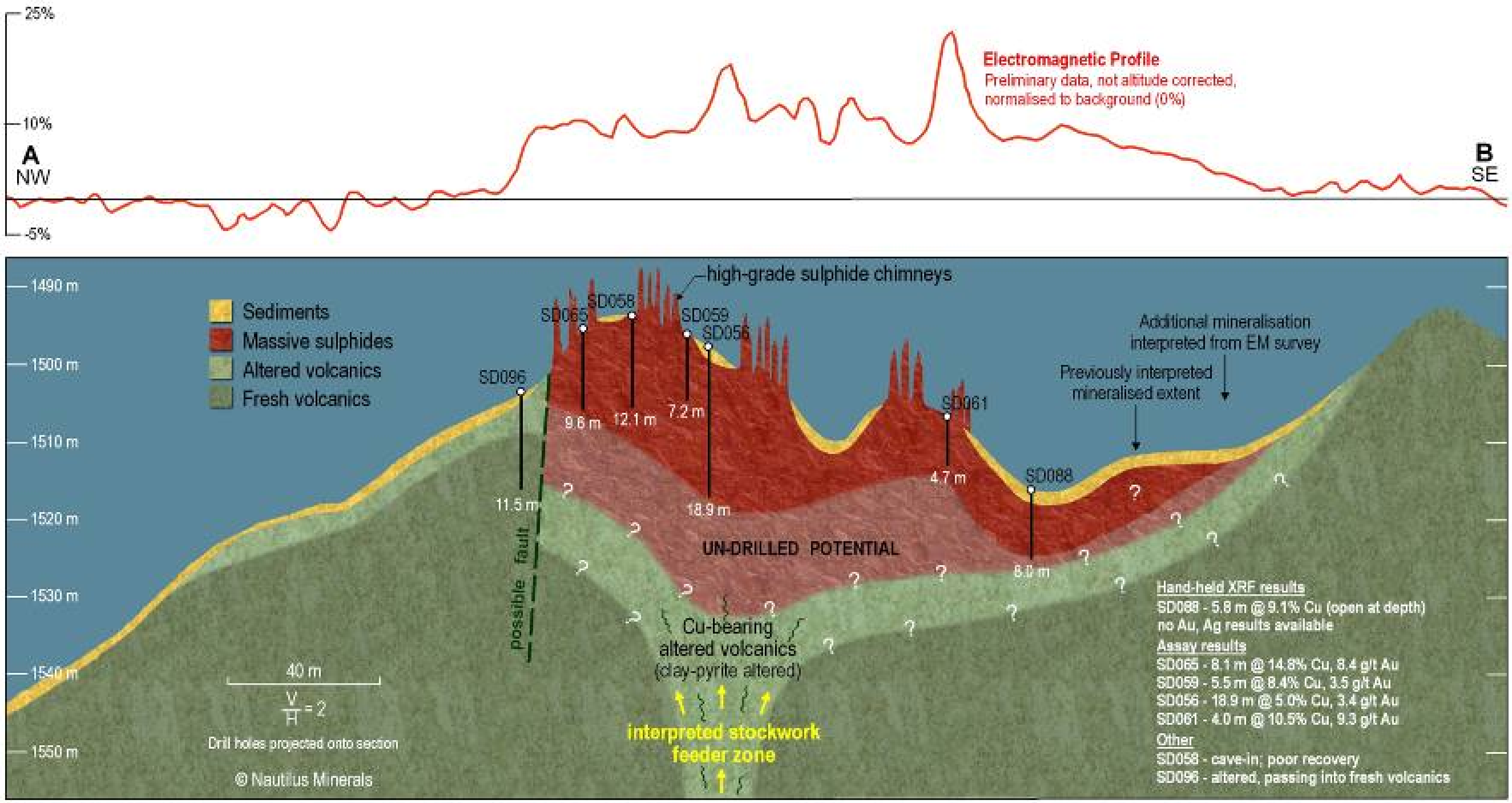
NAUTILUS
Minerals Inc.

