Prospects for the development of polymetallic sulphides/seafloor massive sulfides in the ridges of the South Atlantic and Indian Oceans

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SENSITIZATION SEMINAR OF ISA
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Outline

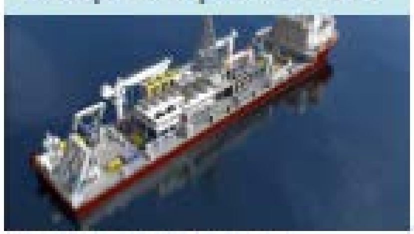
- Introduction
- Hydrothermal processes and seafloor massive sulfides (SMS): discovery and progress
- Global distribution & Geological setting of SMS
- Formation, Size & Morphology
- Metal Grades (e.g. rare-metals) & Resources
- Active & Inactive SMS: environmental issues
- Exploration methods & Exploitation approaches
- Conclusing remarks

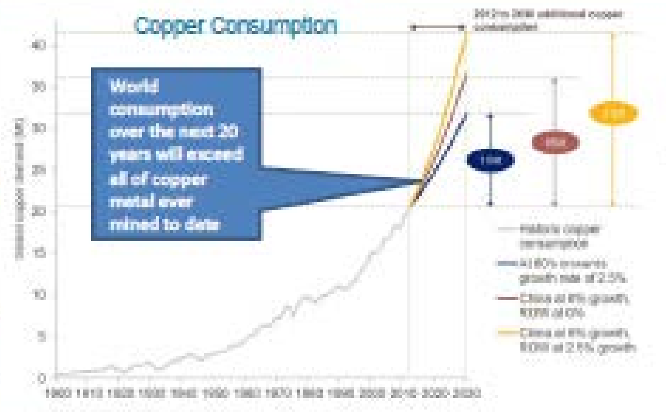
Why go to the sea?

