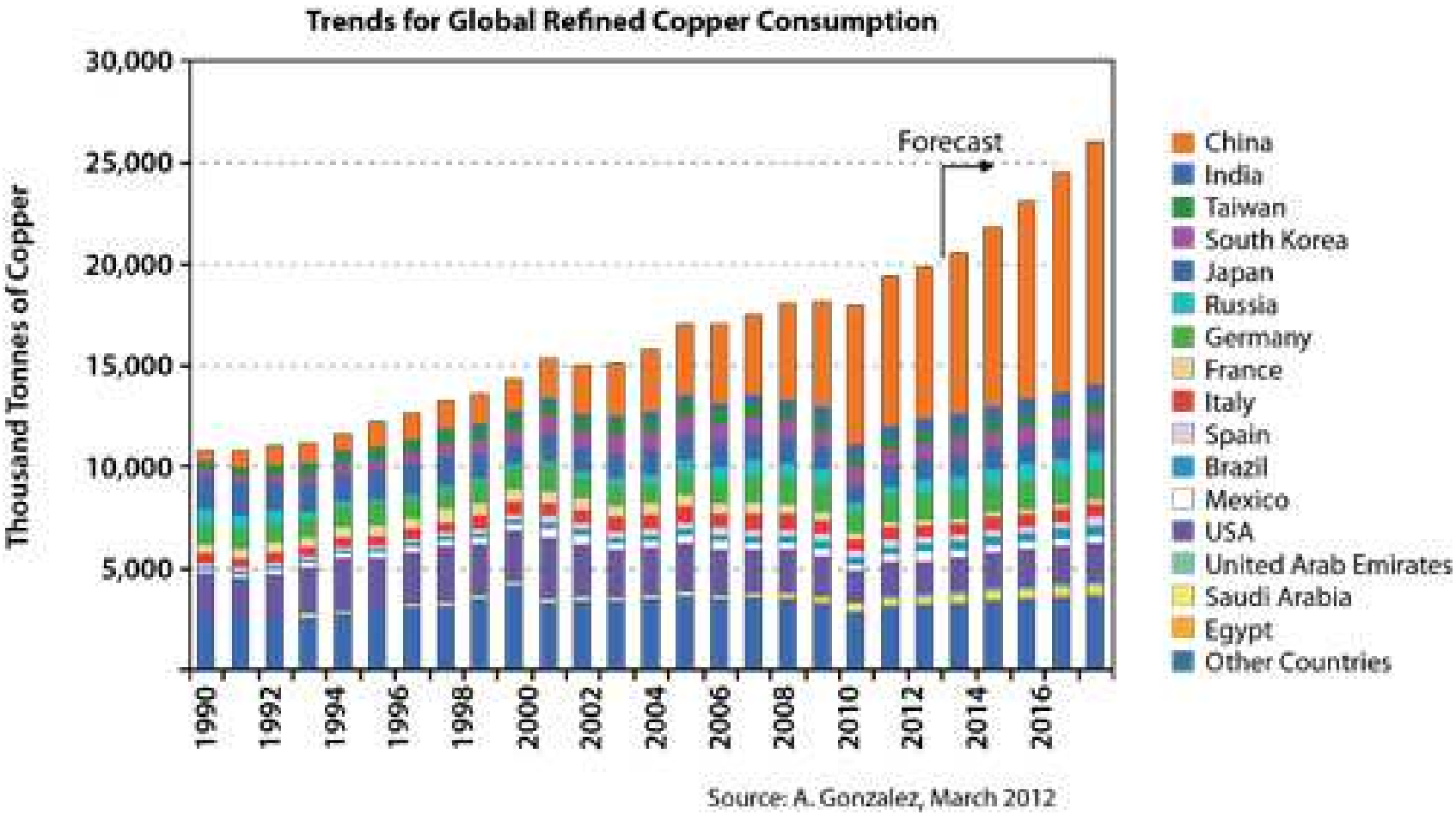
Deep Sea Mining:
State-of-the-Art and Future Perspectives

Dr. Jörg Benndorf
Lisabon, September 2014

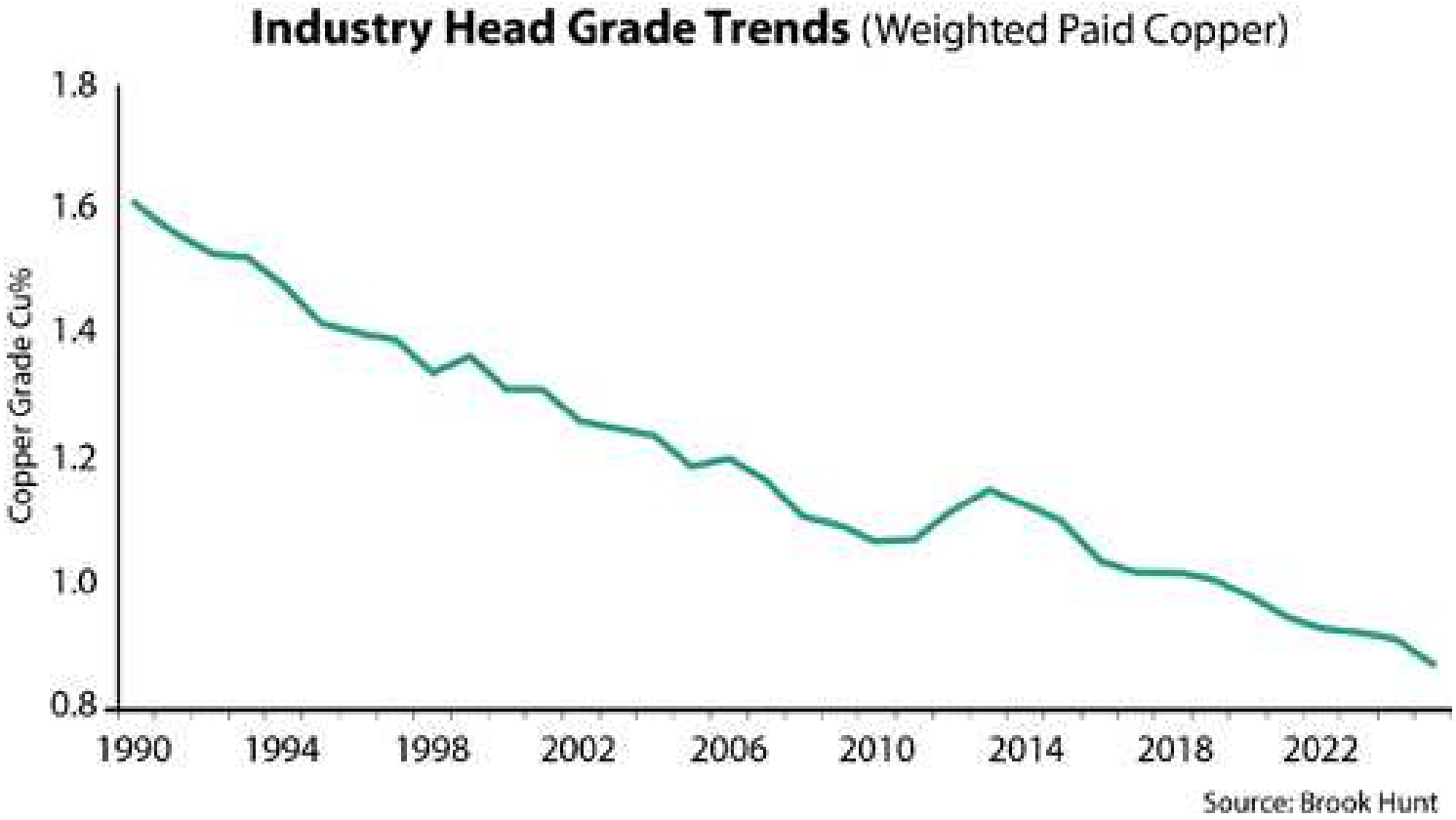
Agenda

- The demand for minerals - key drivers
- Deep sea mineral resources
- Deep sea mining technology: state-of-the-art and gaps
- Seabed vs. land-based mining
- Conclusions and potential future scenarios

Deep Sea Mining – Key Drivers



Deep Sea Mining – Key Drivers



Deep Sea Mining – Key Drivers

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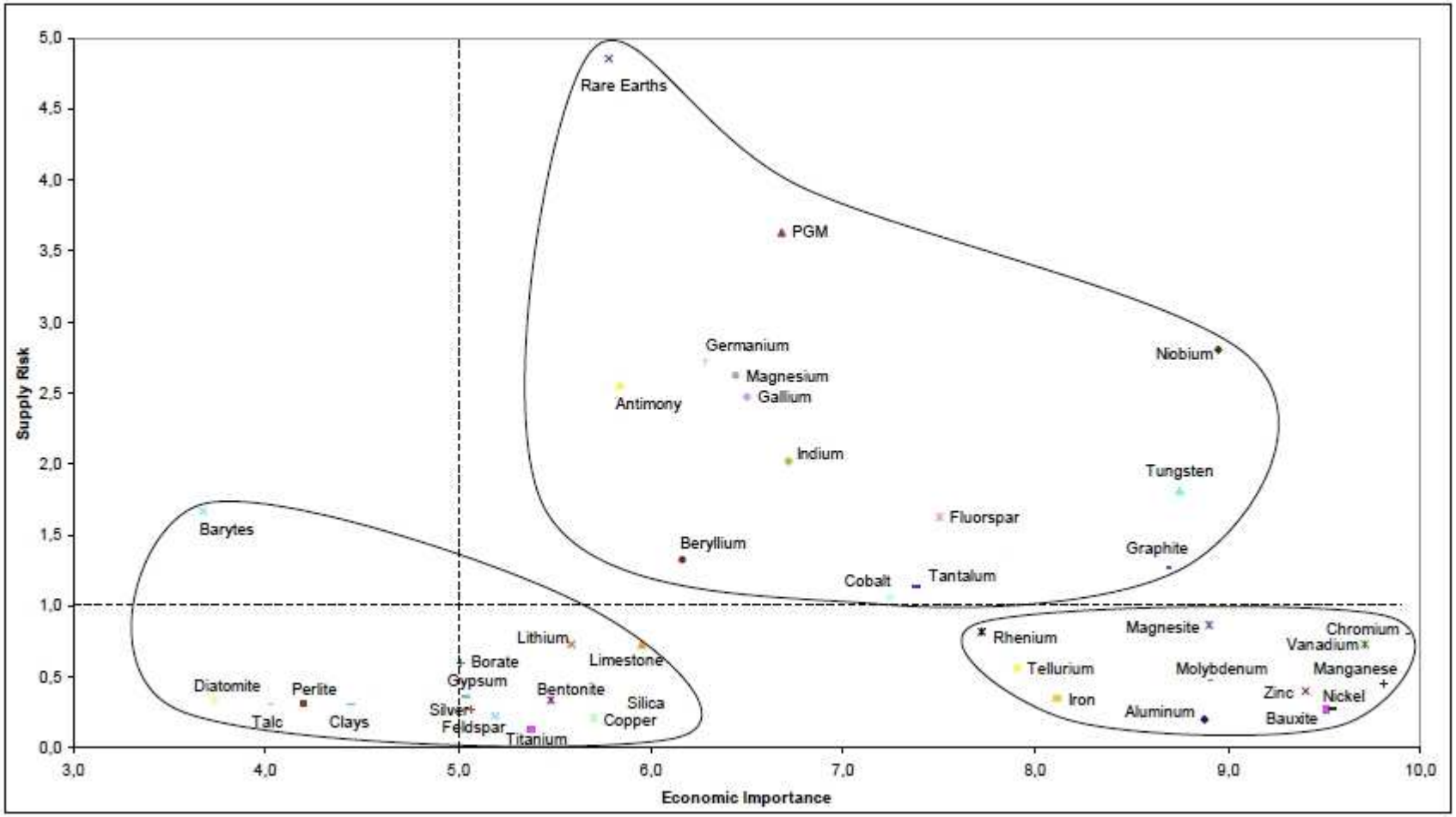


Source: Critical raw materials for the EU, European Commission, 2010

Are there alternative sources to secure Europe's supply with raw materials?

