Seafloor Massive Sulfides and potential future minerals

Georgy Cherkashov
VNIIOkeangeologia
St Petersburg, Russia
Outline

• Seafloor Massive Sulfides (SMS)
  • Distribution
  • Exploration methods
  • Resource potential
  • Mining perspectives
  • Challenges and constrains

• Deep-sea muds enriched by Rare Earth Elements (REE)
Milestones of Seafloor Massive Sulfides (SMS) study

• 1873-76  First recovery of metalliferous sediments in the Pacific (HMS Challenger)
• 1886-89  First record of temperature/salinity anomalies in deep of the Red Sea (RV Vityaz)
• 1963-65  Discovery of metalliferous muds and hot brines in the Red Sea
• 1978-79  Discovery of Black Smokers at the East Pacific Rise
• 1985 Discovery of SMS deposit at the Mid-Atlantic Ridge (TAG area)
• 1986 Discovery of SMS deposits at the Island Arc System (Manus basin)
• 2010 Approval of SMS Exploration Regulations by International Seabed Authority
• 2011 First contract of SMS Exploration signed
• 2017 First pilot test of excavation and ore lifting system (Okinawa Trough, Japan)
## Characteristics of deep-sea mineral deposits

<table>
<thead>
<tr>
<th>Deposits type</th>
<th>Setting/Depth, m</th>
<th>Major components</th>
<th>Discovery, year</th>
<th>Status/Stage of works</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>Basins (4000-5000)</td>
<td>Cu, Ni, Co, Mn, Mo, REE</td>
<td>1872-1876</td>
<td>Exploration</td>
</tr>
<tr>
<td>Crusts</td>
<td>Seamounts (1000-2000)</td>
<td>Co, Cu, Mn, Pt, REE</td>
<td>1872-1876</td>
<td>Exploration</td>
</tr>
<tr>
<td>SMS</td>
<td>Volcanic structures (1500-4000)</td>
<td>Cu, Au, Zn, Ag, Pb</td>
<td>1978-1979</td>
<td>Exploration</td>
</tr>
</tbody>
</table>
Morphostructural setting of marine minerals

- Rift valleys
- Abyssal hill
- Seamounts
- Abyssal plain
- Mid oceanic ridge
- Ocean basin
- Continental rise
- Continental slope
- Continental shelf
- Continental margin
- Oil
- Natural gas
- Phosphorites
- Placers
- Aggregates

- 1500 m
- 4500 m

Polymetallic sulfides
Global distribution of hydrothermal vents and SMS deposits
Marine minerals in the Area versus EEZ/ECS

<table>
<thead>
<tr>
<th></th>
<th>Seabed</th>
<th>Nodules</th>
<th>Sulphides</th>
<th>Crusts</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISA jurisdiction - The Area</td>
<td>~ 55%</td>
<td>~ 80%</td>
<td>~ 60%</td>
<td>~ 45%</td>
</tr>
<tr>
<td>Coastal State continental shelf</td>
<td>~ 45%</td>
<td>~ 20%</td>
<td>~ 40%</td>
<td>~ 55%</td>
</tr>
</tbody>
</table>

Brekke, 2018
>400 known sites of hydrothermal activity
280 sites of polymetallic massive sulfides
190 active (black) smoker sites

Are these sites a resource for humankind?

- constantly new deposits are being found
- many are Cu or Au-rich

- 56% at mid-ocean ridges
- 28% in back-arc environments
- 16% on submarine volcanic arcs
- <1% on intraplate volcanoes

Distribution of seafloor hydrothermal systems in the ocean
Seafloor Massive Sulfides:
Totally > 400 sites
Area - 58%, EEZ - 36%, ECS - 6%.

