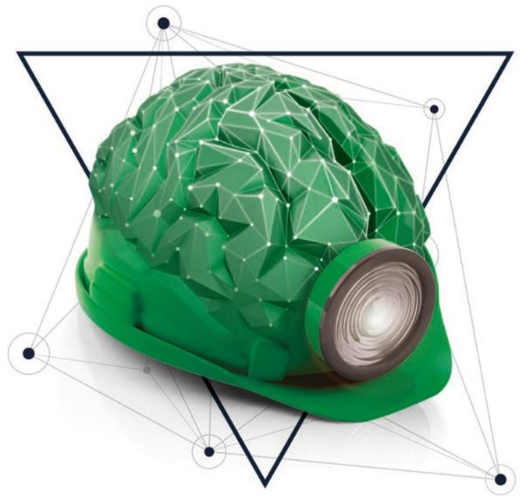
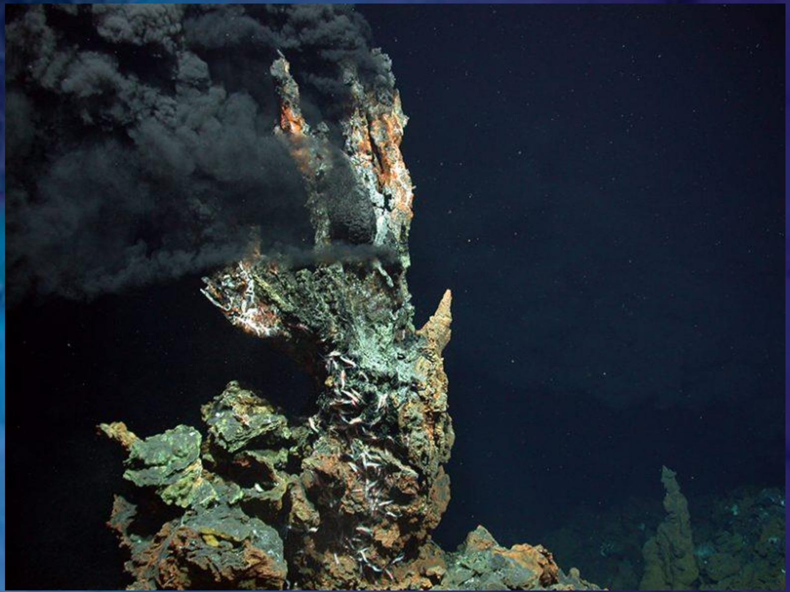
Sea floor exploration



Norbert Zajzon
University of Miskolc

MISKOLCI EGYETEM
UNIVERSITY OF MISKOLC



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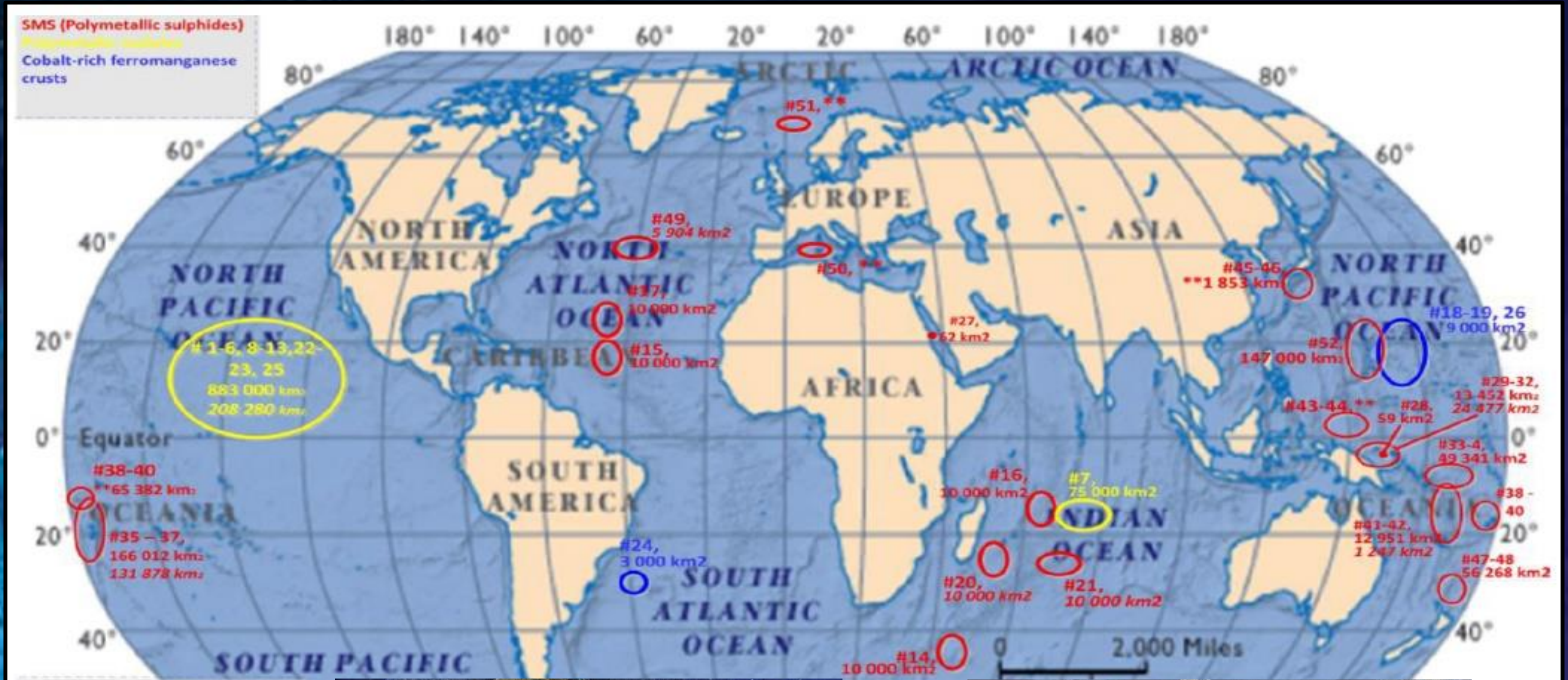
Underwater deposit types

- Flooded mines on land
  - Flooded open pits (VAMOS)
  - Flooded underground mines (UNEXMIN-UNEXUP/Robominers)
- Off shore deposits
  - Near shore deposits on the continental platform
  - Deep sea deposits
- For detailed exploration and mining all the different types facing similar difficulties with some differences
  - Needs surface and drilling (access to the material), and material characterisation (can be „in-situ”)
  - For production control: few key parameters of the mined material need to be monitored „continouously”

Deep sea ore deposit types

- Polymetallic nodules
- Co-rich Fe-Mn crusts
- SMS / VMS / SedEx
  - Black smokers (chimneys)
  - Sulphide muds
  - Solidified, buried old deposits