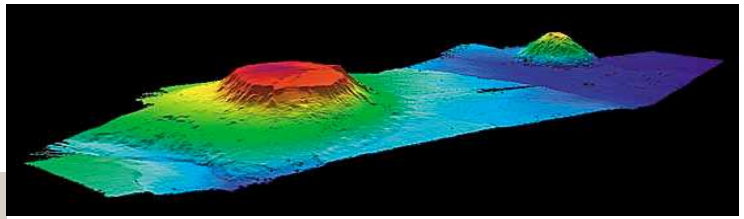
Jules Verne (1870):

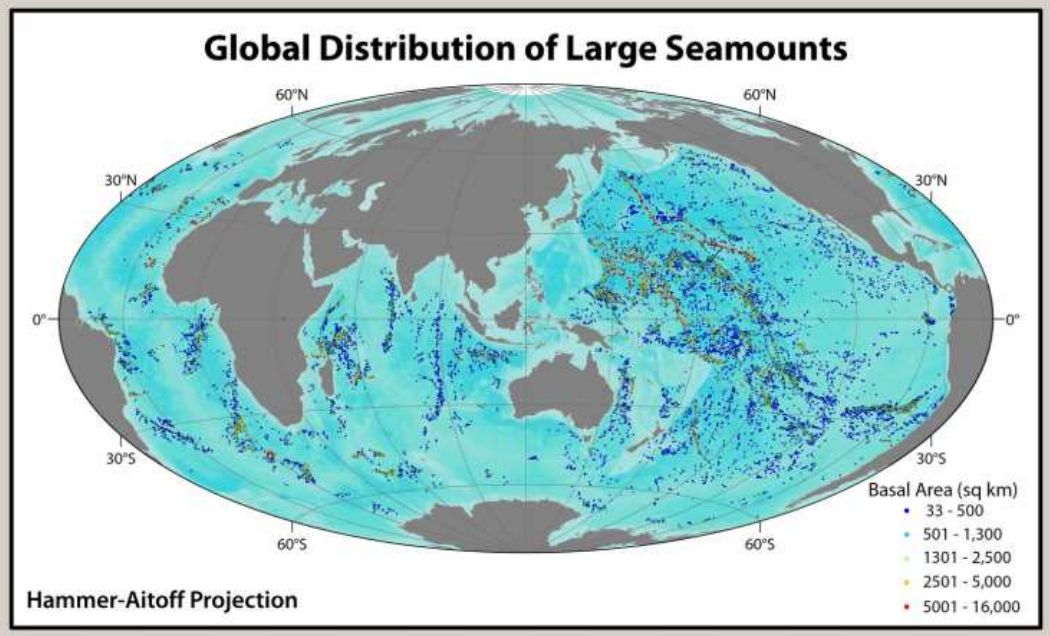
“20.000 leagues under the sea”:

“In the depths of the oceans there are mines of zinc, iron, silver and gold that would be quite easy to exploit”

Deep Sea Mining – Mineral Resources

- Cobalt-rich crusts on seamounts





- Slopes of submarine mountains (seamounts) and volcanoes at depths of 800 – 2500 m in the Pacific Ocean are often covered by a crust of cobalt, titanium, cerium, manganese and nickel.
- These deposits also were precipitated from seawater, possibly under the influence of bacteria.
- Hydrothermal activity is a possibility for the origin of the metals.
- The formation times are probably tens of millions of years.

Deep Sea Mining – Mineral Resources

- Polymetallic Nodules

- formed over millions of years
- minerals precipitated from the water around sea-floor detritus (such as shark teeth, whale ear bones, and pebbles)
- contain valuable metals iron, manganese, copper, cobalt and nickel and REE.
- at depths greater than 4,000 metres.
- potato-sized

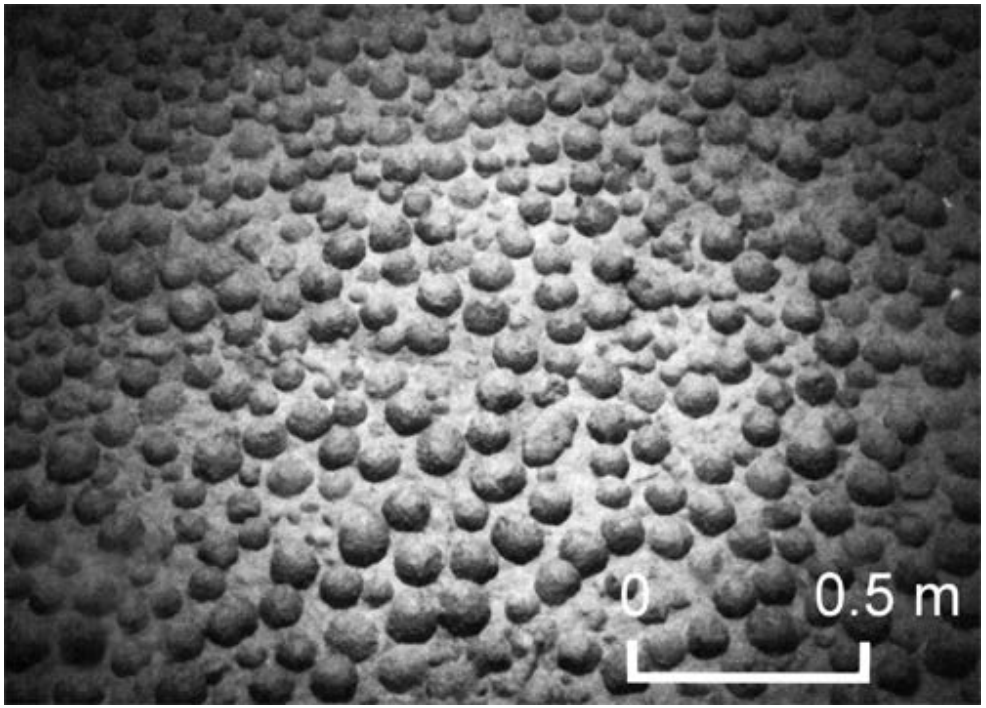
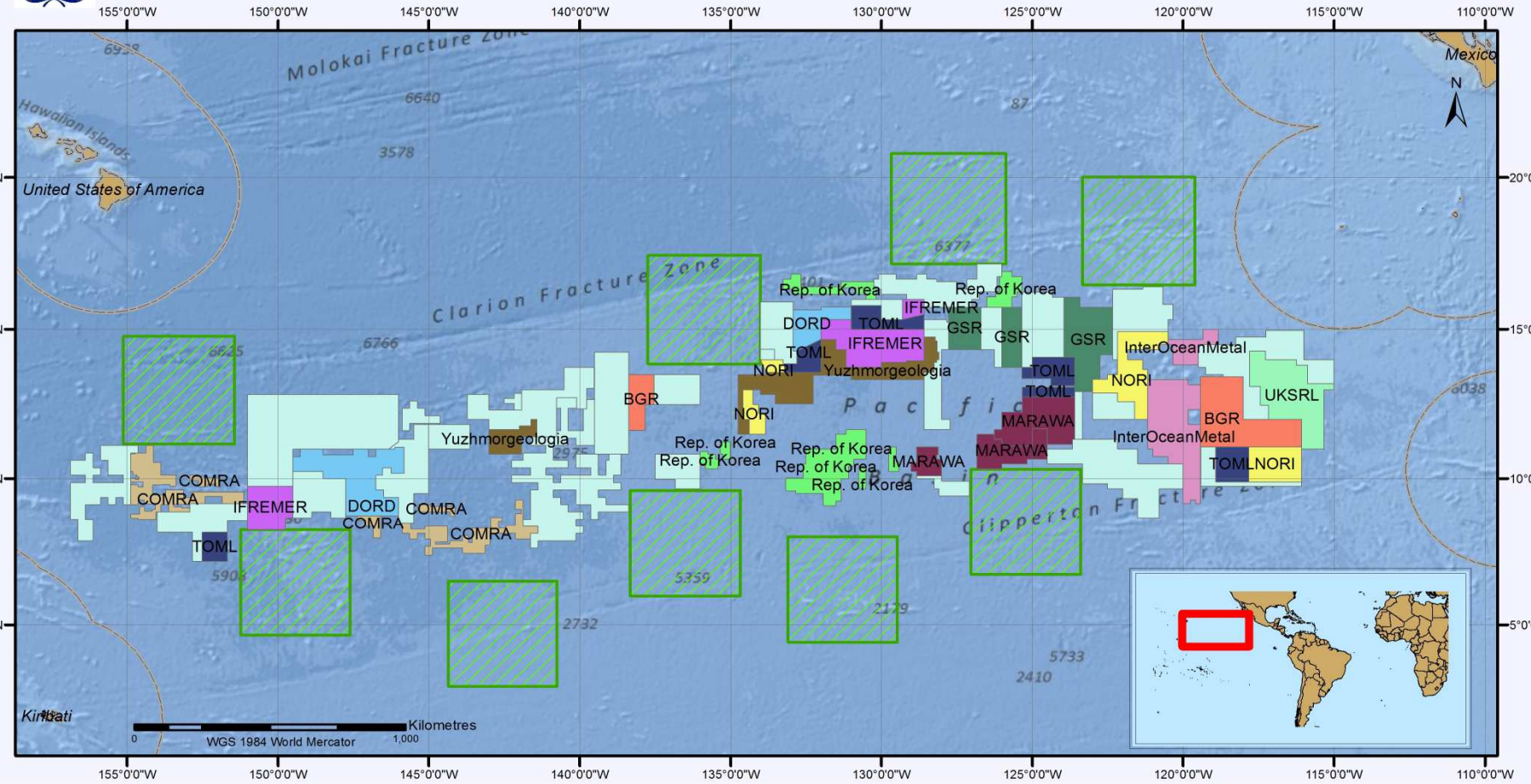