Figure 2

SOLWARA 1 PROSPECT, EL 1196

SCHEMATIC CROSS-SECTION

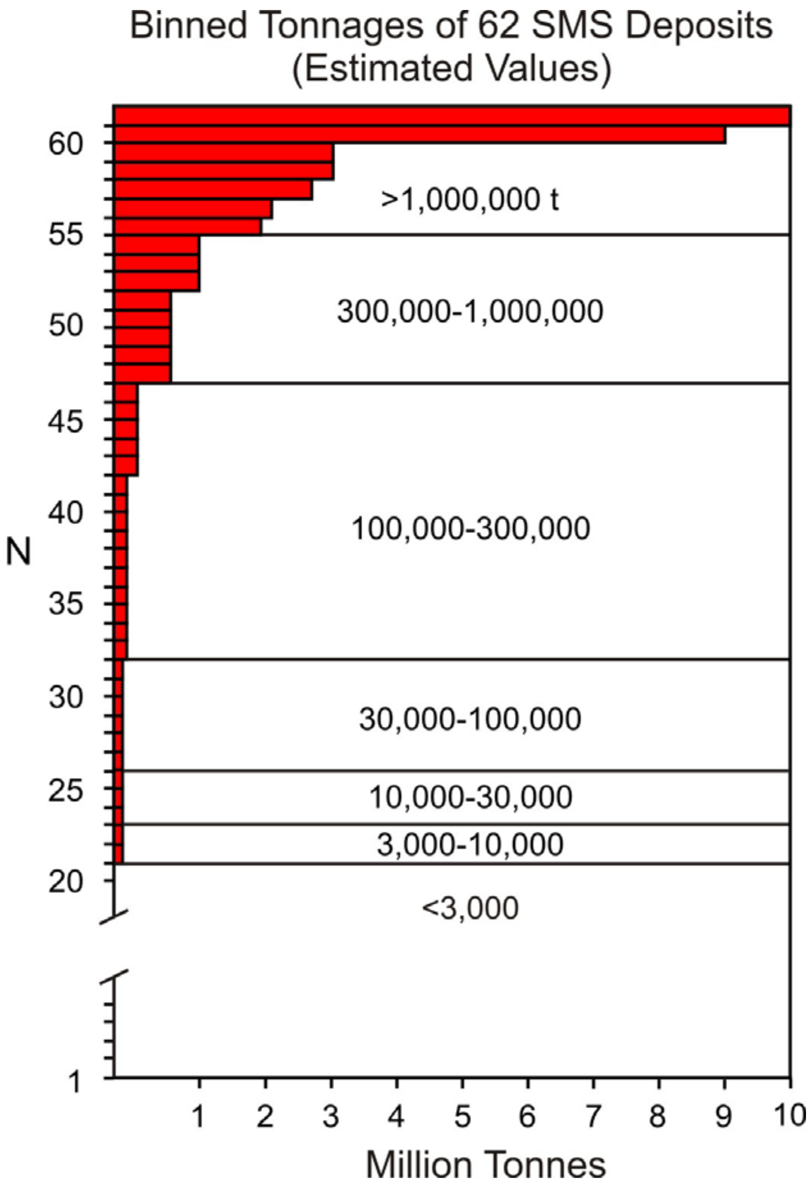
20 September 2007



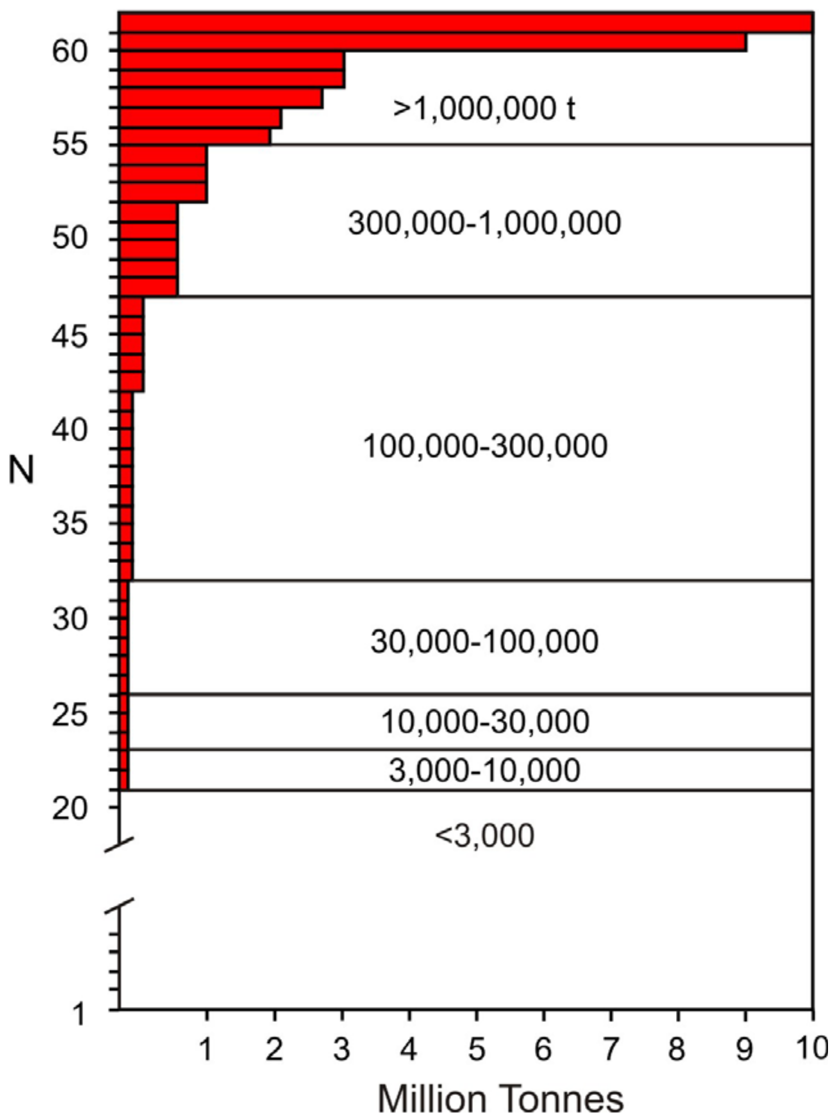
Solwara1 cross-section2 EM Profile A4 Sep07.mxd

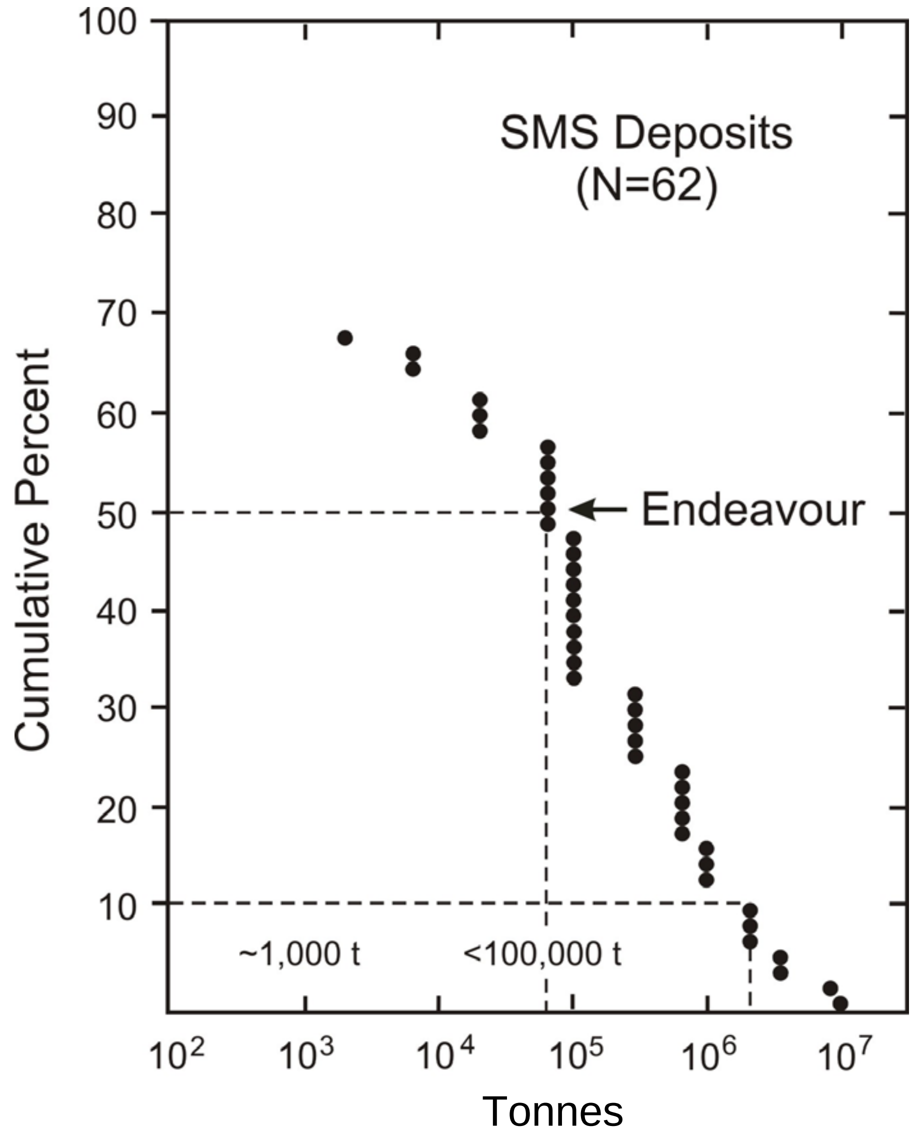
Calibrating estimates of deposit sizes ...

Using drill-indicated sizes of a few SMS deposits, it is possible to “calibrate” the size distribution of other SMS occurrences