NAUTILUS Minerals

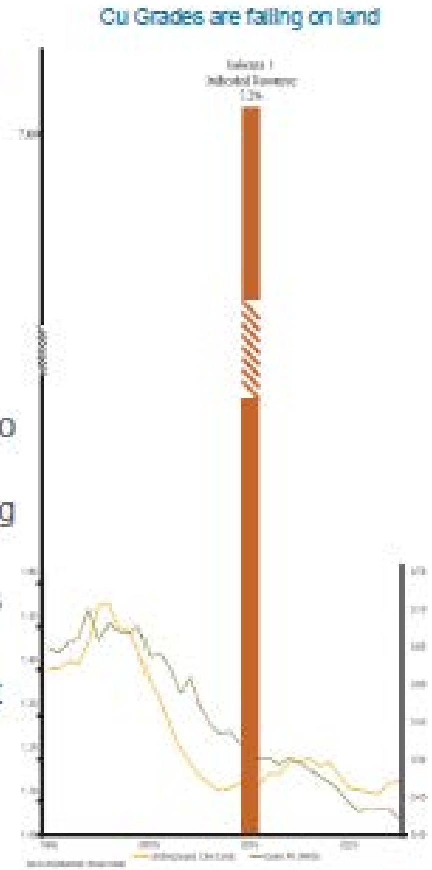
Land-based mine

Deep sea production



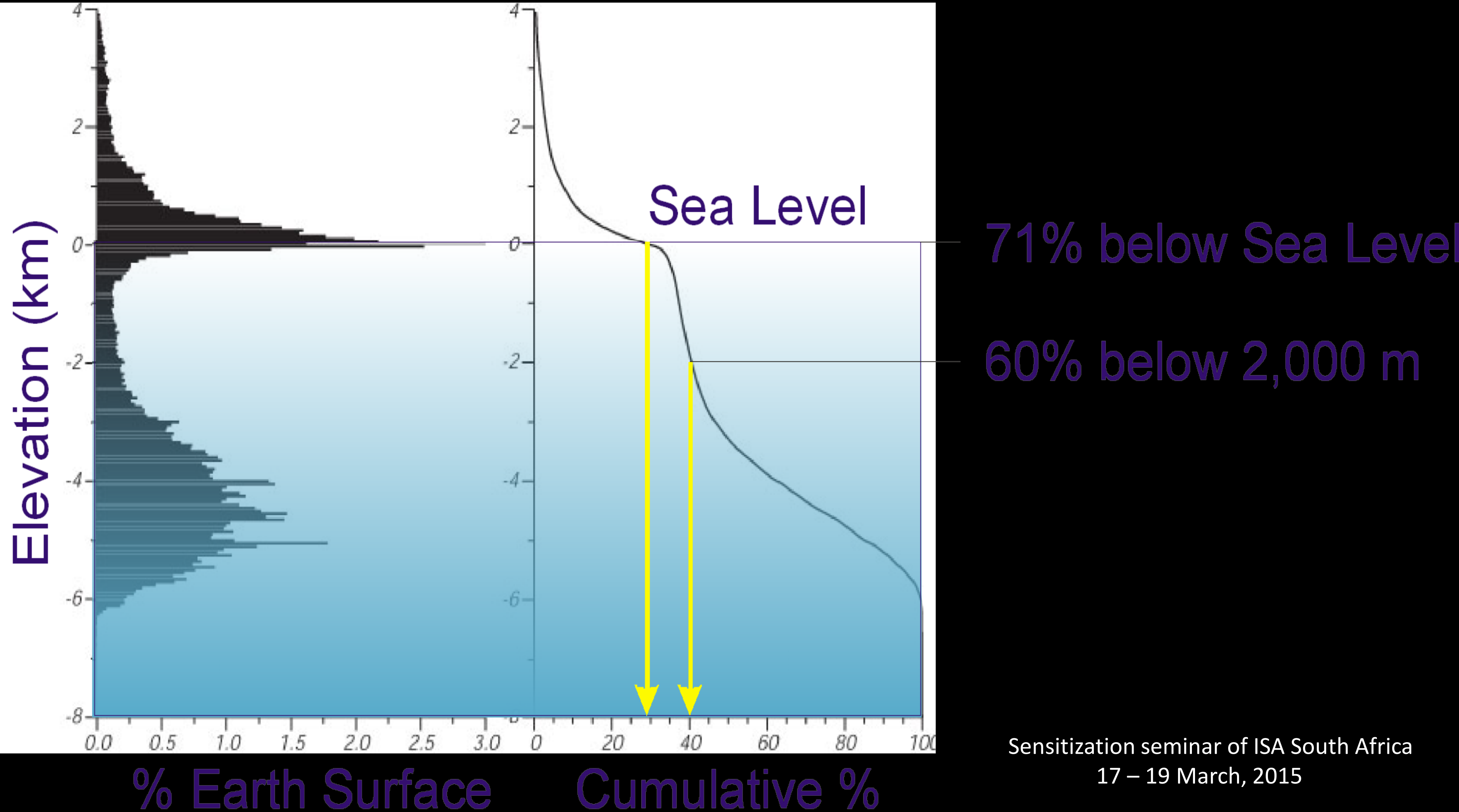


- World's demand for metals continues to rise
- Land resources are stretched; declining grades, more waste, larger footprints
- Seafloor contains enormous resources of key metals (Cu, Ni, Co, Mn, Au, Zn)
- 40+ years of Oil and Gas development and R&D to leverage off
- *VERY HIGH GRADES*



MARINE MINERALS: THE FUTURE OF SUPPLY

EARTH'S HYPSOMETRIC CURVE



The potential for commercial minerals per unit area in the oceans and seabed appear to be similar to that of the terrestrial lands.

Thus, almost $^{2}/_{3}$ of the global mineral resources are in, or under, the sea and are virtually undeveloped.

Exclusive economic zones (gray) and the Area (white)

Half of the global seabed minerals are now controlled by nations within the

Exclusive Economic Zones.

Another half is a “common heritage of mankind”, is administered by ISA within

the Area

MARINE MINERALS

In the EEZ (shallow water)

- **SAND & GRAVEL (AGGREGATES)**
- **PLACERS (e.g. GOLD, DIAMONDS, TIN)**
- **PHOSPHORITES**
- **GAS HYDRATES**

In the Area & EEZ (deep water)

- **Polymetallic NODULES**
- **Co-rich CRUSTS**
- **Seafloor Massive Sulfides (SMS)**