Foto from Ian Wright. 'Marine minerals - Nodules, crusts and vents', Te Ara - the Encyclopedia of New Zealand, updated 21-Sep-12

Polymetallic Nodules Exploration Areas in the Clarion-Clipperton Fracture Zone

Areas under contract and areas reserved for the International Seabed Authority



Contract area or contract approved as of 28 February 2013

- Marawa Research and Exploration Ltd (Kiribati)
- Bundesanstalt für Geowissenschaften und Rohstoffe (BGR; Germany)
- China Ocean Mineral Resources Research and Development Association (COMRA; China)
- Deep Ocean Resources Development Company (DORD; Japan)
- G-TEC Minerals Resources NV (GSR; Belgium)
- Government of the Republic of Korea
- Institut français de recherche pour l'exploitation de la mer (IFREMER; France)
- Interoceanmetal (IOM; Bulgaria, Cuba, Czech Republic, Poland, Russian Fed., Slovakia)
- Nauru Ocean Resources Inc. (NORI; Nauru)
- Tonga Offshore Mining Ltd (TOML, Tonga)
- UK Seabed Resources Ltd (UKSRL, UK)
- Yuzhmorgeologia (Russian Federation)

Reserved area* **Area of particular environmental interest (APEI)**** **Exclusive Economic Zones (VLIZ, 2011)**

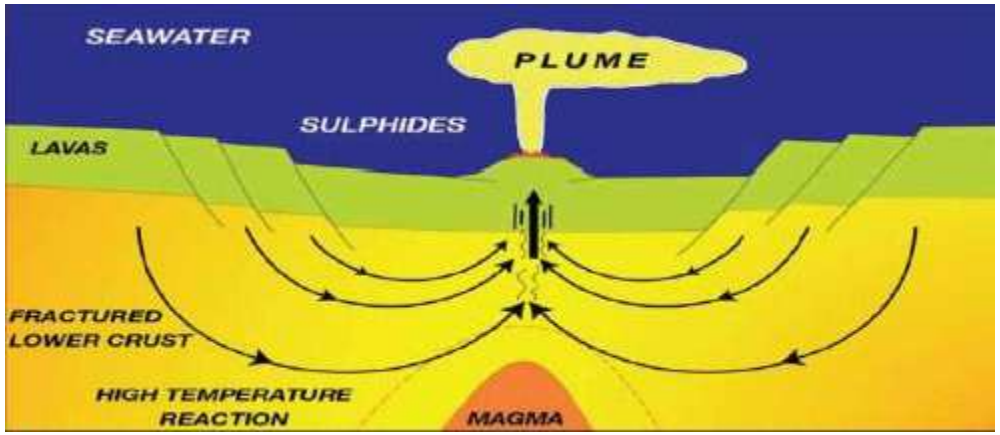
* In the case of polymetallic nodules, the so-called parallel system provides that each application for exploration by a developed State must cover two parts of "equal estimated commercial value". One part is allocated to the applicant and the other is to become the reserved area, which is set aside for the conduct of activities by the Authority or developing States.

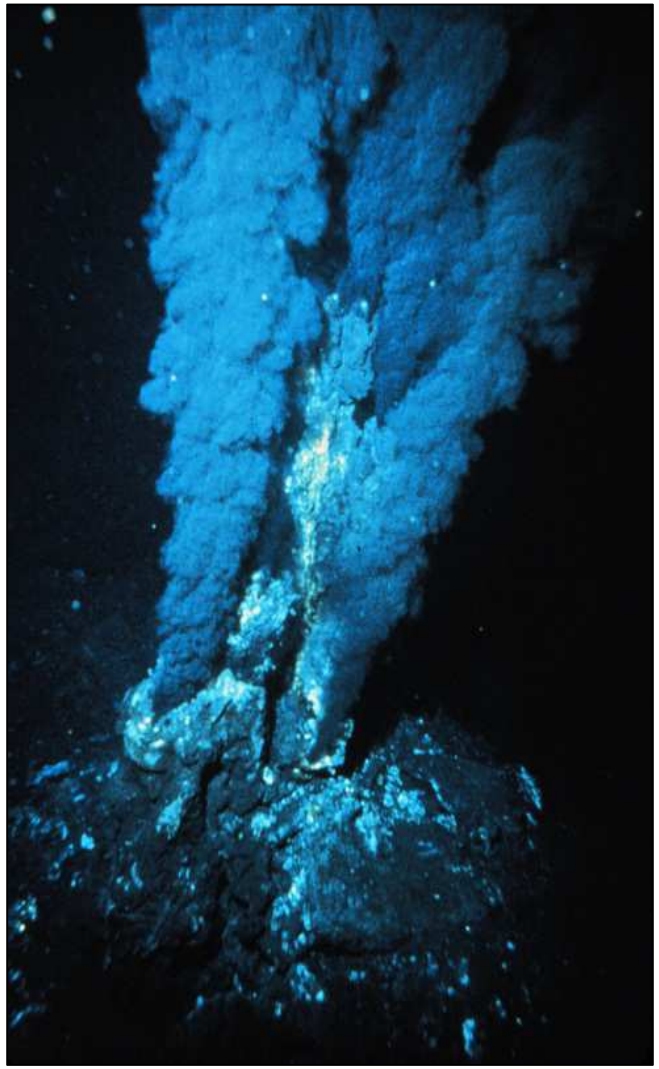
** In July 2012, the Authority adopted an environmental management plan for the Clarion-Clipperton Zone to be implemented on a provisional basis over an initial three-year period. The plan includes the designation of a network of areas of particular environmental interest (ISBA/18/C/22).