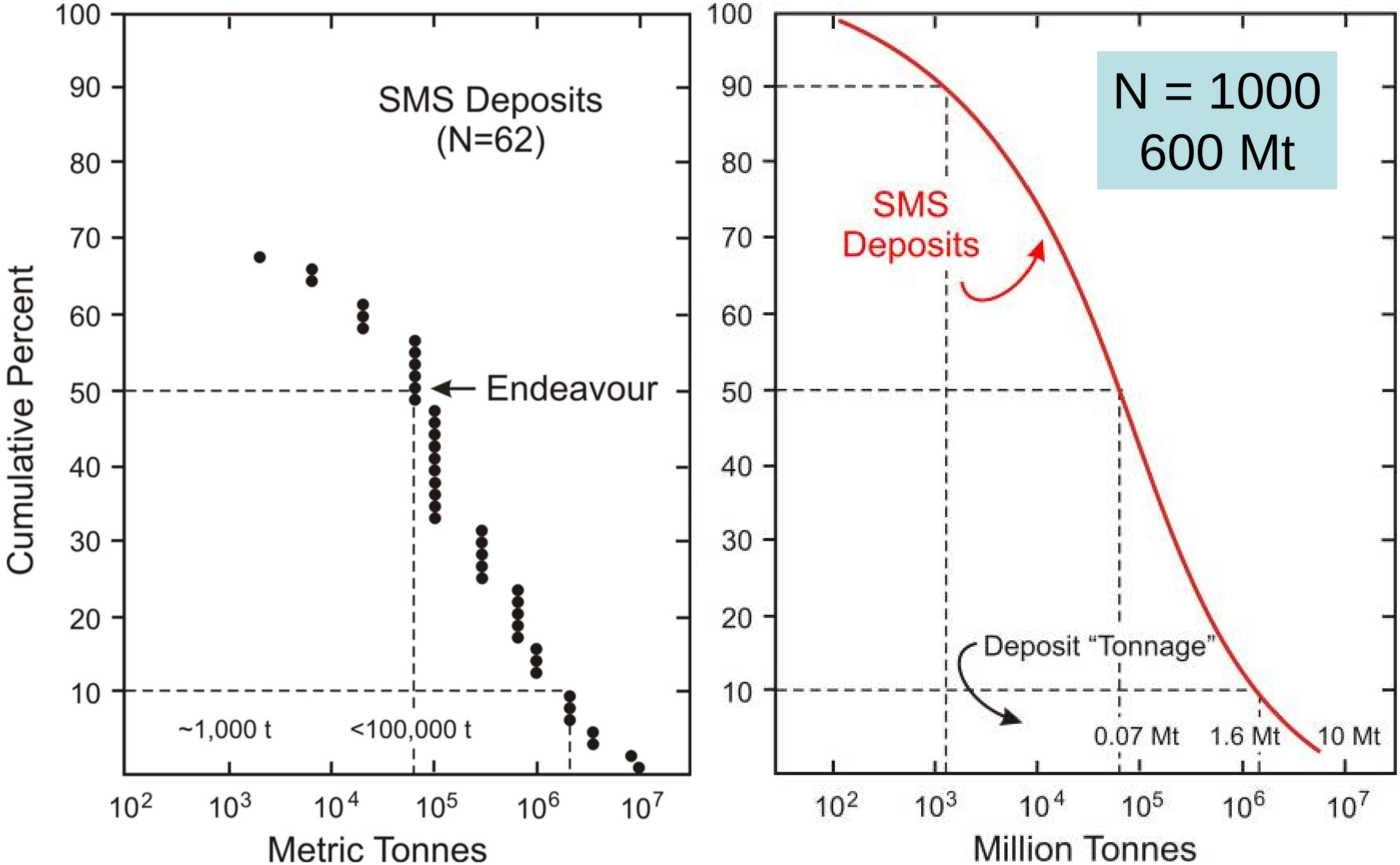


SMS Tonnage Curve

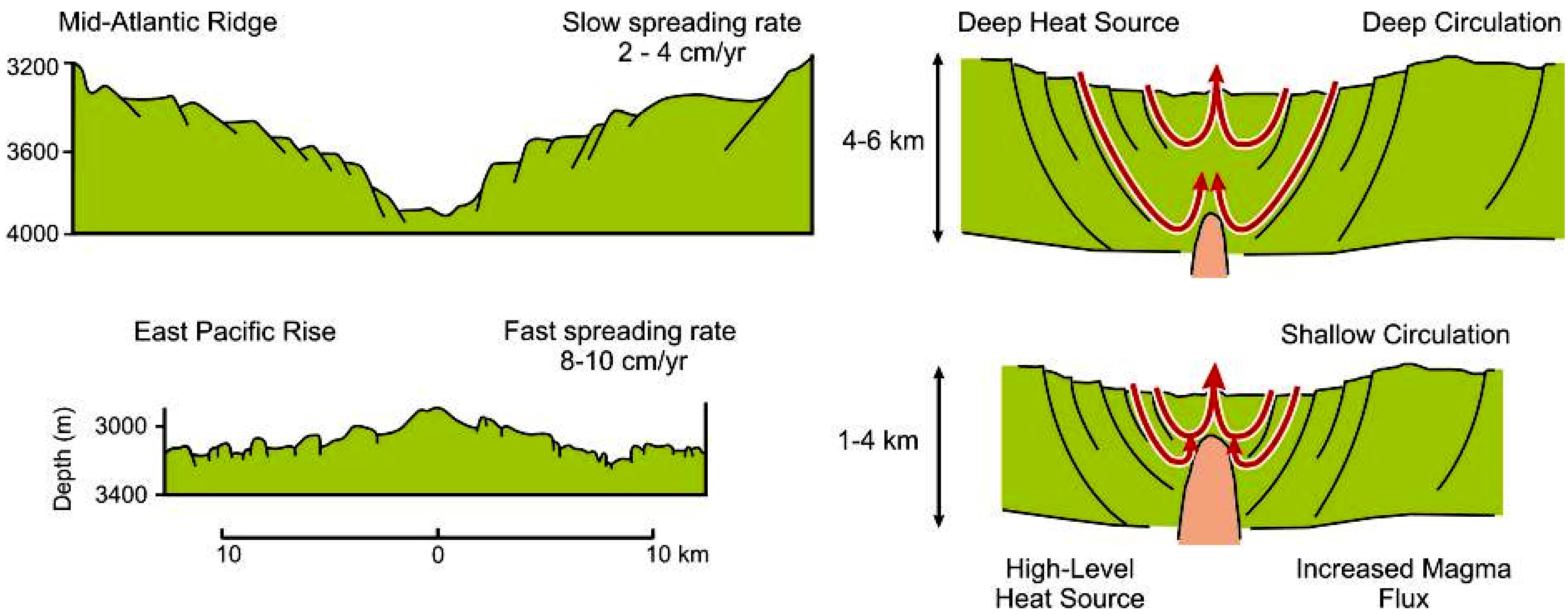




Cumulative Tonnage for the Neovolcanic Zones

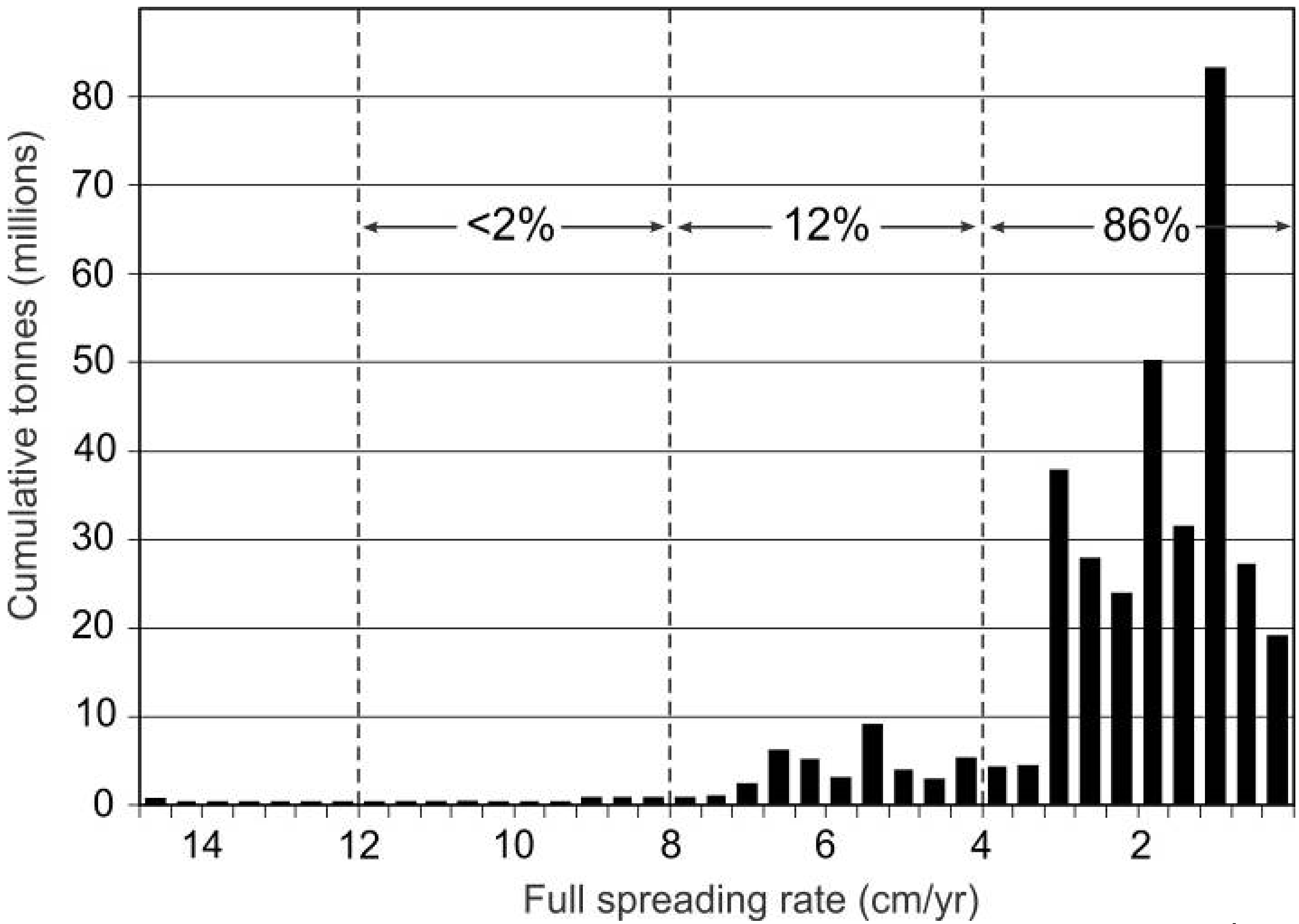


Size matters