Petersen et al., 2016 with additions
General scheme of hydrothermal system and SMS deposit formation

Baker, Beaudoin 2013
Exploration methods for SMS deposits
HOMESIDE underwater vehicle:
An Advanced Tool for Hydrothermal Plume Hunting and Polymetallic Sulphide Exploration

Freitag et al., 2019
Deep-towing system for detection of SMS deposit

Blue mining project
Active and inactive **SMS** in Atlantic and Indian oceans

Indian ocean, German Exploration Area

- **Status 2018:**
  - 18 Active
  - 25 Inactive SMS deposits

Atlantic Ocean, Russian Exploration Area

- **Status 2018:**
  - 7-10 Active
  - 7-10 Inactive SMS deposits

Schwarz-Schampera et al, 2018
### Characteristics of deep-sea minerals

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nodules</th>
<th>Crusts</th>
<th>Massive sulfides</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morphology</strong></td>
<td>2-D deposits on the bottom sediments</td>
<td>2-D deposits on the rocks</td>
<td>3-D deposits on the rocks and sediments</td>
</tr>
<tr>
<td><strong>Mineralogy</strong></td>
<td>Oxides &amp; Hydroxides</td>
<td>Oxides &amp; Hydroxides</td>
<td>Sulfides</td>
</tr>
<tr>
<td><strong>Chemistry/Major elements</strong></td>
<td>Mn, Ni, Co, Cu</td>
<td>Co, Mn, Cu (REE?)</td>
<td>Cu, Zn, Pb, Au, Ag</td>
</tr>
<tr>
<td><strong>Grade distribution</strong>*</td>
<td>Homogeneous on regional scale</td>
<td>Homogeneous on regional scale</td>
<td>Very heterogeneous on regional and local scale</td>
</tr>
<tr>
<td><strong>Formation</strong></td>
<td>Hydrogenetic &amp; Diagenetic</td>
<td>Hydrogenetic</td>
<td>Hydrothermal</td>
</tr>
<tr>
<td><strong>Age (max), years</strong></td>
<td>(n \times 10^7) mm/10^6</td>
<td>(n \times 10^7) mm/10^6</td>
<td>(n \times 10^5) Fast</td>
</tr>
<tr>
<td><strong>Ancient analogues</strong></td>
<td>No</td>
<td>No</td>
<td>Volcanogenic Massive Sulfides (VMS)</td>
</tr>
<tr>
<td><strong>Footprint</strong></td>
<td>150 km(^2)</td>
<td>25 km(^2)</td>
<td>0.2 km(^2)</td>
</tr>
<tr>
<td><strong>Processing technology</strong></td>
<td>New</td>
<td>New</td>
<td>Exist/traditional for VMS</td>
</tr>
</tbody>
</table>

* Petersen et al., 2016
# Components and global resources of deep-sea mineral deposits

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<tr>
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<th>Nodules</th>
<th>Crusts</th>
<th>SMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major components</strong></td>
<td>Mn, Ni, Co, Cu</td>
<td>Co, Mn, Cu, REE</td>
<td>Cu, Zn, Pb, Au, Ag</td>
</tr>
<tr>
<td><strong>Minor components/Byproducts</strong></td>
<td>Mo, Li, REE, Tl, Zr, Ti, Ge</td>
<td>Te, Mo, Bi, W, Ti, Pt, V, Nb, Y</td>
<td>Se, Te, Ge, Bi, As, Cd, Ga, Tl, In</td>
</tr>
<tr>
<td><strong>Global resources, mln t</strong></td>
<td>38 900 (Sergeev et al., 2017)</td>
<td>35 100 (Halbach et al., 2017)</td>
<td>4 000</td>
</tr>
<tr>
<td><strong>Resources in “Prime zones”, mln t</strong></td>
<td>21 100 (CCZ) (Hein et al., 2013)</td>
<td>7 533 (NPPCZ) (Hein et al., 2013)</td>
<td>100 (NAEZ)</td>
</tr>
</tbody>
</table>

CCZ – Clarion-Clipperton Zone  
NPPCZ – North Pacific Prime Crust Zone  
NAEZ – North Atlantic Equatorial Zone
Model of SMS hydrothermal mound based on geophysical data (seismic and conductivity)

Sub sea-floor Massive sulfides Not confirmed by drilling!