http://www.isa.org.jm/en/scientific/exploration

Deep Sea Mining – Mineral Resources

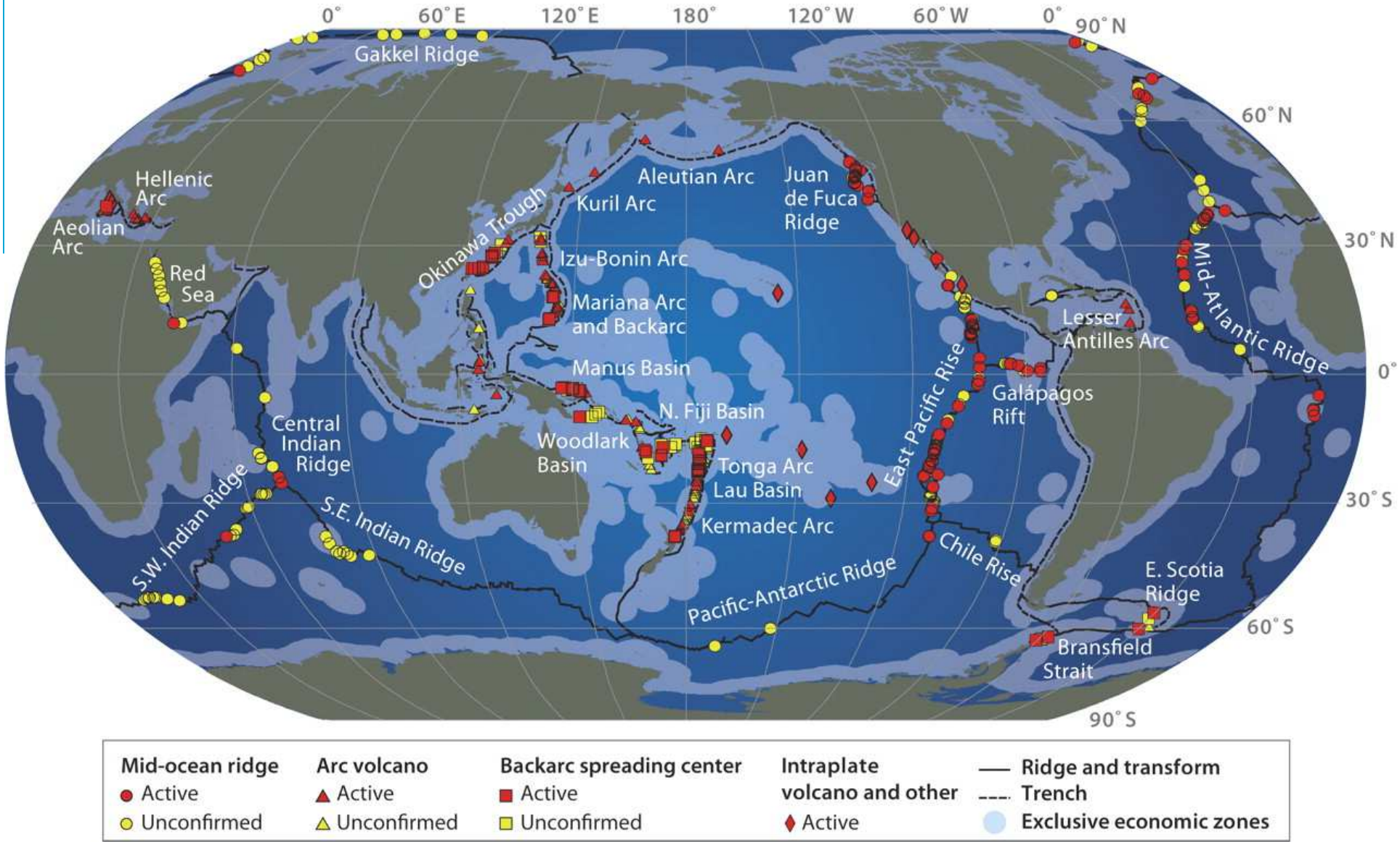
- Sea Floor Massive Sulphides



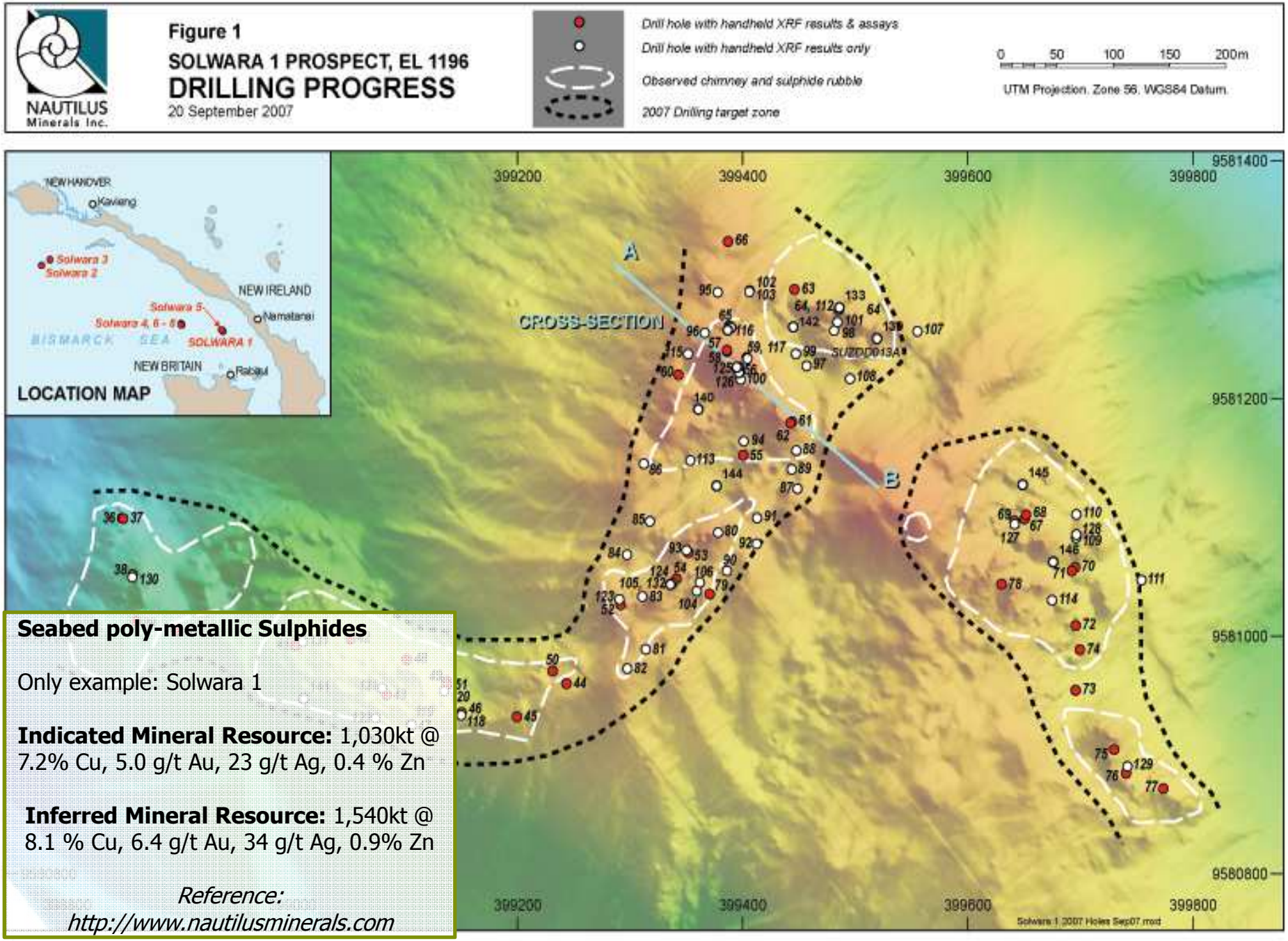


- Aqueous fluids, seeping through the seabed are heated by the influence of submarine magmatism.
- These fluids are enriched in minerals by leaching them out the they typically contain iron, copper, zinc, sulphur, and possible gold and silver.
- Via faults these hydrothermal fluids can reach the surface of the seabed. There they cool, leading to deposits of copper and zinc sulphides.

Global distribution of seafloor hydrothermal systems and related mineral deposits.



Hannington M et al. Geology 2011;39:1155-1158



Seabed poly-metallic Sulphides

Only example: Solwara 1

Indicated Mineral Resource: 1,030kt @ 7.2% Cu, 5.0 g/t Au, 23 g/t Ag, 0.4 % Zn

Inferred Mineral Resource: 1,540kt @ 8.1 % Cu, 6.4 g/t Au, 34 g/t Ag, 0.9% Zn

Reference:
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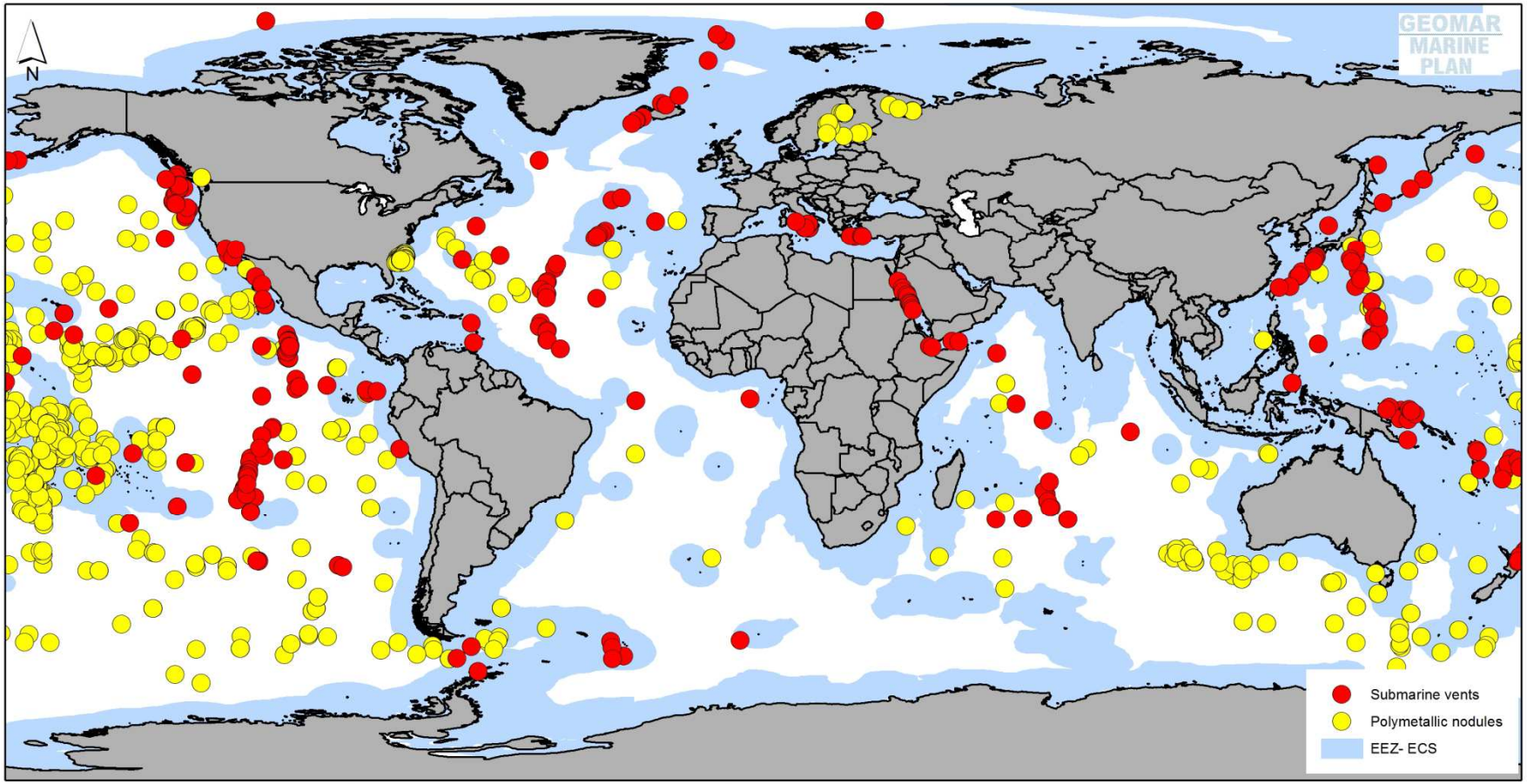
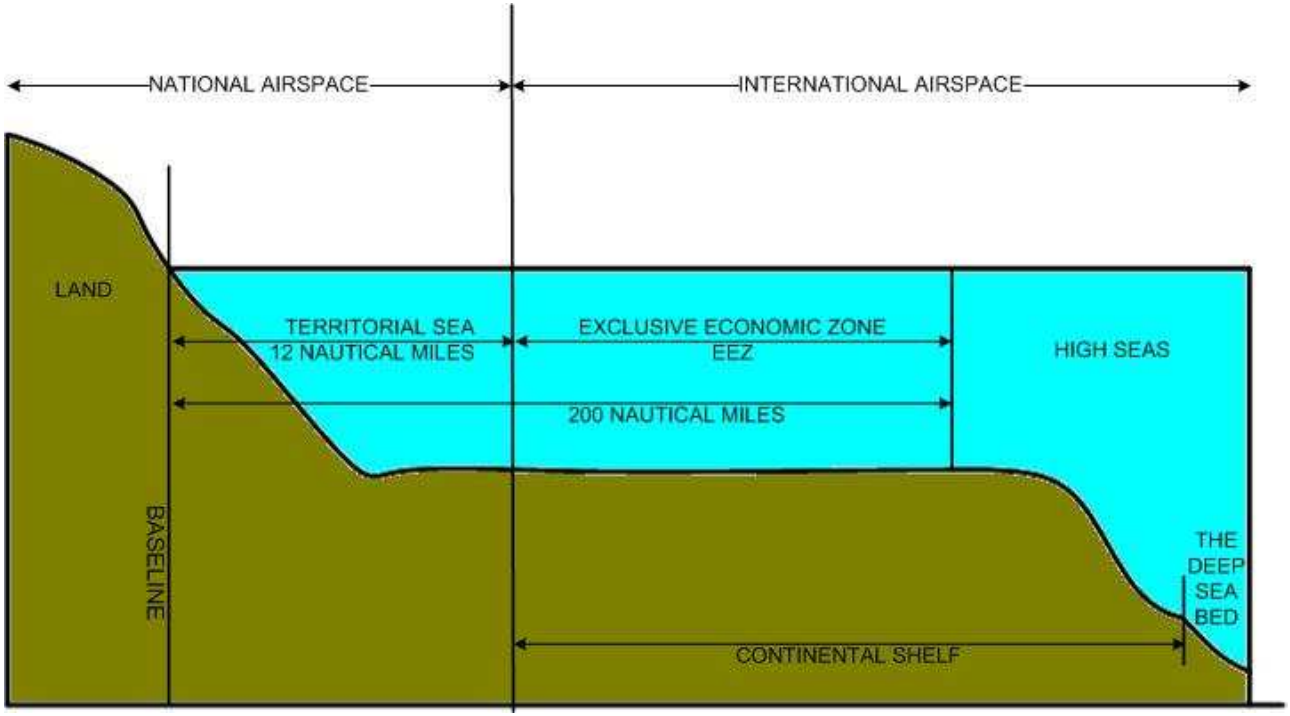
Deep Sea Mining – Mineral Resources



Source: ISA, 2014a. International Seabed Authority Web GIS Application. International Seabed Authority (ISA), Kingston, Jamaica.

Who belong Resources to?