- Different scales of hydrothermal convection
- Fast versus slow, shallow versus deep

Most of the Tonnage is on Slow Ridges

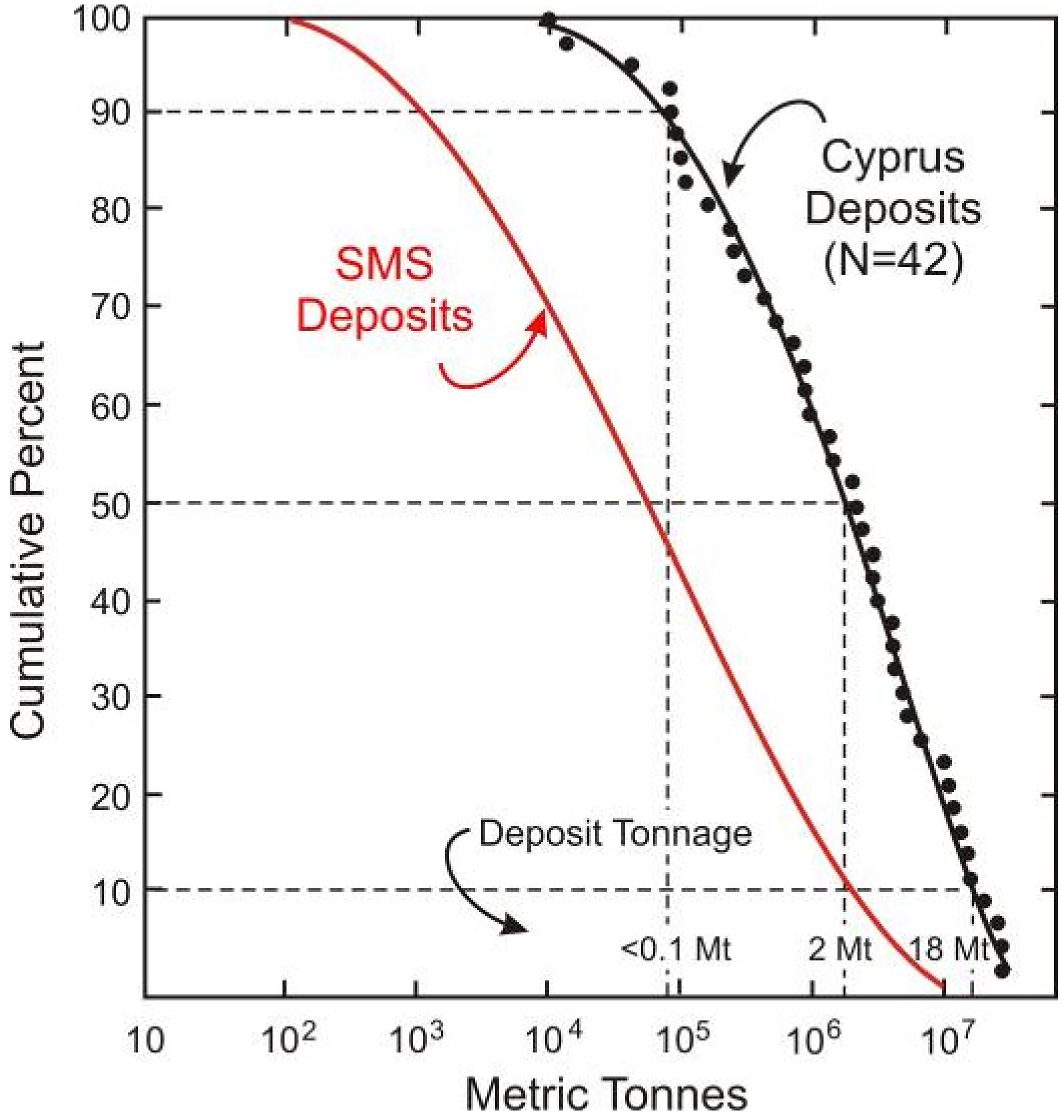


Hannington et al., 2011

A comparison with Cyprus deposits ...