Characteristics of deep-sea minerals

Type of marine minerals	Setting/ Depth, м	Main metals	Age, years
Nodules	Abissal plains (4000-5000)	Copper, nickel, manganese	$n \times 10^6$ - $n \times 10^7$
Crusts	Seamounts (1000-2500)	Cobalt, nickel, manganese	$n \times 10^6$ - $n \times 10^7$
Massive sulfides	**Volcanic structures (1500-4000)**	**Copper, gold, zinc, silver**	$n \times 10^0$ – $n \times 10^5$

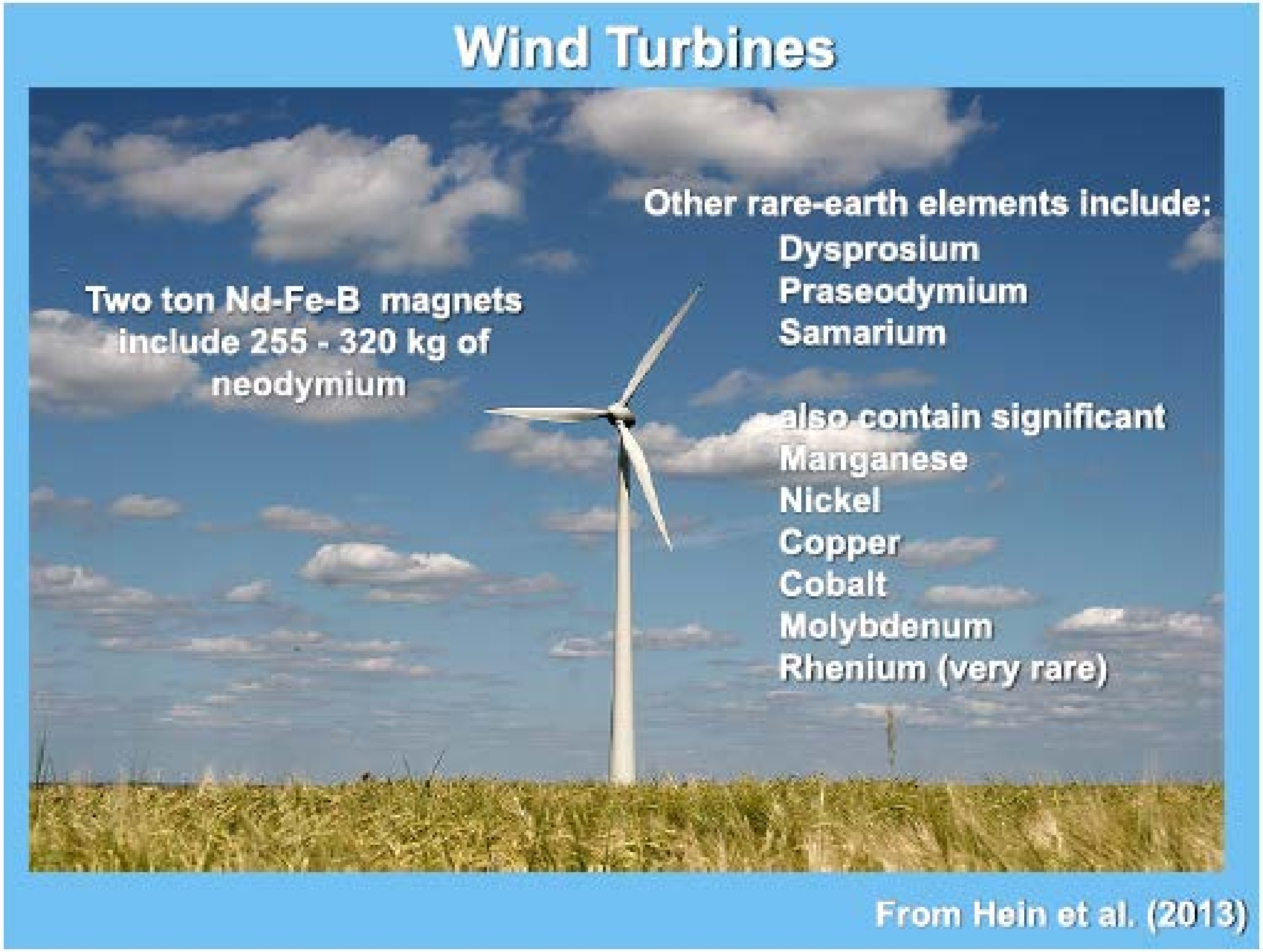
Rare elements in marine minerals as potential bypoducts