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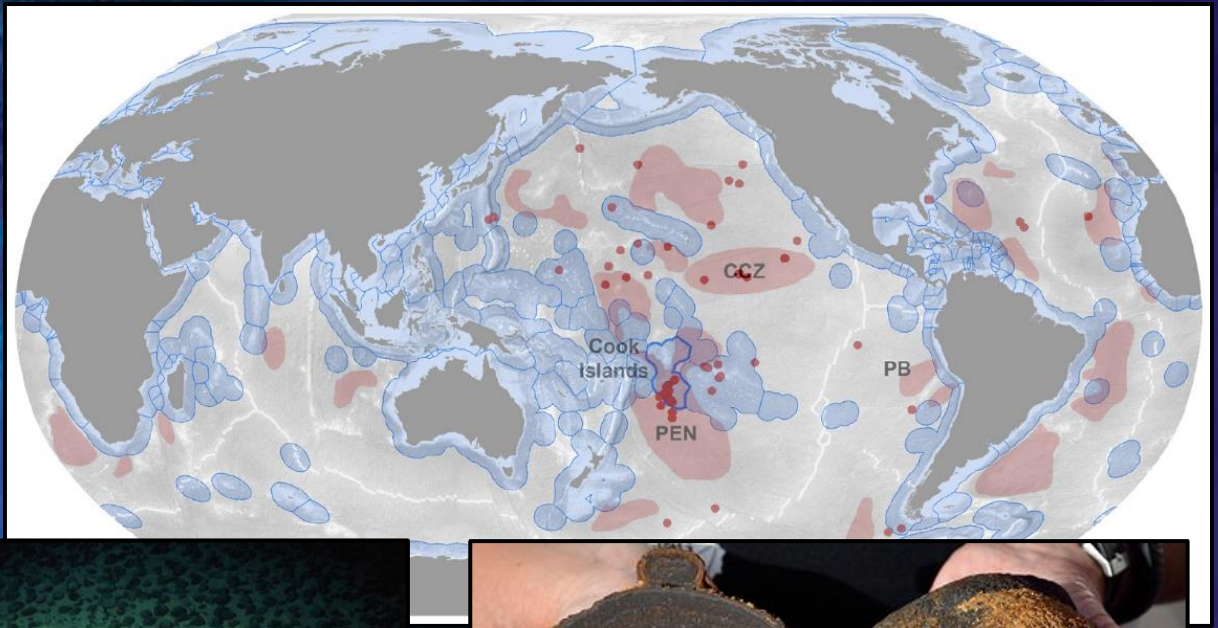
Polymetallic nodules

- Depth: 3000 – 6000 m
  - Economic interest: 4000 – 5000 m
- Thickness: 15 – 75 kg/m^2 (wet)
- Potential area: 38 M km^2 (19% EEZ)
- Simple mineralogy: vernardite, todorokite, birnessite, non.crystalline Fe-oxyhyrdoxies



Mean content of selected elements of manganese nodules in various locations (source [10,17]). Abbreviations: CCZ=Clarion Clipperton Zone; CIOB=Central Indian Ocean Basin).

	CCZ	CIOB	Peru Basin	Cook Islands
Mn (wt%)	28.4	24.4	34.2	16.1
Ni (wt%)	1.3	1.1	1.3	0.4
Cu (wt%)	1.1	1.0	0.6	0.2
Co (wt%)	0.21	0.11	0.05	0.41
Ti (wt%)	0.28	0.40	0.16	1.20
Mo (ppm)	590	600	547	295
Li (ppm)	131	110	311	–
REE+Y (ppm)	813	1039	403	1665

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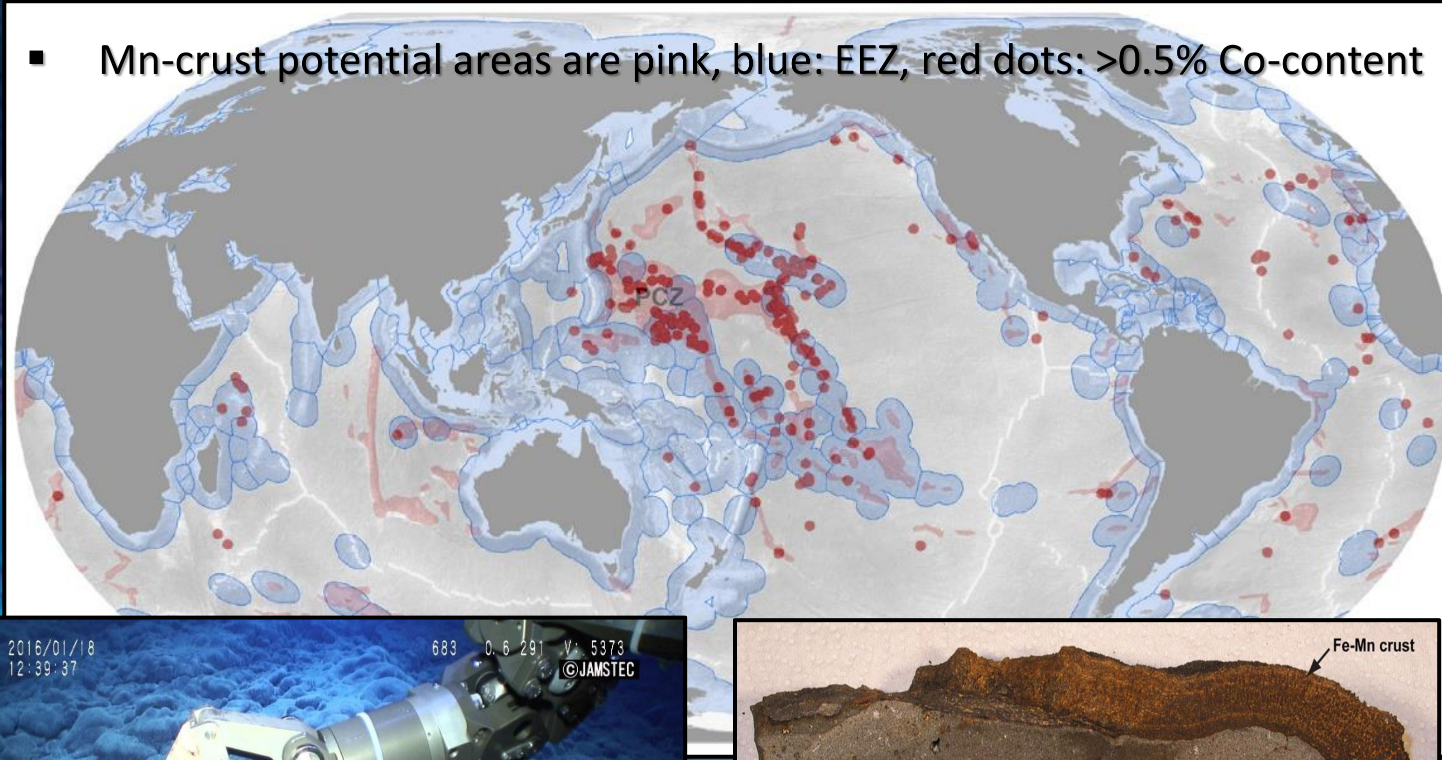
Co-rich ferromanganese crusts

- Depth: 400 – 7000 m
  - Economic interest: 800 – 2500 m
- Thickness: 1 – 260 mm
- Potential area: 1.7 M km^2 (54% EEZ)
- Simple mineralogy: vernardite, non-crystalline Fe-oxyhyrdoxies

Mean content of selected elements of ferromanganese crusts in various regions (source [11]). Abbreviation: PCZ=Prime Crust Zone.