Data from land-based mining include only those deposits of sufficient size to have been drilled

If uneconomic deposits are included, the median size is no more than about 100,000 t, similar to SMS

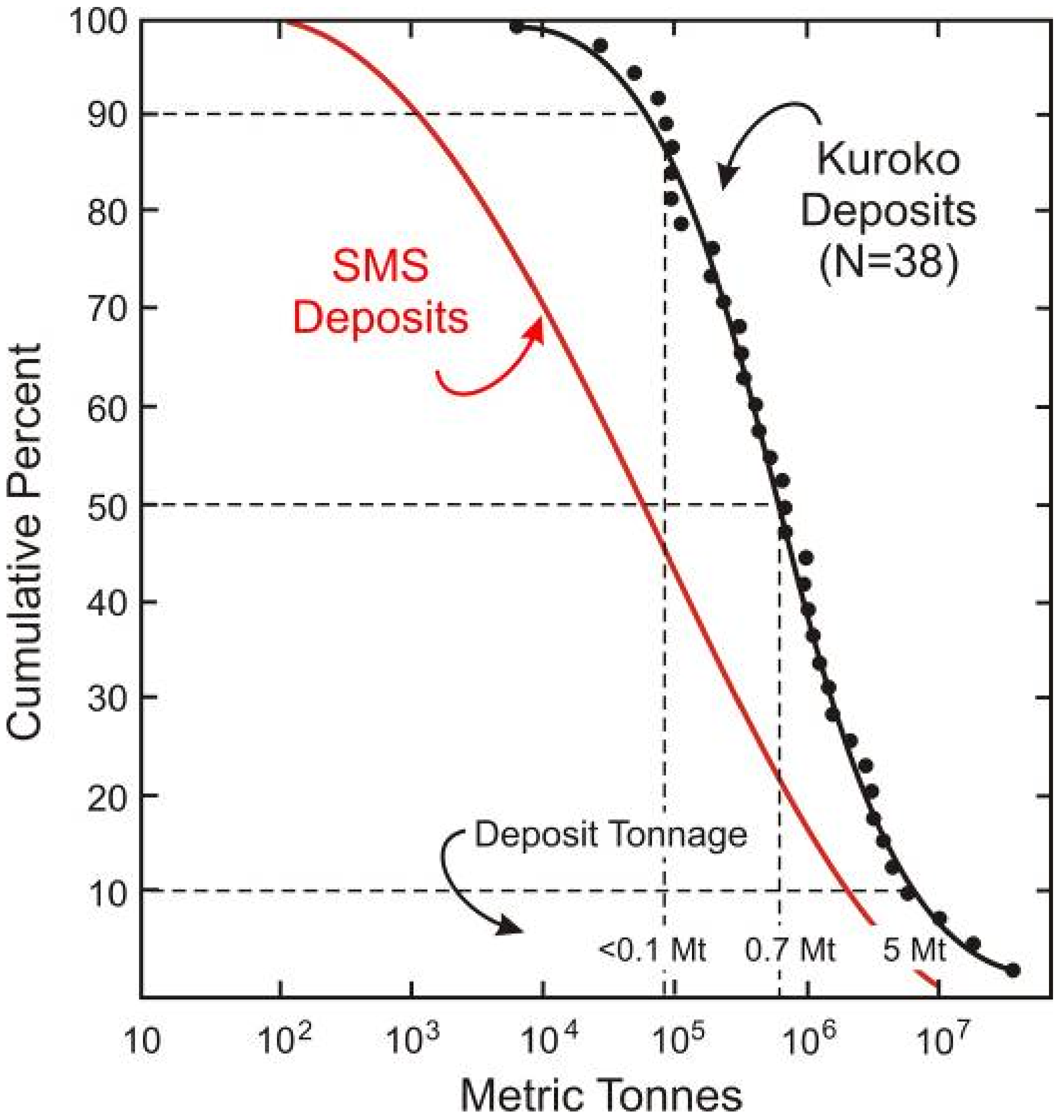


USGS Deposit Models

A comparison with the Kuroko deposits ...

The Kuroko deposits of Japan are higher grade and slightly smaller than the Cyprus deposits ...

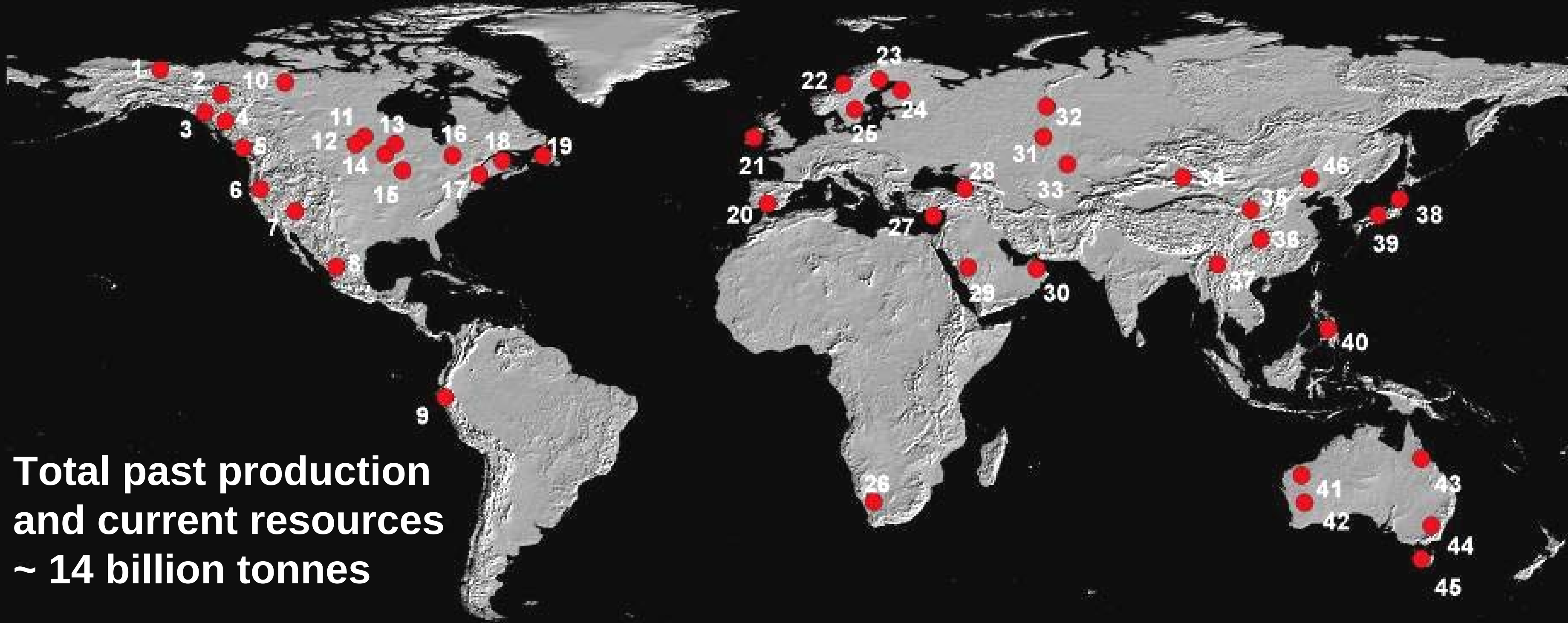
... but still an order of magnitude larger than the median deposit size of known SMS



USGS Deposit Models

Global Distribution of VMS Deposits

Hannington, unpubl.

