Seafloor Massive Sulfide Deposits

Towards an Estimate of Global SMS Potential

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)

Blue Growth
Scenarios and drivers for Sustainable Growth from the Oceans, Seas and Coasts

Final Report

Call for tenders No. MARE/2010/01
Client: European Commission, DG MARE
Rotterdam/Brussels, 13th August 2012
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
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”
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

TECTONIC SETTING
- Sedimented environments
- Back-arc basin
- Arc volcano
- Ridge-hotspot

Hannington et al., 2005
Water Depth

Hannington et al., 2005
### Grade Distribution

Average bulk compositions of 95 SMS deposits, 3869 surface samples

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

- **Cu**
  - Bimodal
  - Felsic
  - Mafic

- **Zn**
  - Bimodal
  - Felsic
  - Mafic
Average grades of surface samples

N = 3869

Hannington, unpubl.
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)
# Trace Elements in Ancient VMS

## Table 4
Concentration ranges of selected trace elements in VMS

<table>
<thead>
<tr>
<th>Concentrations</th>
<th>Trace elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>To 10,000 ppm</td>
<td>As, Sb, Cd</td>
</tr>
<tr>
<td>To 1,000 ppm</td>
<td>Co, Sn, Se</td>
</tr>
<tr>
<td>To 500 ppm</td>
<td>Ni, Mo, Bi, In, Te</td>
</tr>
<tr>
<td>To 100 ppm</td>
<td>Hg, Tl, W, Ge, Ga</td>
</tr>
</tbody>
</table>

*Hannington, in press*
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
In each 5 x 5 deg map, the areas considered to be “permissive” for deposits ranged from 25,000 to 100,000 km².
Hannington et al., 2011

Distance between deposits (km)

<table>
<thead>
<tr>
<th>Fast-intermediate</th>
<th>Slow</th>
<th>Arc-back arc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Deposit number (n = 106)

Average spacing (km)

Control area (n = 32)

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.

<table>
<thead>
<tr>
<th>Number and Spacing of Deposits</th>
<th></th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Five Degree Map Area</th>
<th>Estimated Permissive Area (km²)</th>
<th>Number of Occurrences In the Area (N=106)</th>
<th>Average Spacing (km) Between Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>In &quot;the Area&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. EPR, 13°N</td>
<td>80,000</td>
<td>8</td>
<td>54</td>
</tr>
<tr>
<td>2. EPR, 9°N</td>
<td>50,000</td>
<td>4</td>
<td>23</td>
</tr>
<tr>
<td>3. EPR, AHA Field</td>
<td>50,000</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>4. EPR, 7°S</td>
<td>40,000</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>5. EPR, 17°S</td>
<td>50,000</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>6. EPR, 18°S</td>
<td>60,000</td>
<td>9</td>
<td>120</td>
</tr>
<tr>
<td>7. EPR, 37°S</td>
<td>50,000</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>8. MAR, TAG and Broken Spur</td>
<td>50,000</td>
<td>2</td>
<td>300</td>
</tr>
<tr>
<td>9. MAR, 24°N and Snakepit</td>
<td>45,000</td>
<td>2</td>
<td>175</td>
</tr>
<tr>
<td>10. MAR, 14°N and Logatchev</td>
<td>60,000</td>
<td>3</td>
<td>87</td>
</tr>
<tr>
<td>11. MAR, 5°S</td>
<td>60,000</td>
<td>2</td>
<td>108</td>
</tr>
<tr>
<td>12. Central Indian Ridge</td>
<td>50,000</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
The missing heat $= 1.8 \times 10^{12}$ W (Mottl, 2003)
How many black smokers are there?

- $1.8 \times 10^{12}$ 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
What if you could just suck it up?

Medusa
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

<table>
<thead>
<tr>
<th>Deposit Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPR-type</td>
<td>&lt;0.01 Mt</td>
</tr>
<tr>
<td>EPR-type deposits range from meters to 10s of meters in diameter.</td>
<td></td>
</tr>
<tr>
<td>Galapagos-Type (TAG, MAR)</td>
<td>1-2 Mt</td>
</tr>
<tr>
<td>Galapagos-Type deposits are 150 m in diameter, 40 m high.</td>
<td></td>
</tr>
<tr>
<td>Sunrise, Solwara (Manus)</td>
<td>2-5 Mt</td>
</tr>
<tr>
<td>Sunrise, Solwara deposits are 300 m in diameter.</td>
<td></td>
</tr>
<tr>
<td>Middle Valley (JFR)</td>
<td>10 Mt</td>
</tr>
<tr>
<td>Middle Valley deposits are massive sulfide and subseafloor replacement.</td>
<td></td>
</tr>
<tr>
<td>Atlantis II Deep (Red Sea)</td>
<td>90 Mt</td>
</tr>
<tr>
<td>Atlantis II Deep deposits are metalliferous sediment.</td>
<td></td>
</tr>
</tbody>
</table>
Mass Accumulation Rates

Hannington, unpubl.