	PCZ	South Pacific	Atlantic	Indian
Fe (wt%)	16.9	18.1	20.9	22.3
Mn (wt%)	22.8	21.7	14.5	17.0
Ni (wt%)	0.42	0.46	0.26	0.26
Cu (wt%)	0.10	0.11	0.09	0.11
Co (wt%)	0.67	0.62	0.36	0.33
Ti (wt%)	1.16	1.12	0.92	0.88
REE+Y (wt%)	0.24	0.16	0.24	0.25
Bi (ppm)	43	22	19	30
Mo (ppm)	461	418	409	392
Nb (ppm)	52	59	51	61
Pt (ppm)	0.5	0.5	0.6	0.2
Te (ppm)	60	38	43	31
Zr (ppm)	548	754	362	535



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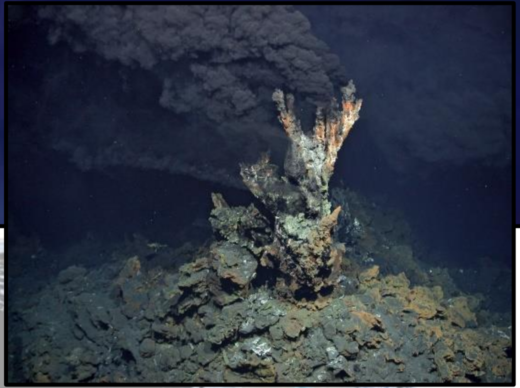
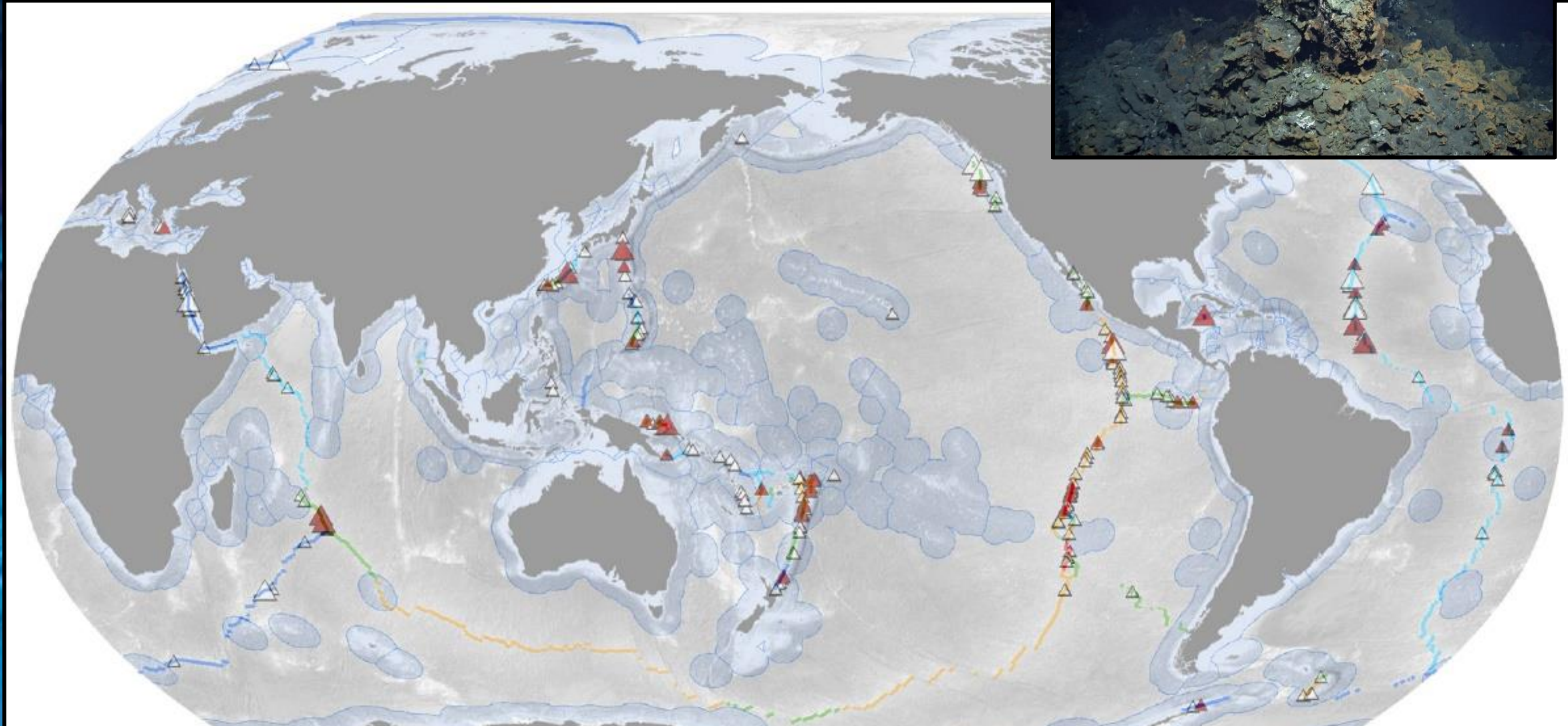
Seafloor Massive Sulphide deposits 1.

- Depth: 2000 – 3000 m economic depth
- Potential area: 3.2 M km^2 (42% EEZ)
- Many unknown volcanic-arc-related systems
  - 1000 – 5000 large sulphide deposits estimated
  - Increasing number, but usually small in size
  - Solid, or metal bearing muds





Spreading rate from blue (<20mm/y) to red (>140mm/y), hydrothermal systems are triangles (red: >5% Cu, or > 15% Zn, or >5 ppm Au, large symbols: > 1 Mt)

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Seafloor Massive Sulphide deposits 2.

- Geochemical data: 142 sites but only from 34 is >54 samples almost only from surface, only few deposits drilled scientifically
- Chemical composition is highly variable
- Mineralogy is complex: pyrite, chalcopyrite, pyrrhotite, sphalerite, galena, sulphates, silicates, gold, silver

Range and mean concentration of selected trace metals in seafloor massive sulfide samples in parts per million (ppm; source GEOMAR). Note that these elements are not routinely measured for seafloor massive sulfides and therefore the number of analyses varies considerably.