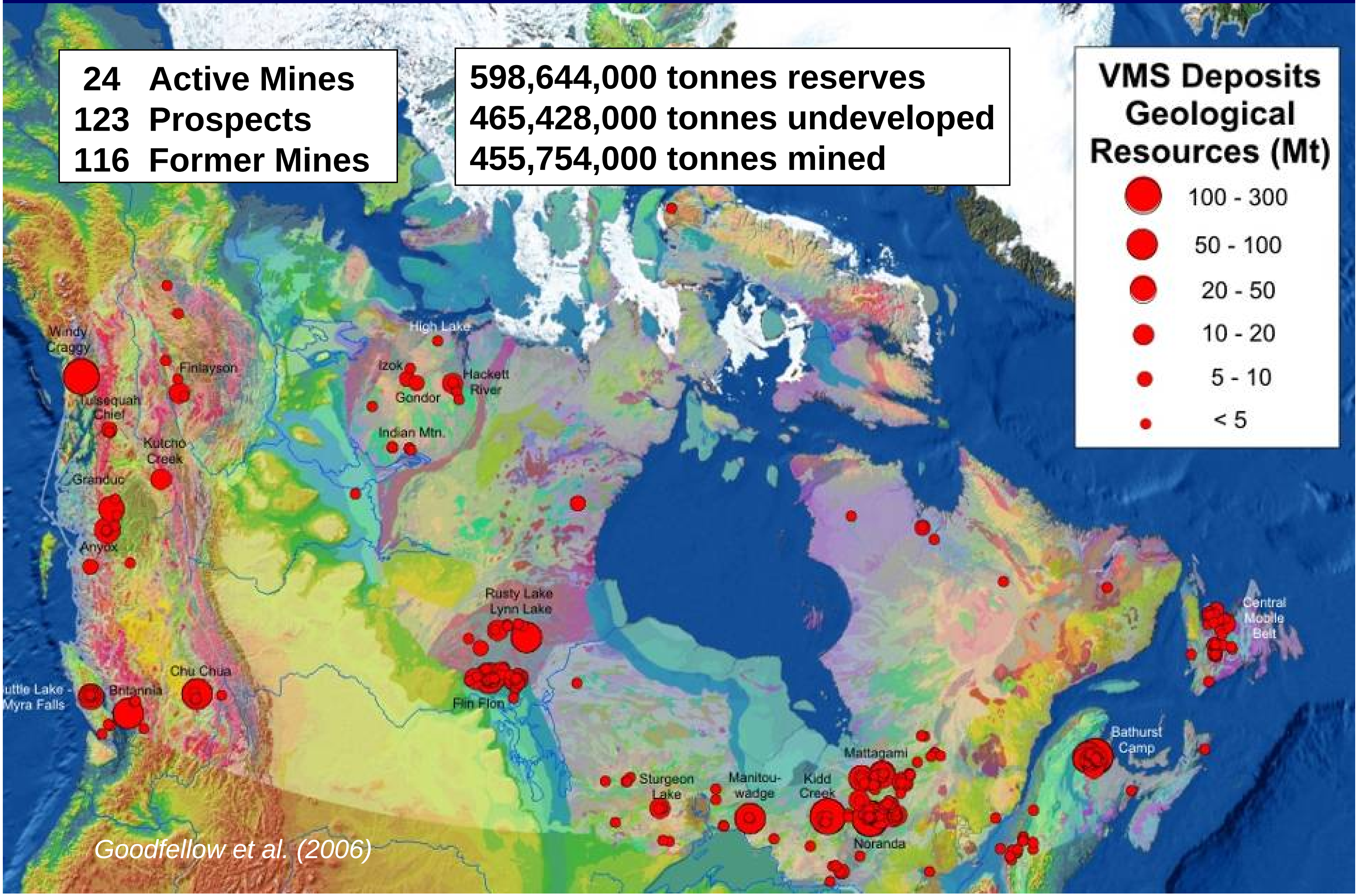


1. Alaska, Brooks Range 33 Mt
2. Finlayson, Yukon 20 Mt
3. Windy Craggy 300 Mt
4. Northern Cordillera 100 Mt
5. Myra Falls 30 Mt
6. Shasta, Klammath 35 Mt
7. Jerome, Arizona 40 Mt
8. Central Mexico 120 Mt
9. Tambo Grande 200 Mt
10. Slave 20-30 Mt
11. Ruttan, Manitoba 70 Mt
12. Flin Flon-Snow Lk 150 Mt
13. Geco-Manitouwadge 60 Mt
14. Sturgeon Lake 35 Mt
15. Ladysmith-Rhineland 80 Mt
16. Abitibi 600 Mt
18. Bathurst 250 Mt
19. Central Nfld. 75 Mt
20. Iberian Pyrite Belt 1000 Mt
21. Avoca 37 Mt
22. Trondheim Norway >100 Mt
23. Skellefte Sweden 70 Mt
24. Outokumpu-Pyhslm 90 Mt
25. Bergslagen-Orijarvi 110 Mt
27. Troodos Cyprus 35 Mt
28. Turkey, Black Sea 200 Mt
29. Saudi Arabia 70 Mt
30. Semail Oman 30 Mt
31. Southern Urals >400 Mt
32. Central Urals >100 Mt
33. Rudny Altai >100 Mt
34-36. China >500 Mt
35. Bawdwin-Laochang >40 Mt
38. Hokuroku Japan 80 Mt
39. Besshi Japan 230 Mt
40. Philippines 65 Mt
41-42. WA >75 Mt
43. Central Queensland
44. Lachlan Fold Belt
45. Mt. Read Tasmania 150 Mt

Unmined Resources in Canadian VMS

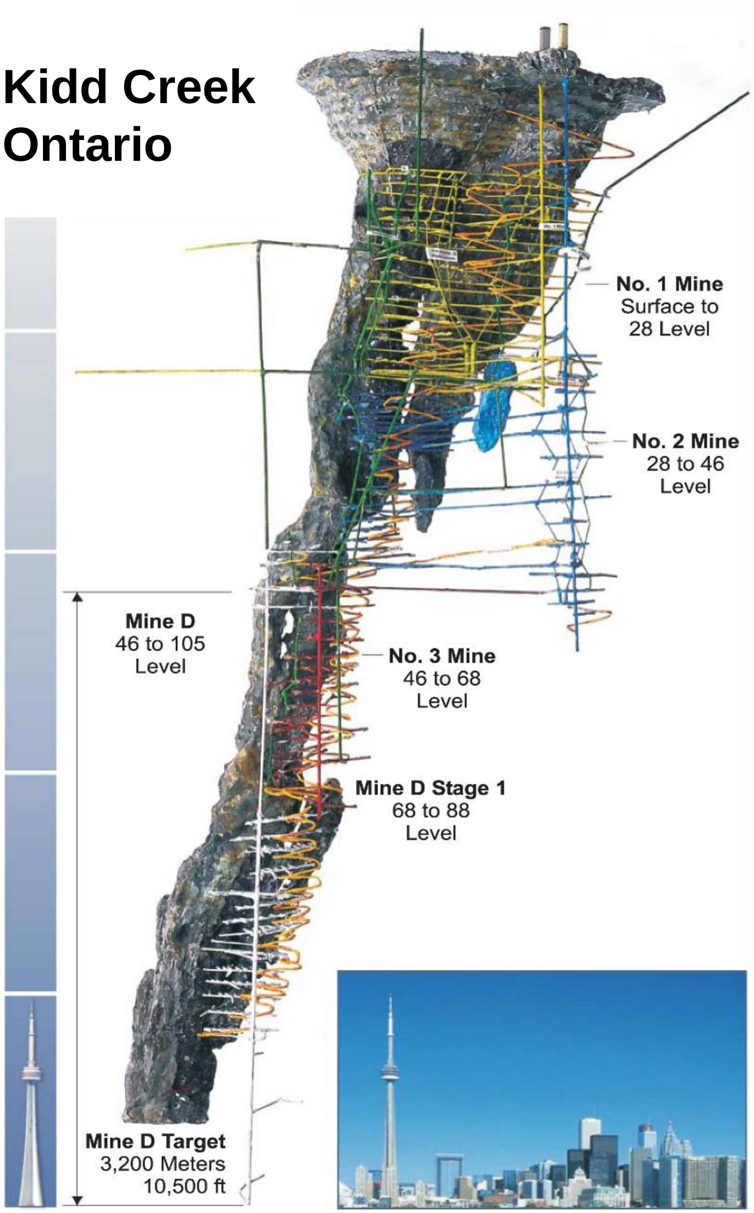
24 Active Mines
123 Prospects
116 Former Mines