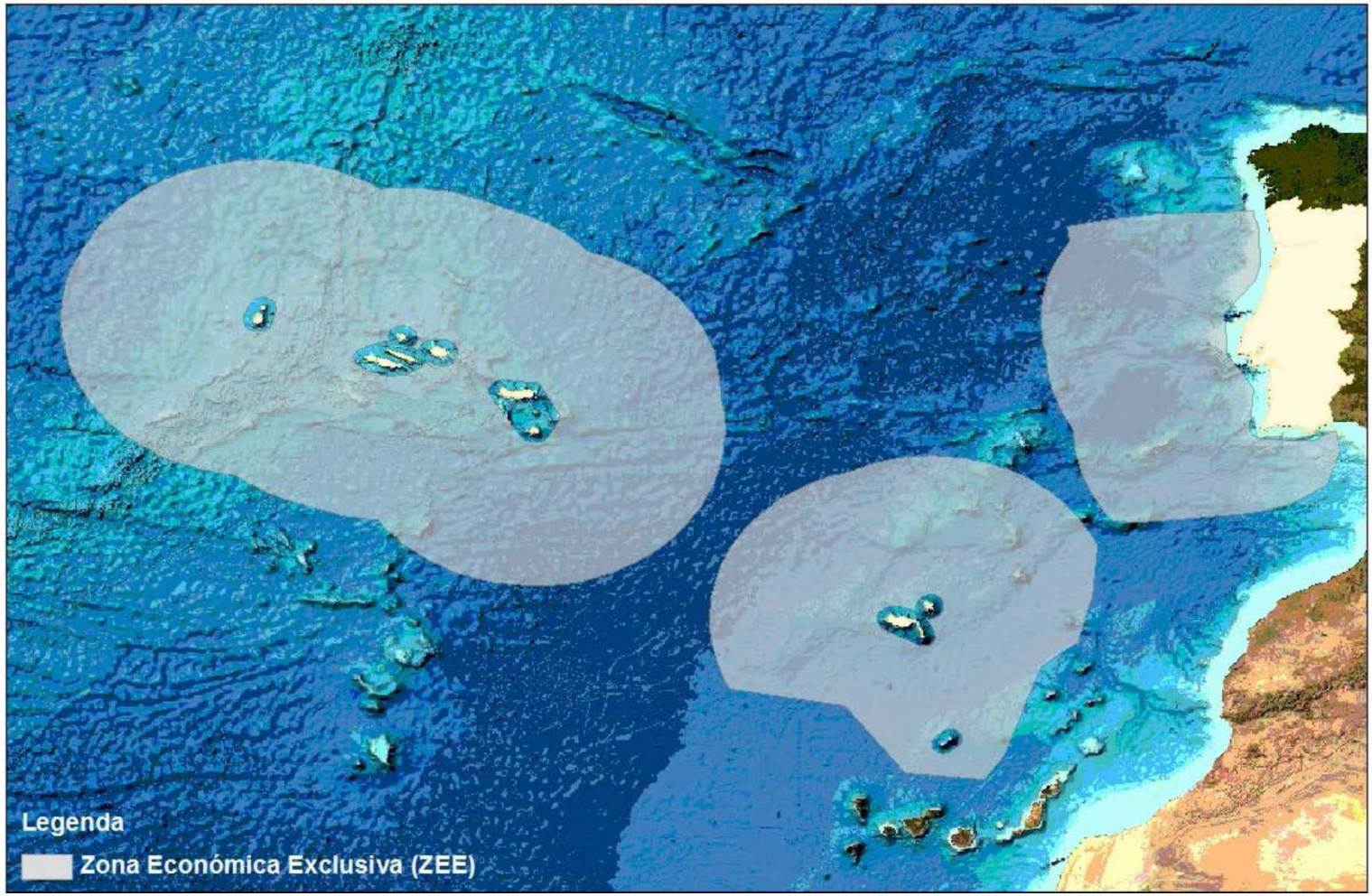


Regulation United Nations Convention on the Law of the Sea (**UNCLOS**).

An **exclusive economic zone (EEZ)** is a 200-nautical-mile sea area measured from the low-water baseline (the level reached by the sea at low tide) of a state's coast or of an inhabitable island under its sovereignty. Under UNCLOS, a state has sovereign jurisdiction over the area's living and non-living marine resources.

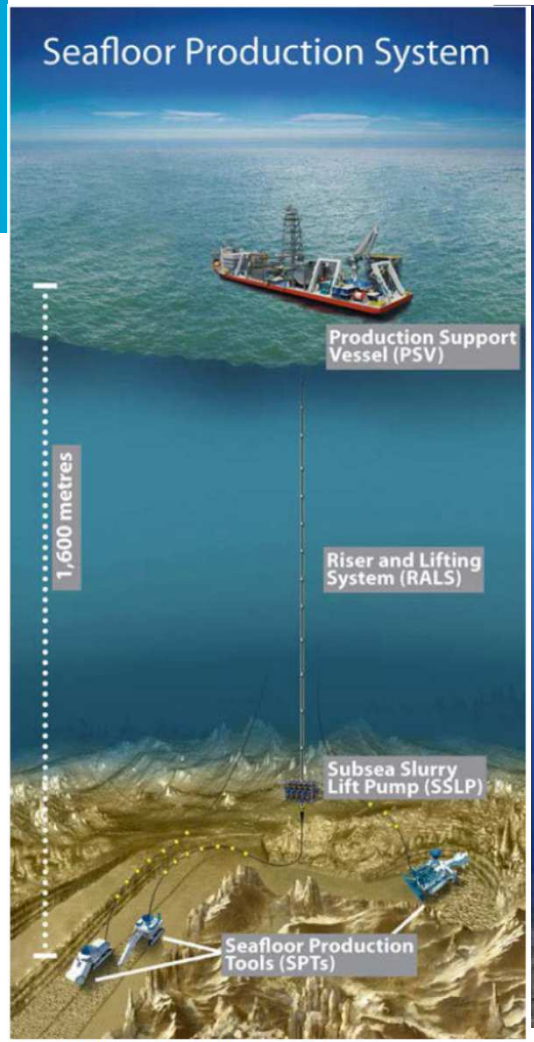
International Seabed Authority **(ISA**) supervises mining outside the EEZ's.

EEZ of Portugal

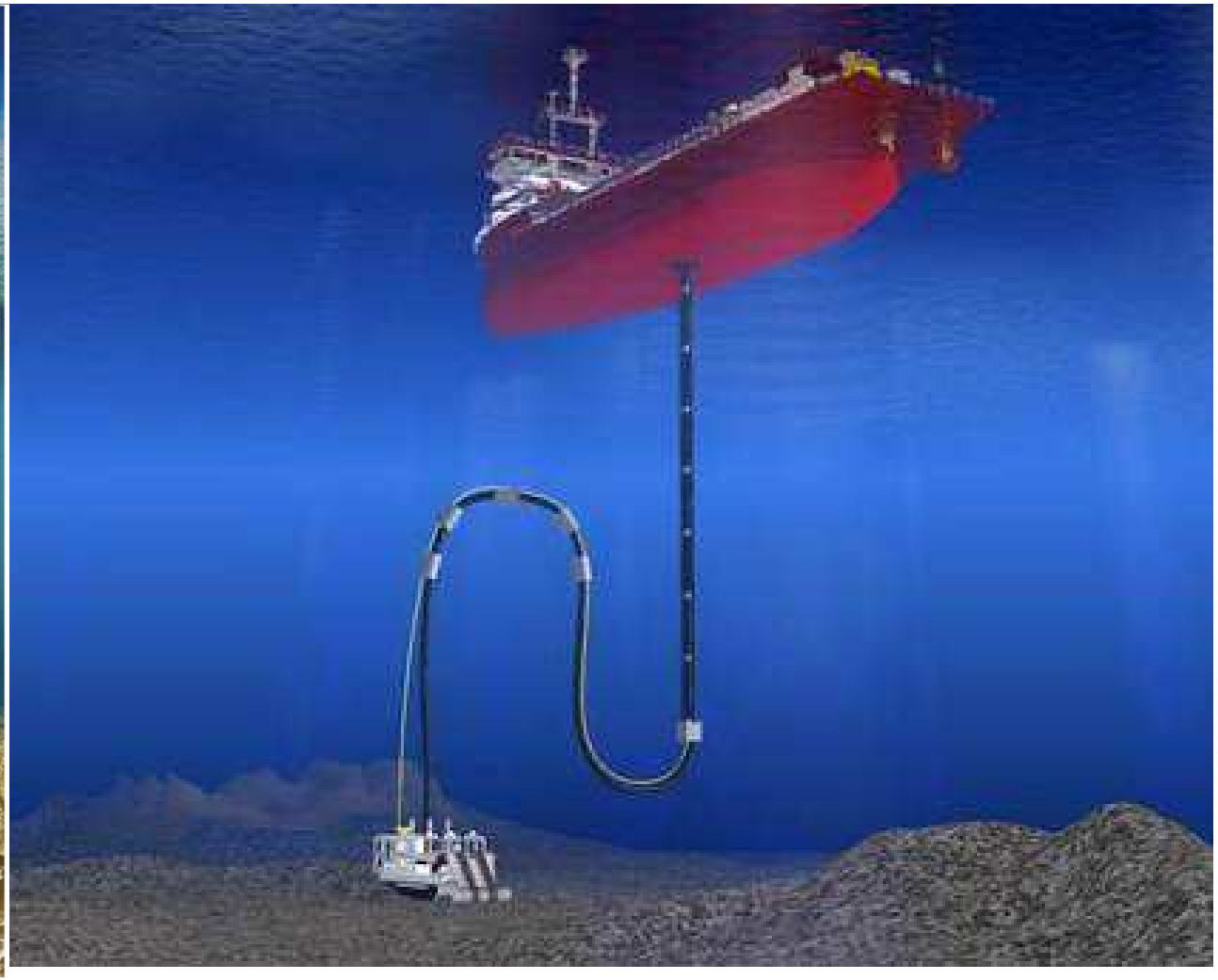


Portuguese Hydrographic Institute - http://www.hidrografico.pt/download-gratuito.php