Element	N	Range (ppm)	Mean (ppm)
Antimony	3396	< 1–43,500	510
Bismuth	1840	< 1–2000	12
Cadmium	3549	< 1–6300	392
Gallium	1483	< 1–3700	58
Germanium	934	< 1–918	29
Mercury	2252	< 1–95,000	104
Indium	1471	< 1–592	18
Selenium	2278	< 1–9700	115
Tellurium	1374	< 1–431	5
Thallium	1549	< 1–1600	38

The mean metal content of seafloor massive sulfide deposits with respect to their tectonic setting (source GEOMAR). Note that the concentration of the trace metals gold and silver is given in parts per million (ppm). N=number of deposits for which chemical data is included. Abbreviations: MOR=Mid-Ocean Ridges.

Setting	N	Cu (wt%)	Zn (wt%)	Pb (wt%)	Fe (wt%)	Au (ppm)	Ag (ppm)
Sediment-free MOR	51	4.5	8.3	0.2	27.0	1.3	94
Ultramafic-hosted MOR	12	13.4	7.2	< 0.1	24.8	6.9	69
Sediment-hosted MOR	3	0.8	2.7	0.4	18.6	0.4	64
Intraoceanic back arc	36	2.7	17.0	0.7	15.5	4.9	202
Transitional back-arcs	13	6.8	17.5	1.5	8.8	13.2	326
Intracontinental rifted arc	5	2.8	14.6	9.7	5.5	4.1	1260
Volcanic arcs	17	4.5	9.5	2.0	9.2	10.2	197

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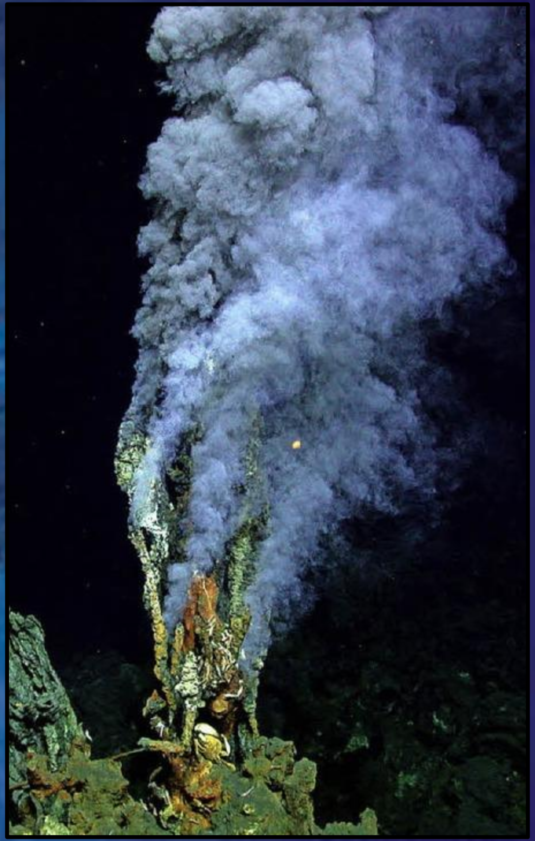
Seafloor Massive Sulphide deposits 3.

- Commonly only surface samples, qualitative assessment only for two locations (Solwara 1 and 12, Papua New Guinea)
- Number of SMS deposits were drilled by small lander-type drilling platform, which provide important chemical information for the upper few metres, but insufficient for resources estimates
- Most size estimates based on visual estimates, and not drilling



Seafloor Massive Sulphide deposits 4.

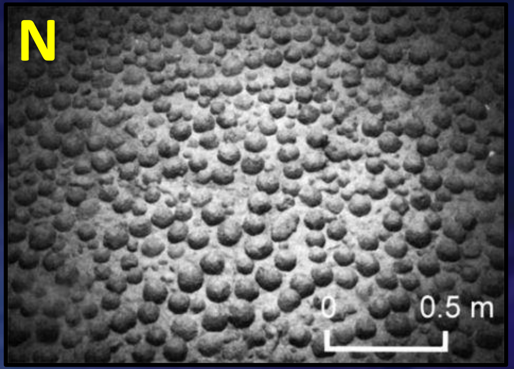
- Current mining scenarios for multi-year mining of SMS require ca. 2 Mt / year production, however only few are reaching 2 Mt total size
- Ca. 10 is sufficient size out of 340 known deposits, maybe integration of some smaller deposits can also be viable
- Exploration of SMS based on geochemical anomalies of the hydrothermal plumes in water column and geophysical recognition of the deposits or the altered rocks (only recent → small deposits)
- Could be buried deposits far from active regions
- **Old → large deposits need new exploration technologies!!**

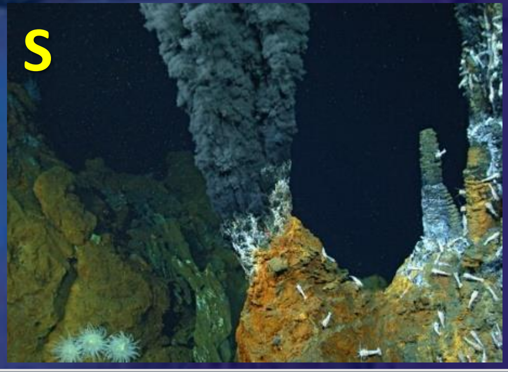
Seafloor massive sulfide occurrences for which size information is available based on drilling information. Abbreviations: ODP = Ocean Drilling Program; ROV = remotely-operated vehicle.

Deposit	Location	Size	Drilling tool/ vessel
Atlantis II	Red Sea	90 Mt	Coring
Middle Valley	Juan de Fuca Ridge	10–15 Mt	ODP-drill ship
TAG	Mid-Atlantic Ridge	4 Mt	ODP-drill ship
Izena	Okinawa Trough	3.4 Mt	Lander-type
Solwara 1	Bismarck Sea	2.5 Mt	ROV-based
Solwara 12	Bismarck Sea	0.2 Mt	ROV-based
Fryer, Pika	Mariana Trough	Small	Lander-type
Iheya North	Okinawa Trough	Small	IODP-drill ship
Logatchev	Mid-Atlantic Ridge	Small	Lander-type
PacManus	Bismarck Sea	Small	ODP-drill ship
PacManus	Bismarck Sea	Small	Lander-type
Palinuro	Tyrrhenian Sea	Small	Lander-type
Suiyo	Izu-Bonin Arc	Small	Lander-type