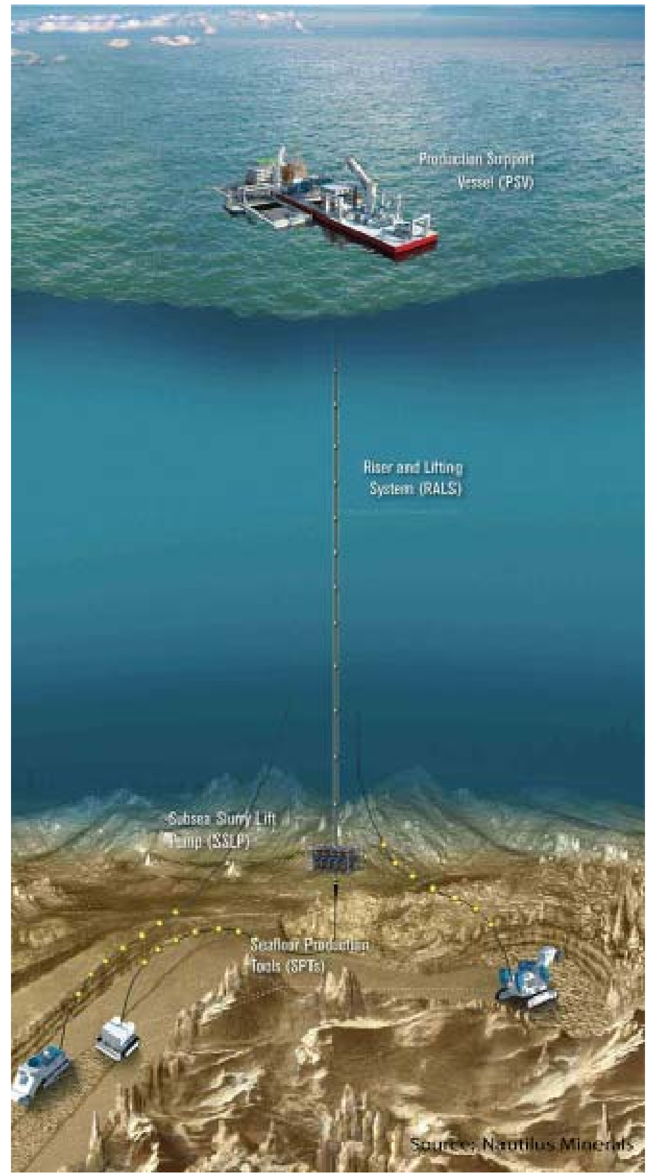
598,644,000 tonnes reserves
465,428,000 tonnes undeveloped
455,754,000 tonnes mined



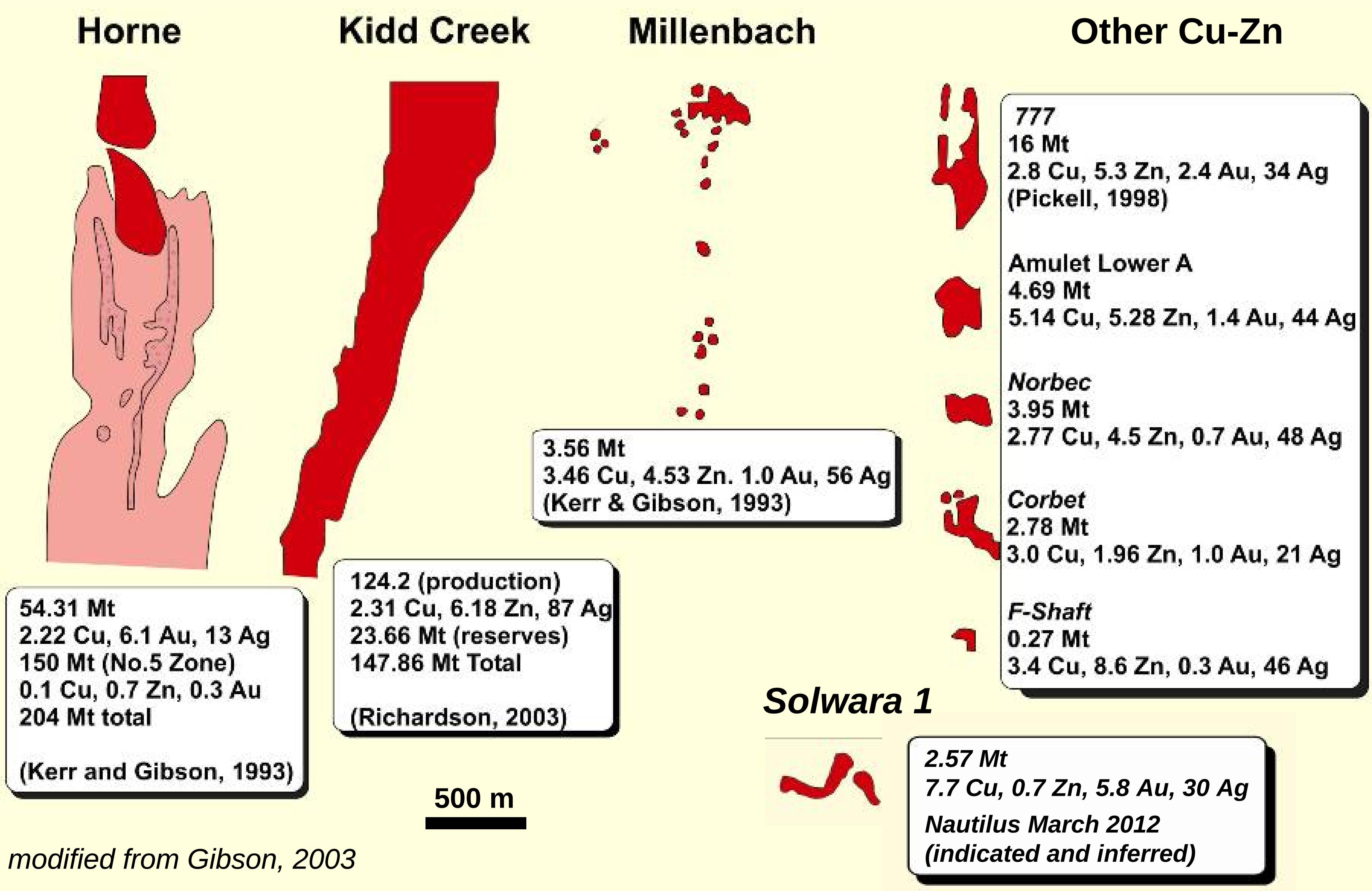
So Why Bother with Seafloor Mining?