Deep Sea Mining – Extraction



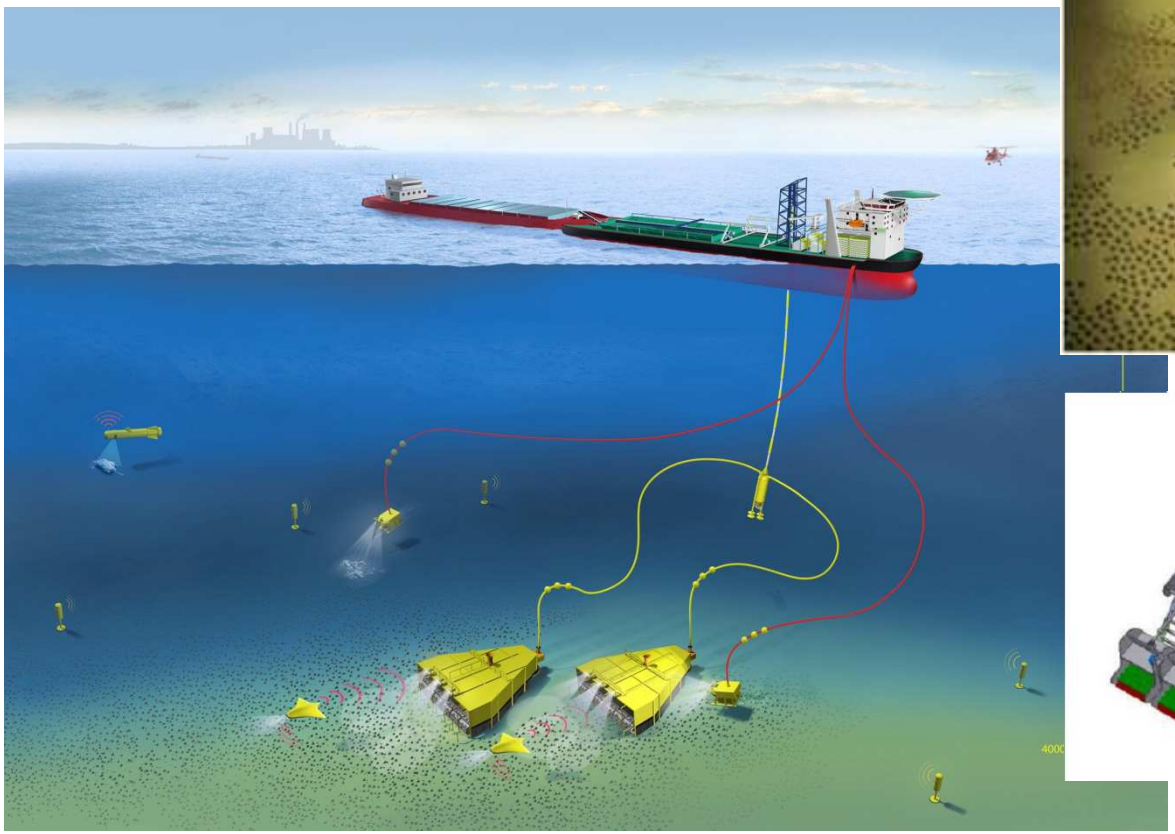
Source: Nautilus Minerals Ltd, 2014

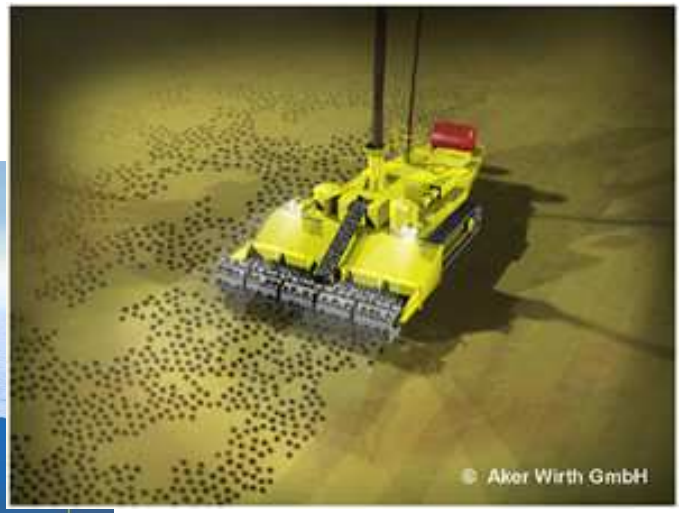


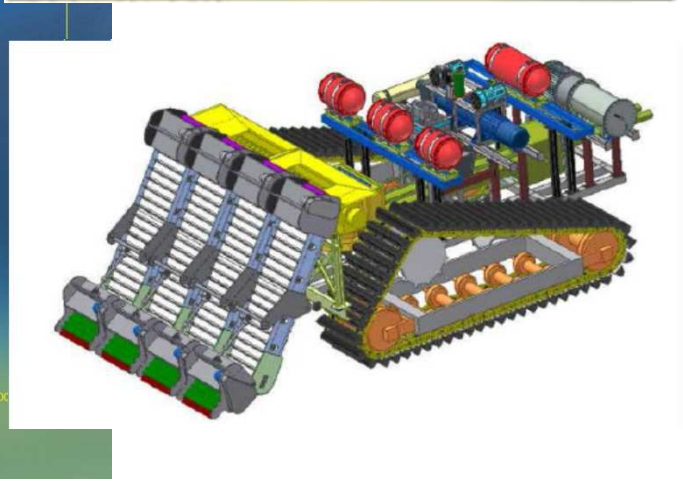
Source: Royal IHC Merwede, 2013

Deep Sea Mining – Extraction

- Extraction Nodules





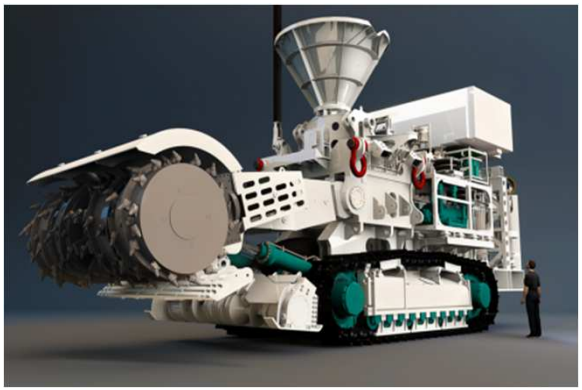
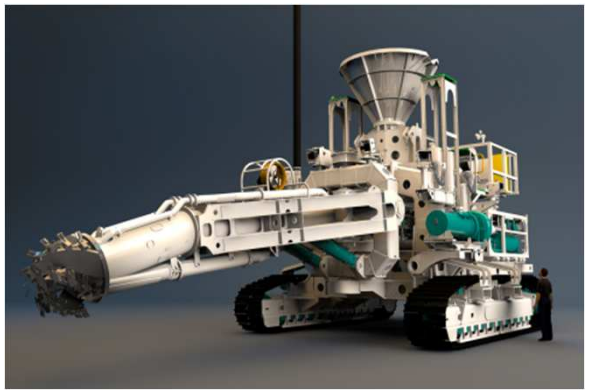


- Collectors as suggested by Aker Wirth in Cooperation with BGR (2009-2012)

Deep Sea Mining – Extraction

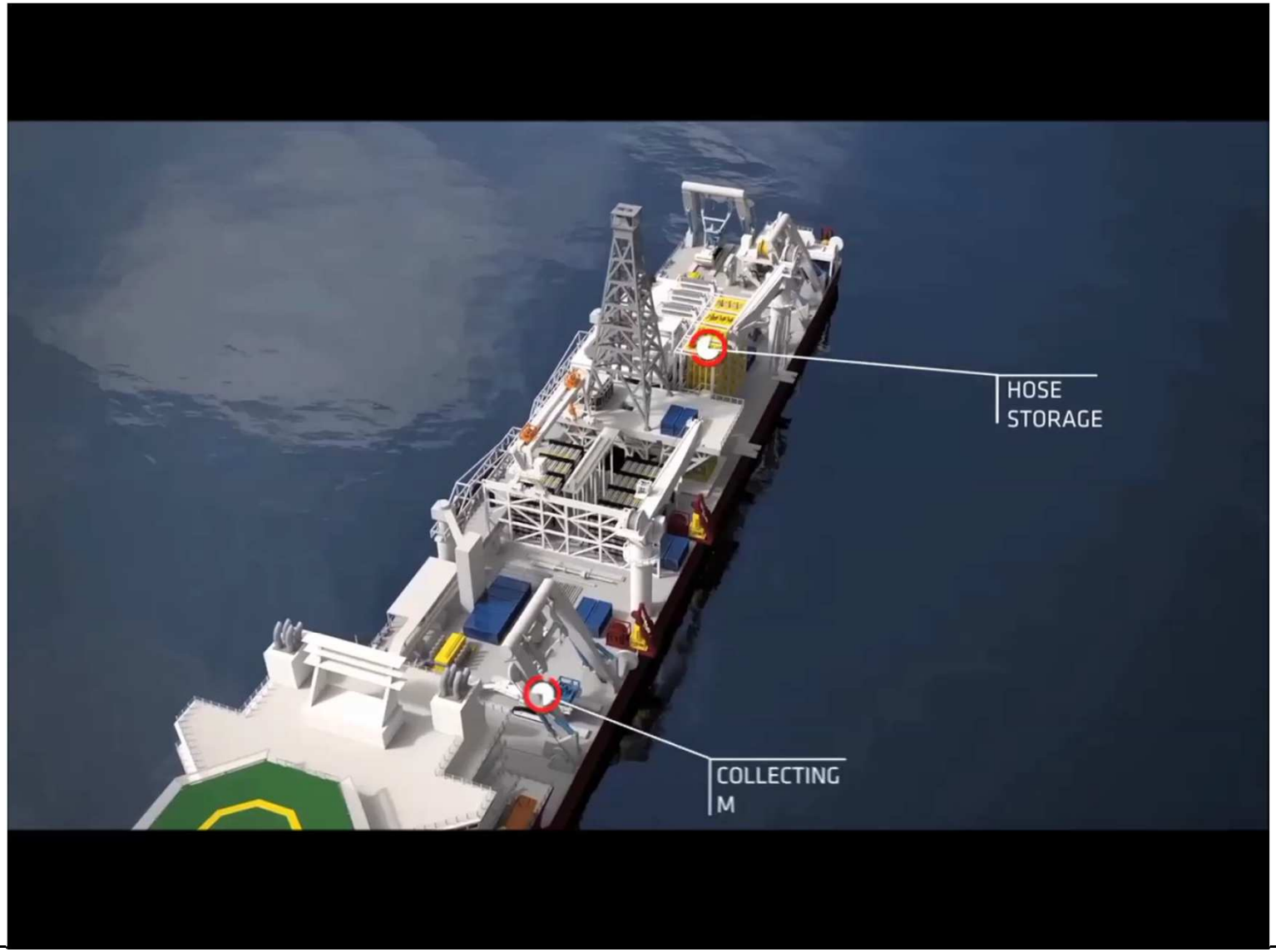
- Extraction SMS

- Currently assembled by Company SMD, Newcastle, UK
- Three machines:
  - Auxiliary Cutter
  - Bulk cutter
  - Collector

Source: Mining Magazine 2014

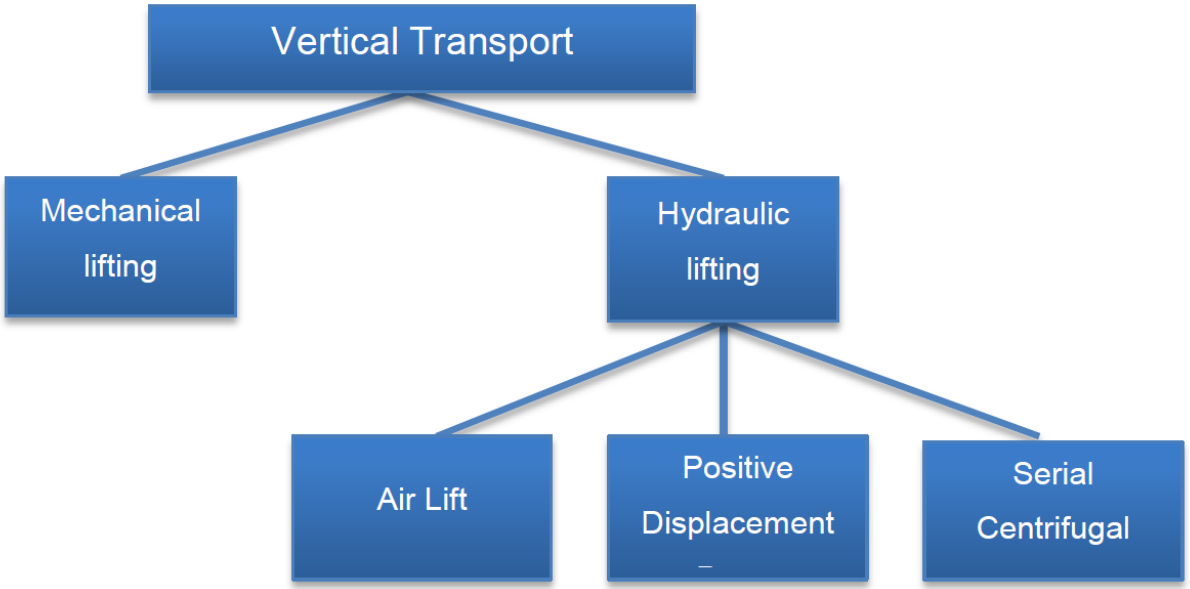
Animation from NAUTILUS: Seabed Extraction System