Characteristics of deep sea mineral resources

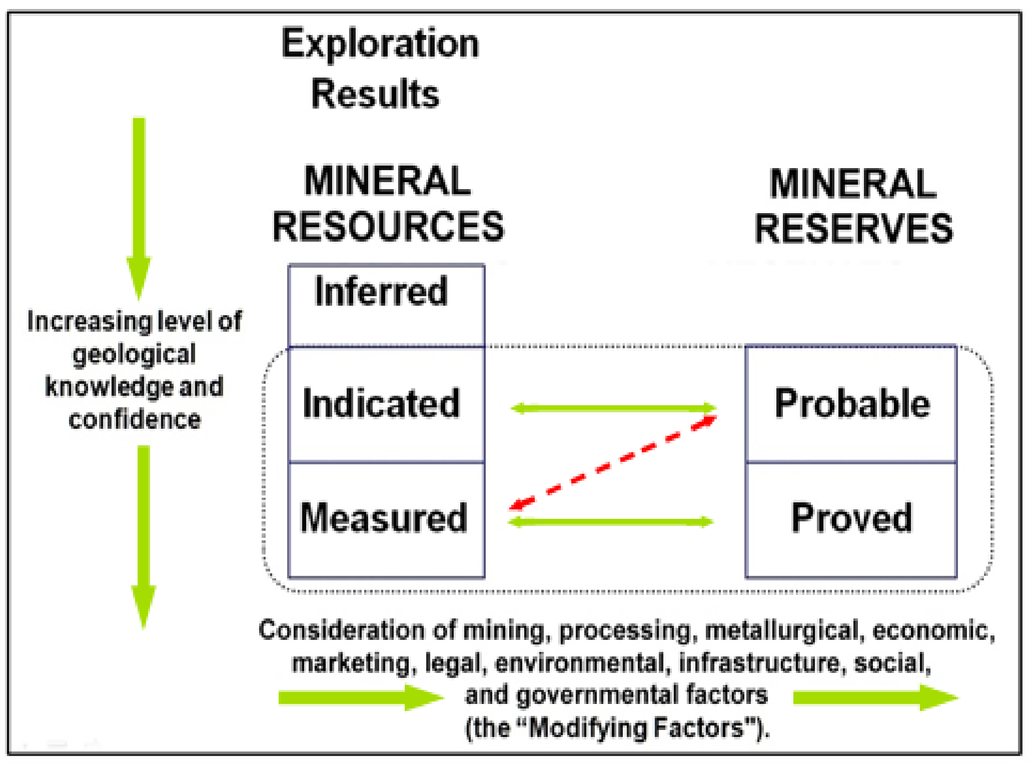
	Manganese nodules	Co-rich ferromanganese crusts	Seafloor massive sulfides
Geological Setting	Sedimented abyssal plains	Upper flanks of old volcanic seamounts	Oceanic spreading centers and young island arc volcanoes
Characteristics	Potato-sized nodules on soft sediment	Up to 25 cm-thick crusts on hard substrate	Ten to hundreds of meter wide mounds
Water depth of greatest economic potential	3000–6000 m	800–2500 m	1000–5000 m
Favorable area ("Area", EEZ, ECS)	38 million km^2 (81%, 14%, 5%)	1.7 million km^2 (46%, 44%, 10%)	3.2 million km^2 (58%, 36%, 6%)
Dimensions	Large 2-D deposits	Large 2-D deposits	Small 3-D deposits
Main metals of interest	Nickel, Copper, Manganese, Cobalt	Cobalt, Nickel, Manganese, Copper	Copper, Zinc, Gold, Silver
Other commodities	Molybdenum, Lithium, Titanium	Titanium, REEs, Platinum, Molybde-num, Bismuth	Cadmium, Gallium, Germanium, Indium, Antimony
Resource estimate	21,100 million tonnes in the Clarion-Clipperton-Zone	7533 million tonnes in the Prime Crust Zone	600 million tonnes in the neovolcanic zone of mid-ocean ridges
Grades	(Clarion-Clipperton) 2.4 wt% Cu+Ni 0.2 wt% Co 28 wt% Mn	(Prime Crust Zone) 0.5 wt% Cu+Ni 0.7 wt% Co 23 wt% Mn	(Occurrence median) 3 wt% Cu 9 wt% Zn 2 ppm Au 100 ppm Ag
Grade distribution	Homogeneous on regional scale	Homogeneous on regional scale	Very heterogenous on regional and local scale
Footprint of 2 mio tonne mining activity on the seafloor	150 km^2	25 km^2	< 0.2 km^2
Knowledge base for resource estimate	Good in the CCZ	Poor	Poor
Resource potential	High	High	Small
Global impact of mining on metal markets	High[a]	High[a]	Low