Kidd Creek Ontario





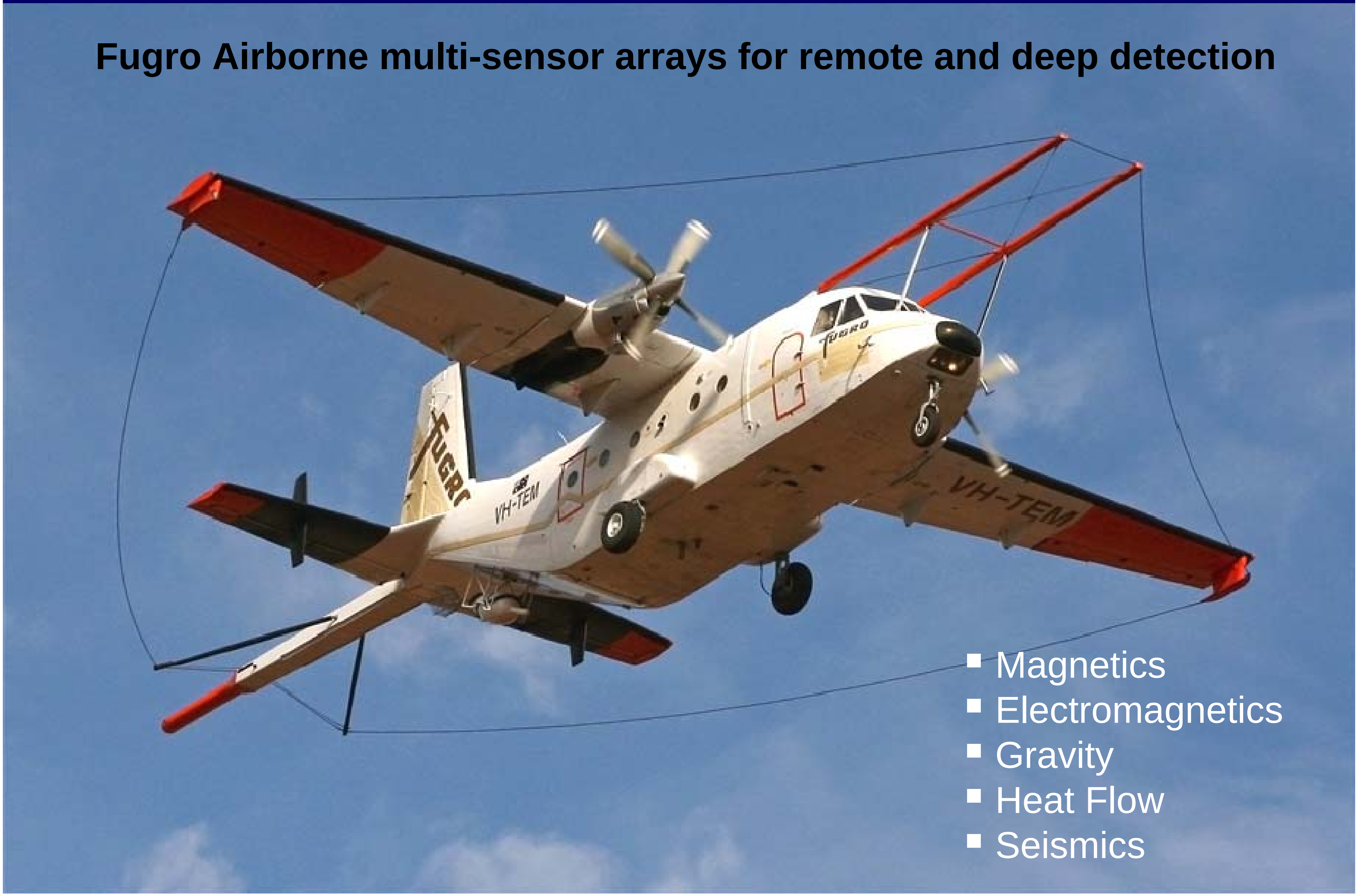
Size Matters



modified from Gibson, 2003

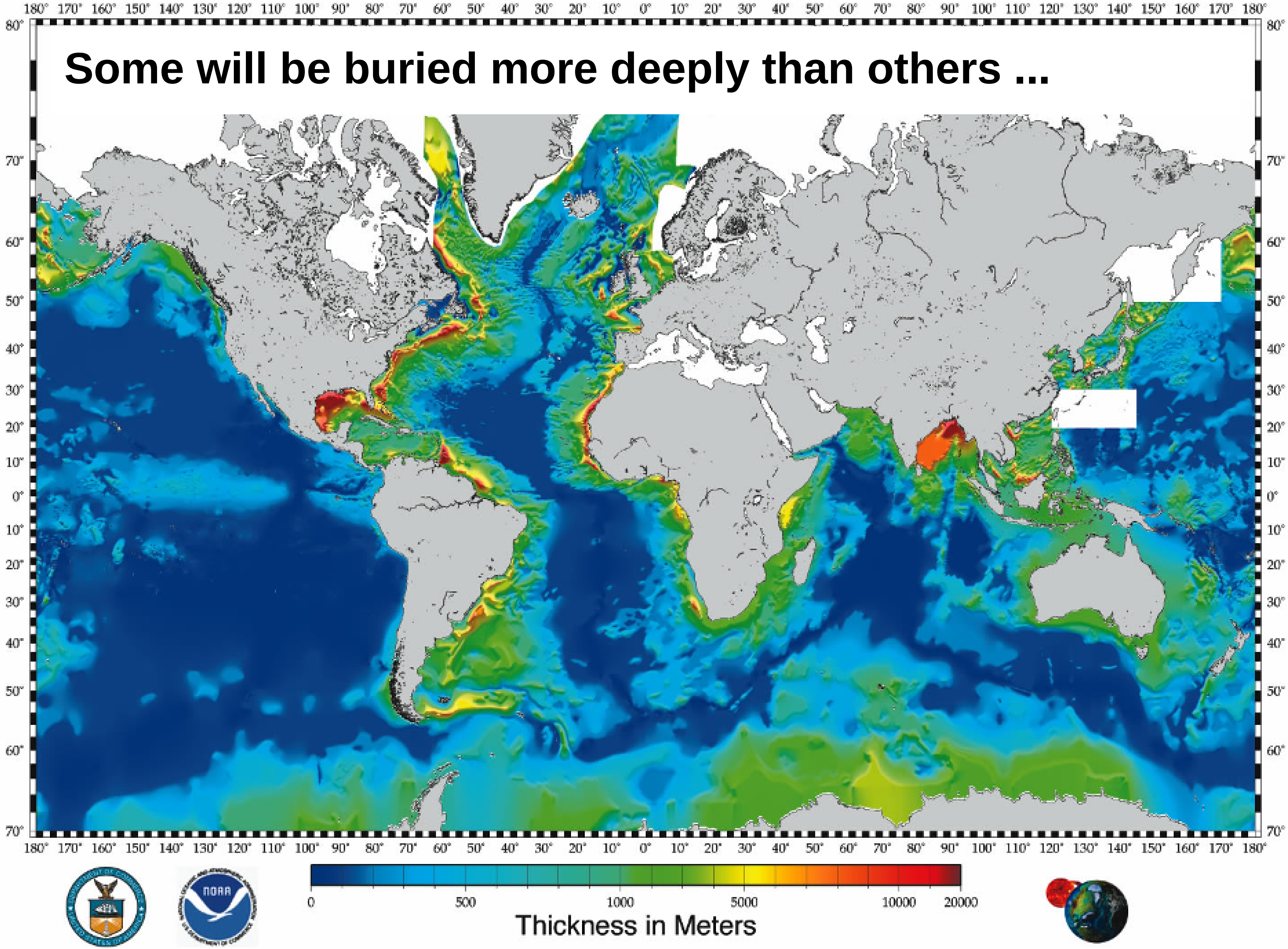
Future of Exploration for Resources in the Sea

Fugro Airborne multi-sensor arrays for remote and deep detection



- Magnetics
- Electromagnetics
- Gravity
- Heat Flow
- Seismics

Some will be buried more deeply than others ...



Horizontal drilling, fracking, solution mining ...

Vast resources in the oceans?