*(100 black smokers at 350°C)
“Footprints” on the Seafloor

Jamieson and Hannington, 2010

WHOI

1 km

SMS Deposits (N=38)

Cumulative Percent

Deposit “Footprint”

Galapagos

Deposit Area (m²)

10 10^2 10^3 10^4 10^5 10^6

~20 m  ~100 m  ~300 m
Difficulties in Measuring the Sizes of Deposits

(Iizasa et al., 1999)

400 m x 400 m
30 m relief
9 million tonnes

(lizasa et al., 1999)
Reliable Estimates Require Extensive Drilling

Figure 1
SOLWARA 1 PROSPECT, EL 1196
ELECTROMAGNETIC RESPONSE vs BATHYMETRY
19 November 2007 © Nautilus Minerals

[Map and diagrams showing electromagnetic response vs bathymetry]
Figure 2
SOLWARA 1 PROSPECT, EL 1196
SCHEMATIC CROSS-SECTION
20 September 2007

25%
10%
5%

Electromagnetic Profile
Preliminary data, not altitude corrected,
normalised to background (0%)

A NW
B SE

- Sediments
- Massive sulphides
- Altered volcanics
- Fresh volcanics

UN-DRILLED POTENTIAL

Cu-bearing altered volcanics
(clay-pyrite altered)

interpreted stockwork feeder zone

Drill holes projected onto section
© Nautilus Minerals

Hand-held XRF results
SD068: 9.6 m @ 9.1% Cu (open at depth)
no Au, Ag results available

Assay results
SD068: 8.1 m @ 14.8% Cu, 8.4 g/t Au
SD059: 5.5 m @ 8.4% Cu, 3.5 g/t Au
SD058: 19.9 m @ 5.0% Cu, 3.4 g/t Au
SD061: 4.0 m @ 10.5% Cu, 9.3 g/t Au

Other
SD059: cave-in, poor recovery
SD064: altered, passing into fresh volcanics

Possible fault

high-grade sulphide chimneys

Additional mineralisation interpreted from EM survey

Previously interpreted mineralised extent
Using drill-indicated sizes of a few SMS deposits, it is possible to “calibrate” the size distribution of other SMS occurrences.
SMS Tonnage Curve

SMS Deposits (N=62)

Cumulative Percent

Tonnes

Million Tonnes

N

>1,000,000 t
300,000-1,000,000
100,000-300,000
30,000-100,000
10,000-30,000
3,000-10,000
<3,000

Endeavour

~1,000 t
<100,000 t
Cumulative Tonnage for the Neovolcanic Zones

- SMS Deposits (N=62)
- Endeavour

- N = 1000
- 600 Mt

- Deposit "Tonnage"
Different scales of hydrothermal convection

- Fast versus slow, shallow versus deep
Most of the Tonnage is on Slow Ridges

Hannington et al., 2011
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
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.

Total past production and current resources ~ 14 billion tonnes

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
17. Bathurst 250 Mt
18. Central Nfld. 75 Mt
19. Iberian Pyrite Belt 1000 Mt
20. Avoca 37 Mt
21. Trondheim Norway >100 Mt
22. Skellefte Sweden 70 Mt
23. Outokumpu-Pyholm 90 Mt
24. Bergslagen-Orijarvi 110 Mt
25. Troodos Cyprus 35 Mt
26. Turkey, Black Sea 200 Mt
27. Saudi Arabia 70 Mt
28. Semai Oman 30 Mt
29. Southern Urals >400 Mt
30. Central Urals >100 Mt
31. Rudny Altai >100 Mt
32. China >500 Mt
33. Bawdwin-Laochang >40 Mt
34-36. Hokuroku Japan 80 Mt
37. Besshi Japan 230 Mt
38. Philippines 65 Mt
39. WA >75 Mt
40. Central Queensland
41-42. 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

VMS Deposits Geological Resources (Mt)
- 100 - 300
- 50 - 100
- 20 - 50
- 10 - 20
- 5 - 10
- < 5

Goodfellow et al. (2006)
So Why Bother with Seafloor Mining?

Kidd Creek
Ontario
Size Matters

Horne

Kidd Creek

Millenbach

Other Cu-Zn

Solwara 1

500 m

54.31 Mt
2.22 Cu, 6.1 Au, 13 Ag
150 Mt (No.5 Zone)
0.1 Cu, 0.7 Zn, 0.3 Au
204 Mt total
(Kerr and Gibson, 1993)

124.2 (production)
2.31 Cu, 6.18 Zn, 87 Ag
23.66 Mt (reserves)
147.86 Mt Total
(Richardson, 2003)

777
16 Mt
2.8 Cu, 5.3 Zn, 2.4 Au, 34 Ag
(Pickell, 1998)

Amulet Lower A
4.69 Mt
5.14 Cu, 5.28 Zn, 1.4 Au, 44 Ag

Norbec
3.95 Mt
2.77 Cu, 4.5 Zn, 0.7 Au, 48 Ag

Corbet
2.78 Mt
3.0 Cu, 1.96 Zn, 1.0 Au, 21 Ag

F-Shaft
0.27 Mt
3.4 Cu, 8.6 Zn, 0.3 Au, 46 Ag

2.57 Mt
7.7 Cu, 0.7 Zn, 5.8 Au, 30 Ag
Nautilus March 2012
(indicated and inferred)

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?

... yes, but where and how much?

WHOI