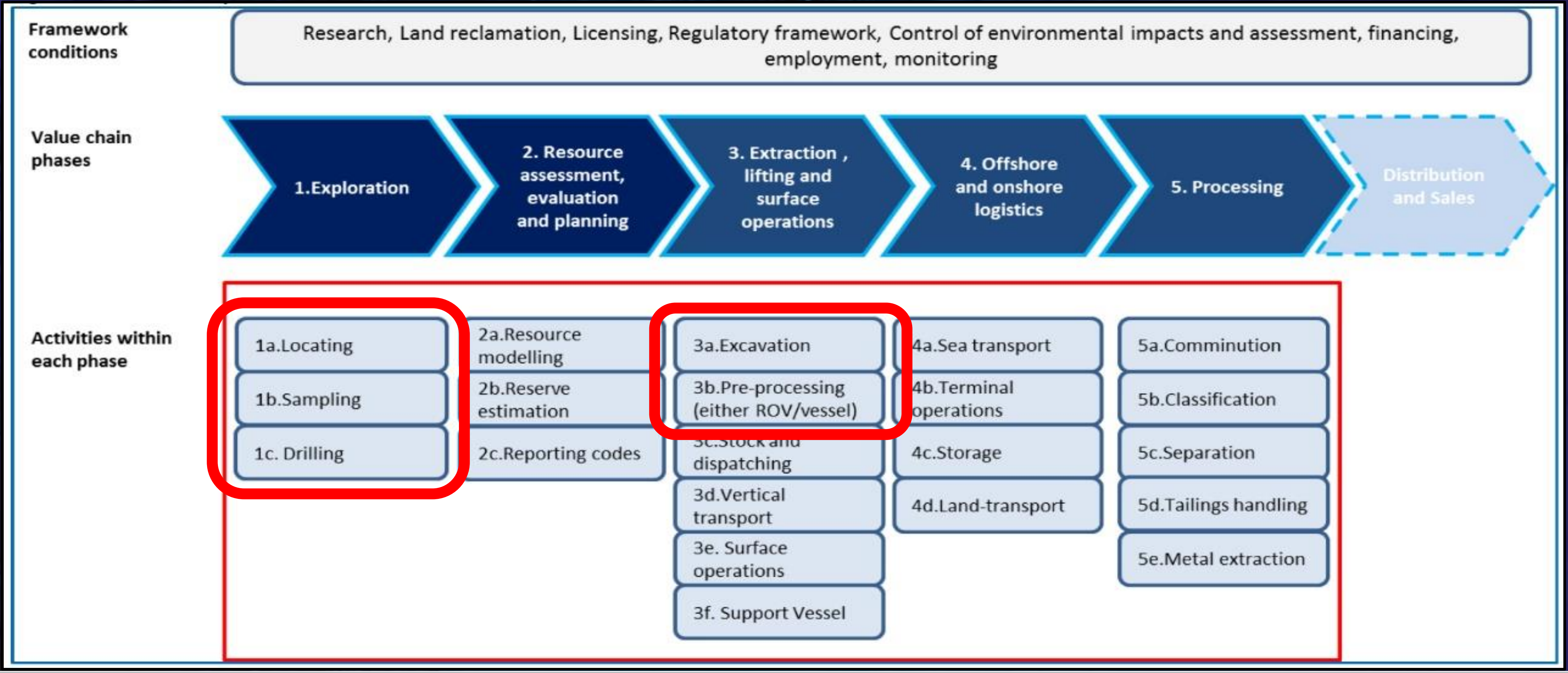
Professional codes of practice

- CRIRSCO: Committee for Mineral Reserves International Reporting Standards
- JORC: Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves
- Other standards...



- Accepted analytical methods in accredited laboratories
- In sea only Nautilus (JORC)

Where to do „*in-situ*” characterization in the value chain



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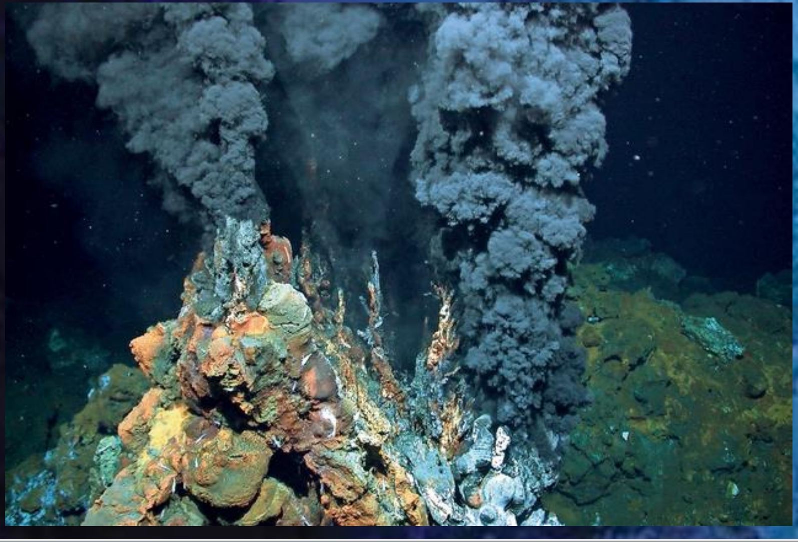
Solutions for exploration and exploitation

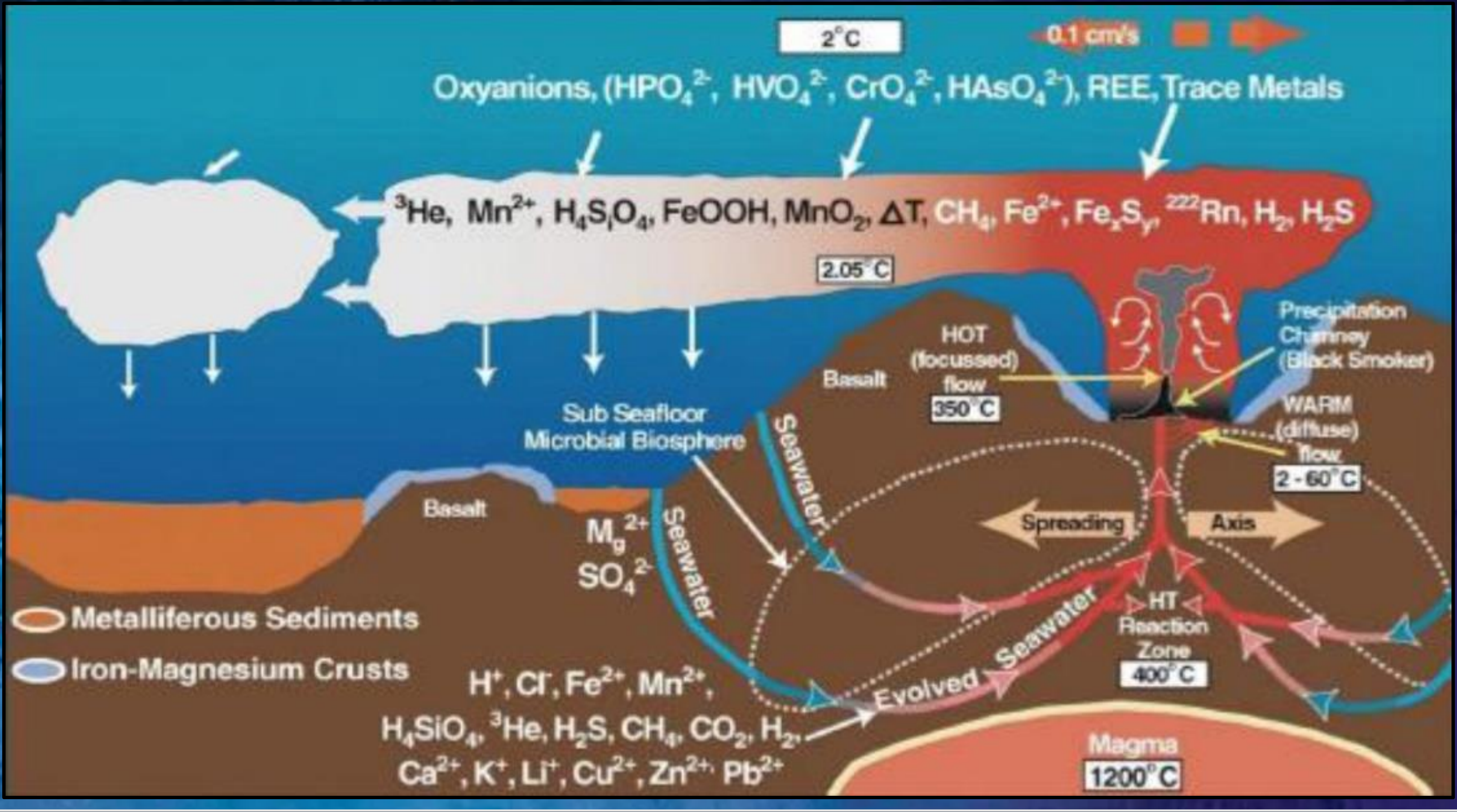
- Short term solution:
  - Sampling on site, analysis at the laboratory (ship, or land)
- Long term solution:
  - *„in-situ"* analysis underwater
  - (partially by technical challenges, more about legalisation...)
- Different groups of analytics:
  - Water-analytical methods
  - Geophysical methods
  - Geochemical-, mineralogical-, phase identification methods of the rocks