*Source: www.**nautilusminerals**.com/*

Deep Sea Mining – Extraction

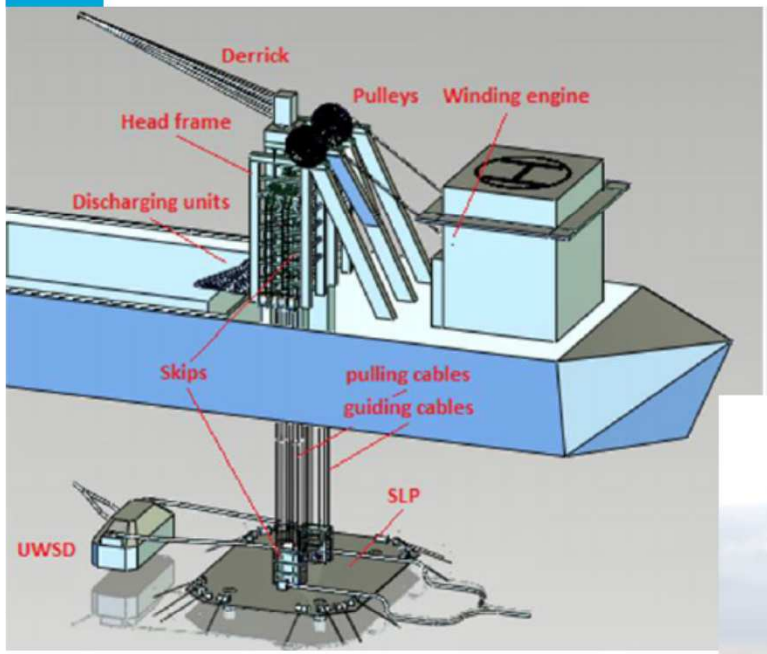
- Vertical Transport

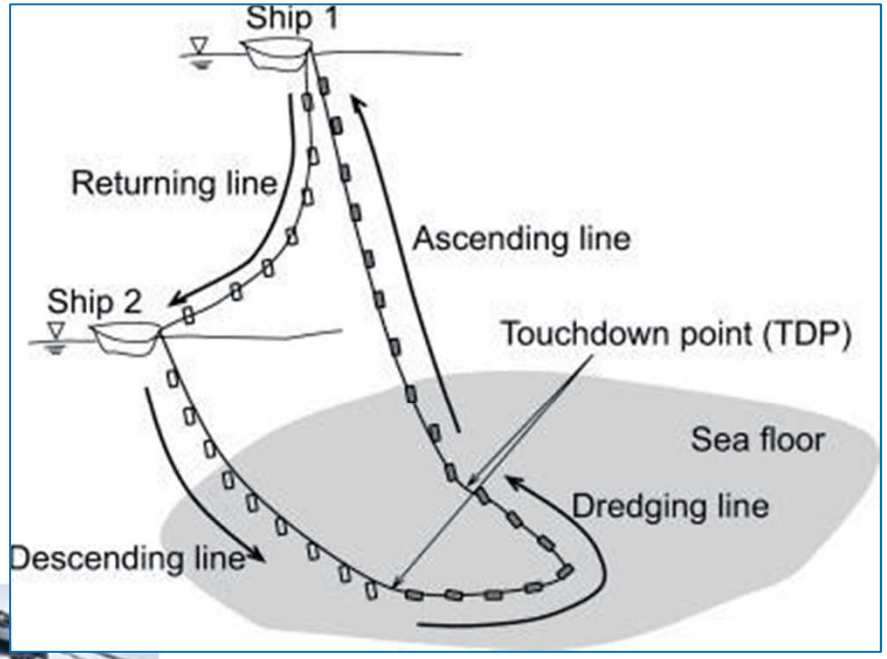


Production capacity:	250 t/h
Minimal fluid velocity in riser (d_p=50mm)	3.6 m/s
Slurry solid content	12 %
Average solid density	2.5 t/m^3

Deep Sea Mining – Extraction

- Vertical Transport





Deep Sea Mining – Extraction

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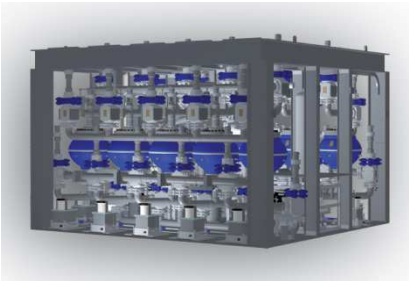
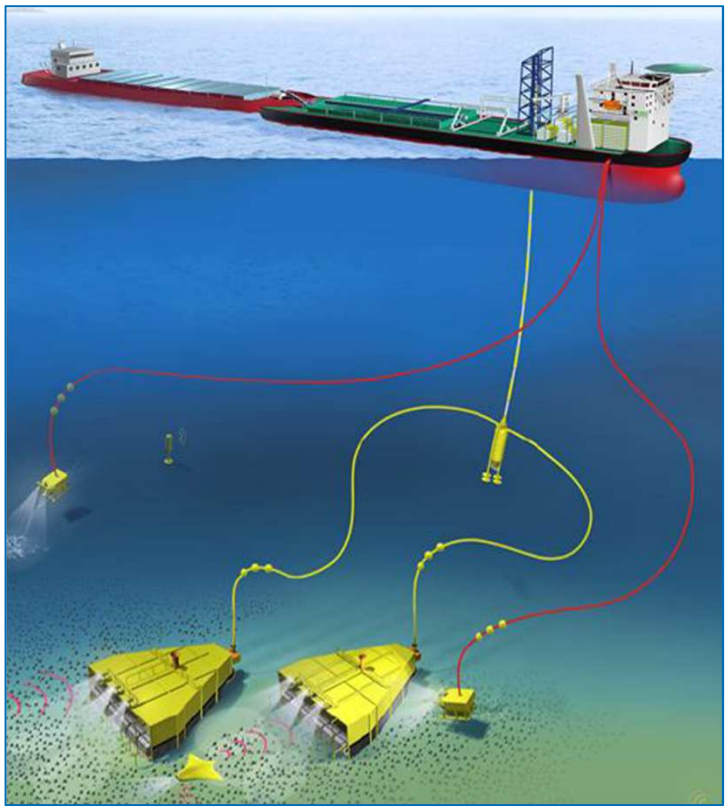
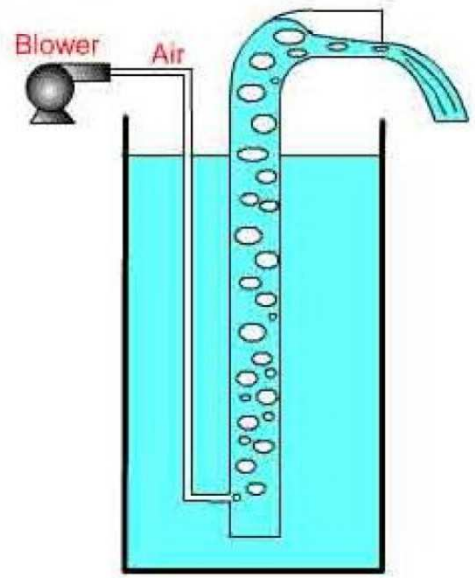
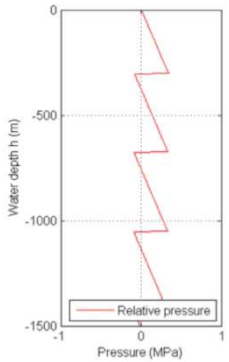






Airlift pump



Deep Sea Mining – Extraction

- Vessel Operations and Shipping

- Dewatering
- Concentrating
- Loading for Transportation to Port

Deep Sea Mining – Processing

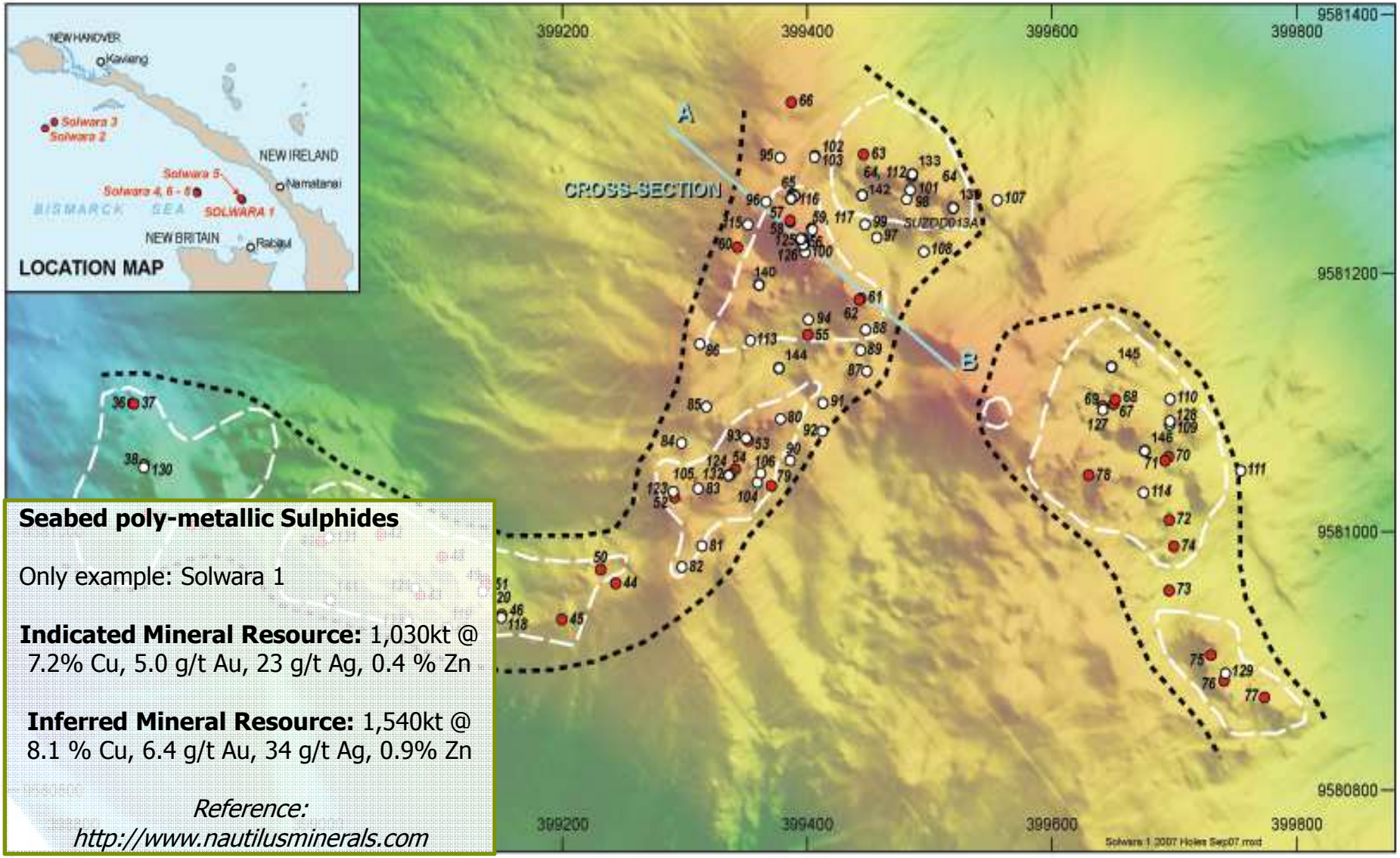
- Current project assume to transport extracted material to port facility for processing
- Can we do better?
  - Commination, classification and separation on a vessel or sea bed
  - Eliminating zero waste material early in the process chain:
  - Sensor based ore/waste selection?
  - Pre-sorting on the seabed?
  - Concentrating on a ship?