Blue mining, 2018
Potential value of metals in different types of deep-sea deposits

Nodules: Co 31%, Ni 32%, Cu 12%, Mn 18%, Zn 0%, REE 7%

Crusts: Co 68%, Mn 13%, Ni 9%, Cu 1%

SMS: Cu 66%, Ag 5%, Au 14%, Zn 15%
Graphical of estimated metals percentage of resources and millions of tons reserves in terrestrial versus submarine mineral deposits.

Metal resources in terrestrial and seabed mineral deposits (Wt.%)

- Cobalt: 96.3% (Terrestrial), 3.7% (Marine)
- Nickel: 84% (Terrestrial), 16% (Marine)
- Manganese: 79.4% (Terrestrial), 20.6% (Marine)
- Molibdenum: 66.7% (Terrestrial), 33.3% (Marine)
- Silver: 45.8% (Terrestrial), 54.2% (Marine)
- Cooper: 64.1% (Terrestrial), 35.9% (Marine)
- Zinc: 76.9% (Terrestrial), 23.1% (Marine)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Terrestrial</th>
<th>Marine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>446</td>
<td>684</td>
</tr>
<tr>
<td>Nickel</td>
<td>22,586</td>
<td>40</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.3</td>
<td>761</td>
</tr>
<tr>
<td>Molibdenum</td>
<td>540</td>
<td>540</td>
</tr>
<tr>
<td>Silver</td>
<td>17</td>
<td>130</td>
</tr>
<tr>
<td>Cooper</td>
<td>5,846</td>
<td>20</td>
</tr>
<tr>
<td>Zinc</td>
<td>1,360</td>
<td>1,800</td>
</tr>
</tbody>
</table>

Source: USGS
Mining technology and perspectives

Leading companies/countries in SMS mining systems development

- Nautilus Minerals
- Bauer (Germany)
- Japan
- China
- India
- ???

www.nautilusminerals.com
Nautilus Minerals Update

June, 2016

Seafloor Mining Tools

Building Momentum
World's First Success in Continuous Ore Lifting test for Seafloor Polymetallic Sulphides

Pilot test of excavating and ore lifting conducted for seafloor polymetallic sulphides under the sea area near Okinawa Prefecture
Conclusive remarks

• Seafloor massive sulfides (SMS) have been discovered later and studied less than the two other main types of marine minerals - ferromanganese nodules and crusts.

• Nevertheless, the data available indicates that SMS are characterized by highly significant (higher than on land) grades of major and rare metals used in high-tech and green technologies.

• New areas for SMS application are still available in the Atlantic and Indian oceans.

• Available exploration methods are efficient for prospecting SMS deposits.

• Due to limited data available resource estimates of SMS still uncertain, have a wide range and could be revised after further exploration studies (drilling!).

• The ratio of active/inactive deposits is still unclear. Further geological studies and environmental consideration (REMP) should be taken into account in the strategy of SMS deposits exploitation.
Conclusive remarks

• Economic model for SMS (similar to nodules one which is currently discussing in ISA) is not established yet

• Extraction of metals from seafloor massive sulfides will not impact on metal market considerably (opposite to nodules and crusts cases)

• The first test mining was conducted in 2017 but development of the mining production systems is still far from completion
Global distribution of seabed minerals, areas under contract with ISA and areas of REE enriched sediments

(Hannington et al, 2017) with adds
REE enriched deep-sea muds as potential future minerals

• The interest to the REE enrichment in pelagic sediments has been initiated by publication of Kato et al in 2011

• The rare earth deposits in the deep-sea sediments belong to the strata-bound type ore deposits. The thickness of REY-rich sediments ranging from a few meters to more than 30 meters

• The central basins of the Pacific and the northwestern Pacific basin have been determined to be the metallogenic prospective area of deep-sea rare earth resource, and more than one million square kilometers area have been delineated as the metallogenic prospective area in the Pacific Ocean with the content of ΣREY 700 ppm as the cut-off grade (similar to onshore REE deposits)

• Similar sediments have been recovered in the Indian Ocean

• The pelagic clay sediments with high P and phillipsite content are the most favorable REY-rich pelagic sediments.

• However the economic value of this type of marine mineral is still uncertain
THANK YOU!