Water chemistry methods

- **<u>ROV or AUV:</u>**

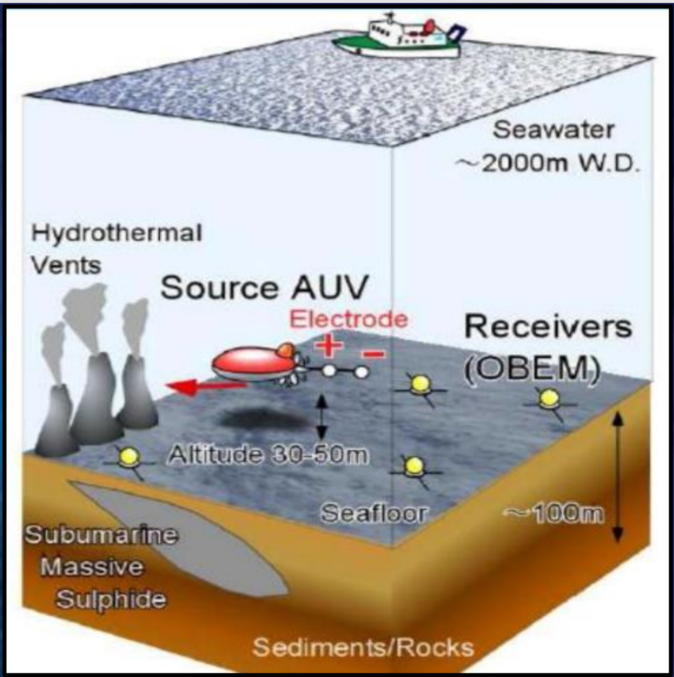
- Water sampling
- On-board analysis
- Finding only recent, active SMS sites



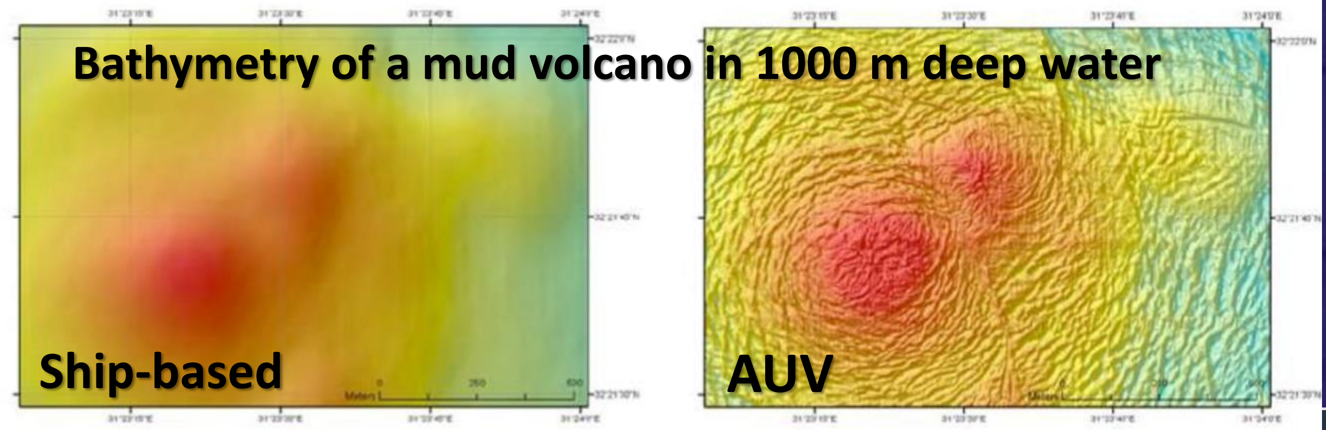


Geophysical methods

- Difference in targeting and detailed exploration
- Geophysics from the surface
  - „Traditional technology” but resolution is usually not satisfactory
- Geophysics on (close to) the bottom
- Geophysics at the rock surface, in the drill holes
  - Analogues to petroleum industry, but different target different drilling fluid, different geometry



Bathymetry of a mud volcano in 1000 m deep water



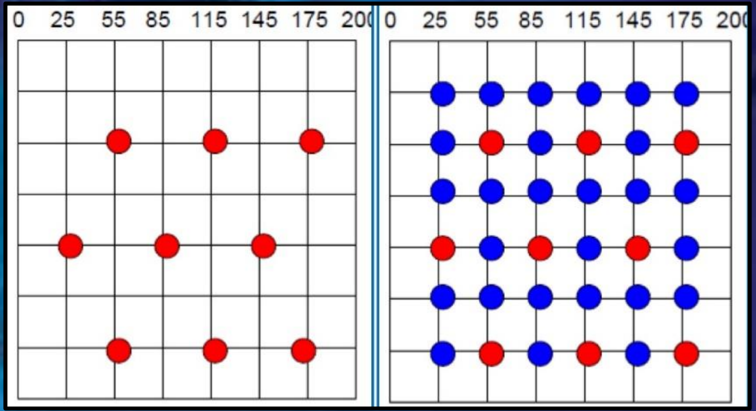
Sampling, Drilling

- Grab samples from the surface
- Below the surface → drilling
- Soft, muddy sediment or solidified hard rock
- Drilling: from ship, from bottom operated rig

Furgo Seacore drilling vessel

Bauer drill rig

Drill grid for early exploration and pre-mining phases for SMS



Solwara 1:

2006: 42 holes with 41% recovery (poor)

2007: 111 holes with 70% → enough for resource estimation

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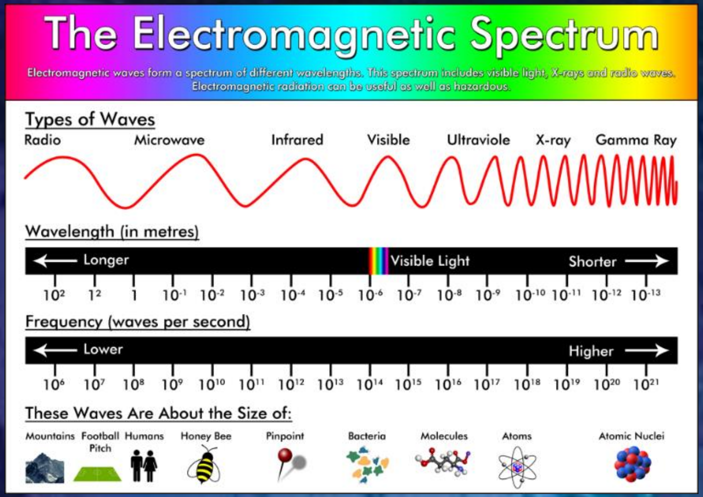
„*In-situ*” analytical methods