Deep Sea Mining – Extraction

- Technology reflection

(1) It is technically feasible to perform deep sea mining
(2) All concepts are mainly concepts tested at an experimental scale
(3) Next step should be lead to prototyping actions and proof the concepts in real environment to understand challenges in system integration
(4) Potential future areas of improvement:
    (1) Continuous improvement of components
    (2) Ore/Waste selection at seabed
    (3) Pre-upgrading on seabed (e.g. sensor derived)
    (4) Seabed production and environmental monitoring

Land-based vs. Seabed Deposits



Seabed poly-metallic Sulphides

Only example: Solwara 1

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Inferred Mineral Resource: 1,540kt @ 8.1 % Cu, 6.4 g/t Au, 34 g/t Ag, 0.9% Zn

Reference:
http://www.nautilusminerals.com

Land-based vs. Seabed Deposits

Copper Deposits (Porphyry Deposits)

Example Escondida Mine: copper-gold-silver

Annual Production: 1.1 million tonnes of copper (100 per cent basis)

Expected Life of Mine 54 years

Reference: bhpbilliton Annual Report 2013

Commodity Deposit [1]	Ore Type	Measured Resources				Indicated Resources			
		Mt	%TCu	%SCu	ppmMo	Mt	%TCu	%SCu	ppmMo
Copper									
Escondida	Oxide	112	0.79	–	–	70	0.68	–	–
	Mixed	80	0.76	–	–	66	0.55	–	–
	Sulphide	5,190	0.67	–	–	2,030	0.54	–	–

Commodity Deposit [1][8][9][10]	Ore Type	Proved Ore Reserves				Probable Ore Reserves			
		Mt	%TCu	%SCu	ppmMo	Mt	%TCu	%SCu	ppmMo
Copper									
Escondida	Oxide	84	0.88	–	–	61	0.71	–	–
	Sulphide	3,760	0.76	–	–	1,340	0.60	–	–
	Sulphide Leach	1,470	0.45	–	–	550	0.42	–	–

Land-based vs. Seabed Deposits

Land-based poly-metallic deposits

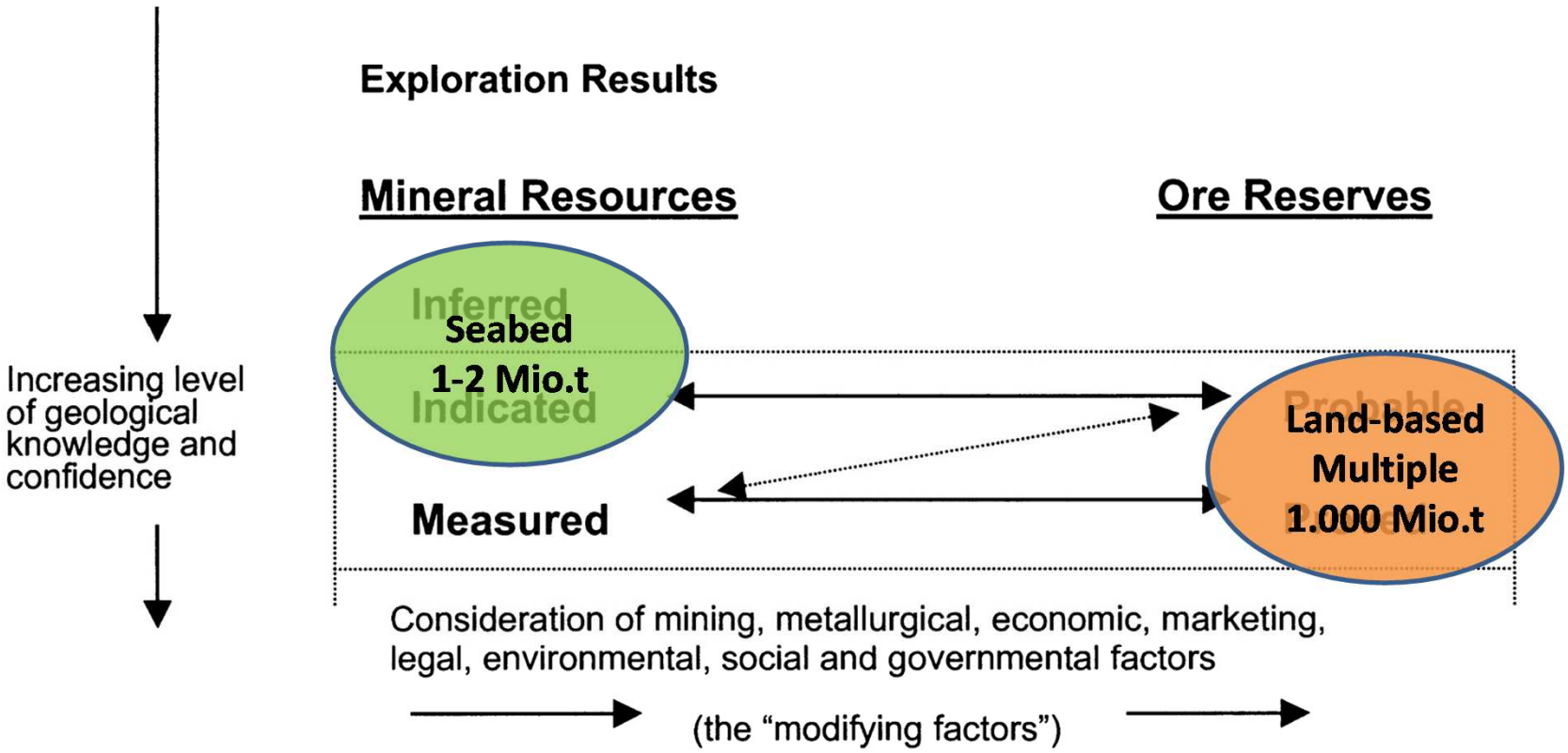
- Large in extension and tonnage (multiple 1.000 Mio t)
- Comparable low grade (e.g. 0.5-1.0% Cu)
- Production: order of magnitudes: 100 Mio. t/a ore + waste according to stripping ratio
- Efficient and set up for long-term (40 years +)

Seabed poly-metallic deposits

- Small in extension and tonnage (1 to 2 Mio t)
- Comparable high grade (about 7-8% Cu)
- Annual production: 1-2 Mio. t
- Current available seabed deposits would be set up for low production of a life of a mine of about 1 year

Currently known and in the context of raw material extraction evaluated seafloor deposits are not sufficient in size to compete against exploitation of land-based deposits.

Land-based vs. Seabed Deposits



Example: JORC Code, produced by the Australasian Joint Ore Reserves Committee (2012)

Deep Sea Mining – Economics

Cost Structure Seabed Mining from Literature:

Item	Capital expenditures	Operating expenditures	Total
Mining system	$ 550 mi.* ($ 372-562 mi.)	$ 100 mi/y* ($ 69-96 mi.) x 20 years = $ 2.0 billion	$ 2.55 billion
Ore transfer	$ 600 mi.* ($ 495-600 mi.)	$ 150 mi/y* ($ 93-132 mi/yr) x 20 years = $ 3.0 billion	$ 3.60 billion
Processing plant	($ 750 mi.)	($250 mi/y) x 20 years = $5.0 billion	$ 5.75 billion
Total	$ 1.90 billion	$ 10.0 billion	$ 11.90 billion

* Rounded off to nearest fifty of the highest value
( ) Values proposed by different Contractors (Source: ISA, 2008a)

Nobuyuki, M., Nobuyuki, O., Takahiro, K., 2013, Sea-Floor Massive Sulfide Mining – Its Possibility and Difficulties to Emerge as a Future Business, In: Proceedings of the 22nd MPES Conference, Dresden, Germany, 14th – 19th October 2013, [pdf]

Example with documented numbers:

Depreciation per year:	*$50 Mio.*
Extraction costs per year:	*$100 Mio.*
Ore Transfer costs per year:	*$150 Mio*
Sum:	*$200 Mio*
Cost/t:	*$80*

This preliminary investigation reveals:

- *Cost/t: Ratio between land-based deposits and seabed deposits is about 1:10*
- *Value of the ore: Ratio between land-based deposits and seabed deposits grades is about 10:1*

Strategy for Seabed mining: early upgrading (post extraction upgrading)

Environmental Considerations

- loss of substrate on the sea floor
- effects of mining on the seabed, the operational plume and re-sedimentation and
- discharge plume and its effects on fauna depending on the depth of discharge
- Instruments:
  - Environmental Impact Assessment (EIA) and
  - Strategic Environmental Assessment (SEA)

Conclusions

- Deep sea mining is exciting
- Deep sea offers mineral resources
- For exploitation we need to know more!

  Resource discovery of sediment - covered deposits

  Environmental impacts
- Technology is conceptual ready
- Future: proof of concept and operational optimization in a test mining site or show case

Personal Opinion

- Is deep sea mining an economic viable option?

  Under current conditions and considering land based alternatives: ***no***
- Potential resource for future generations
- In a sustainable sense:
  - Perform research to increase our knowledge about the deep sea environment
  - Maturation of technology, especially robotics
  - Leave it up to future generation to start exploitation deep sea resources in a responsible way, when resources are needed

Thank You