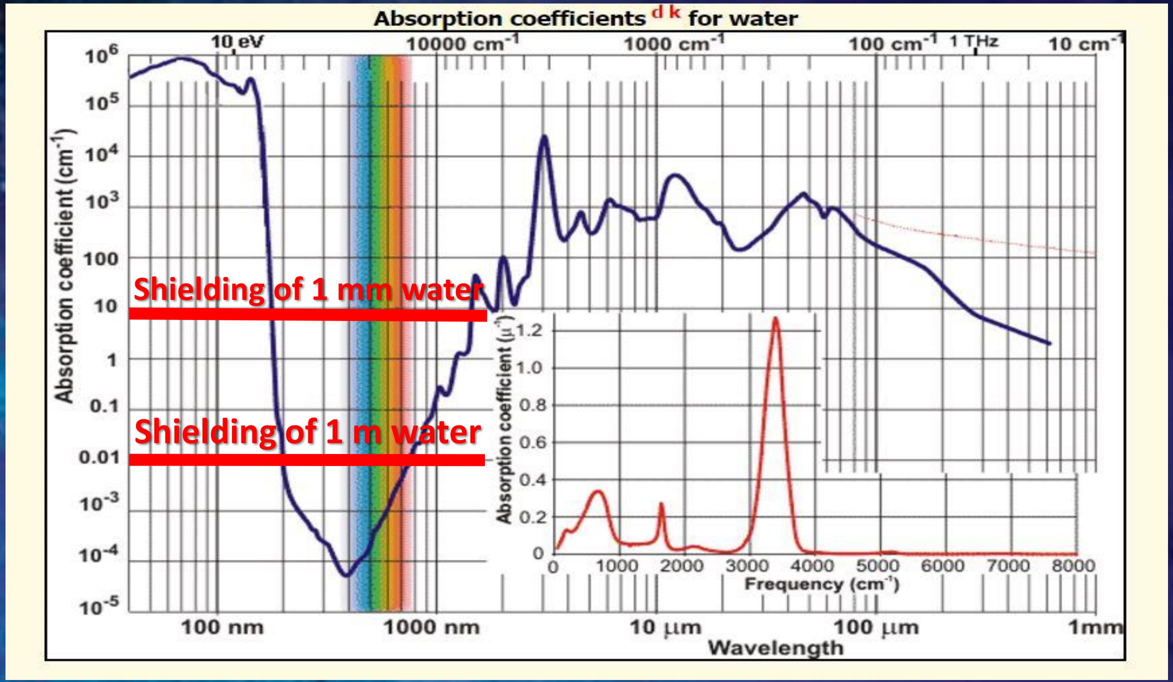
- **What to measure:**
- Main element content
- Trace element content
  - Many low concentration commodities, by-products
- Phase identification
- Texture

- **Difficulties with „in-situ” analysis in the deep sea:**
- Shielding effect of the water
  - Excitation side
  - Detection side
- Solutions for withstanding the high pressure
  - Shielding of the high pressure windows

- **Two big groups of possible methods:**
- Spectroscopy methods using EM radiation
- Identification of the crystal structure (e.g. diffraction)
- **Can be combined with:**
- Physical parameters: eg. density…
- Geophysics

Limitation in the Electromagnetic spectrum and the use of EM methods





- Optical spectroscopy methods (300 – 1000 nm)
  - Multi-, Hyper-spectral imaging (UNEXMIN/UNEXUP)
  - UV-fluorescence imaging (can be spectroscopy)
- Raman-spectroscopy
- LIBS (laser induced breakdown spectroscopy)
- X-ray methods
- Nuclear methods

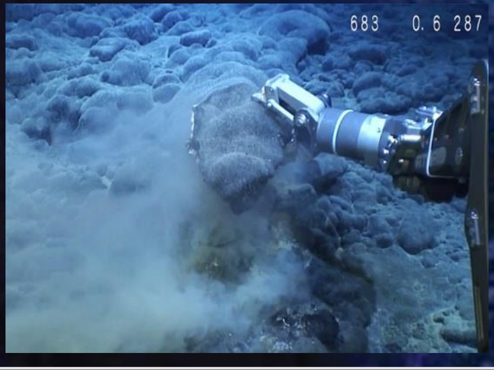
„*In-situ*” analytical methods

- <u>Main element content:</u>
  - XRF spectroscopy
  - Nuclear methods
  - UV-fluorescence
  - LIBS (laser induced breakdown spectroscopy)

- <u>Trace element content:</u>
  - **LIBS (laser induced breakdown spectroscopy)**
  - **XRF spectroscopy**
  - **Nuclear methods**

- <u>Phase identification:</u>
  - **Raman-spectroscopy**
  - Optical methods (300 – 1000 nm)
  - UV-fluorescence

- <u>Texture:</u>
  - **Optical methods (300 – 1000 nm)**
    - **Spectroscopy**
    - **White light imaging**
  - UV-fluorescence
  - Raman-spectroscopy



- **<u>Conclusion:</u>**
  - Few different methods with certain limitations can be used to answer the questions
  - What is a good solution is strongly depends on the certain deposit type, location and task
  - **Research, Development and Innovation (RDI) is needed!!!**

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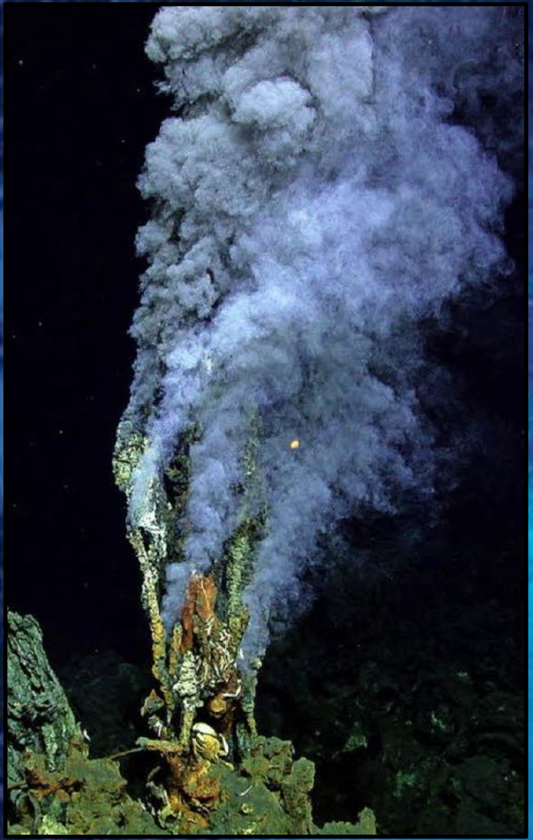

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