	Rare elements
Nodules	Co Li Mo REE Y Zr
Crusts	Bi Mo Nb Pt REE Te Th Sc Ti W Yt Zr
Massive sulfides	**As Cd Ga Ge In Sb Se Te Mo Bi**

Rare metals in high- and green technologies

Application areas	Rare metals in marine minerals
Cell phones, lasers	REE, Ga, Co
Optical diods	Ga, As, In
Semiconductors	Ga, Ge, Bi, Co
Photovoltaic solar cells	Ge, In, Se, Ga, Te
Computer chips	Bi, Te, Ga
Fiber optic cables	Ga, Ge
Liquid crystal and plasma displays	REE, Ge, In
Wind turbines	REE, Co
Hybrid & electric cars batteries	REE, Co

B
D
UV cut glass
- Cerium
Glass and mirrors
polishing powder
- Cerium
LCD Screen
- Cerium
- Yttrium
- Cerium
Diesel fuel additive
- Cerium
- Lanthanum
Hybrid NIMH
battery
- Cerium
- Lanthanum
Hybrid Electric
motor and generator
- Neodymium
-Praseodymium
Catalytic converter
- Cerium/zirconium
25+ electric motors
throughout vehicle
Headlight glass


Wind Turbines
Two ton Nd-Fe-B magnets include 255 - 320 kg of neodymium
Other rare-earth elements include:
Dysprosium
Praseodymium
Samarium
also contain significant
Manganese
Nickel
Copper
Cobalt
Molybdenum
Rhenium (very rare)
From Hein et al. (2013)

Seafloor Massive Sulfides (SMS)

Sampling of Black Smoker

De Ronde, 2011

Hydrothermal processes and seafloor massive sulfides: discovery and progress

Sensitization seminar of ISA South Africa
17 – 19 March, 2015

The Discovery of Black Smokers. 1978-79

EMORY KRISTOF AND ALVIN M. CHANDLER, BOTH NATIONAL GEOGRAPHIC STAFF, BY REMOTE-CONTROL CAMERA (ABOVE); EMORY KRISTOF

Scientists explore rifts in the seafloor where hot springs spew minerals and startling life exists in a

Strange World Without Sun

ACROSS THE BOTTOM of the four oceans of the world runs the largest feature on the face of this planet, a mountain range and rift system some 40,000 miles long. Man has seen with his own eyes scarcely forty miles of this Mid-Oceanic Ridge.

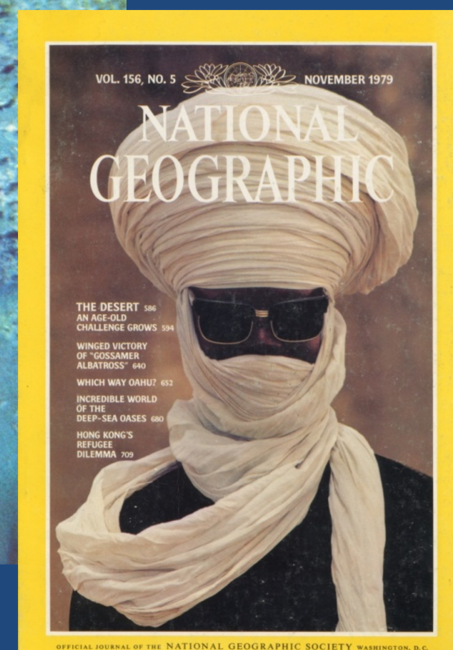
But along those few miles in the past six years, scientists in tiny submarines such as *Alvin* (***above***) have found, in those utterly dark nether depths of the sea, animals and mineral factories unlike any seen before.

In 1979 the latest in a series of expeditions went out into the Pacific to study spreading centers of the ocean floor. These are places where the thin, rigid plates that form the hard crust of our planet are pulling apart, separating as much as eight inches a year. In the cracks molten magma wells up, meets cold seawater, and solidifies into a contorted landscape of black lava.

In such regions the scientists have been witnessing the all but unbelievable. They have seen:

- Huge blood-red worms protruding from forests of white plasticlike tubes (***right***).
- Clams far larger than most shallow-water types, their meat scarlet with hemoglobin.
- Strange dandelionlike creatures moored by threads near fountains of warm water.
- Plumes of even hotter water—350°C (650°F) or more—spewing black clouds of

680

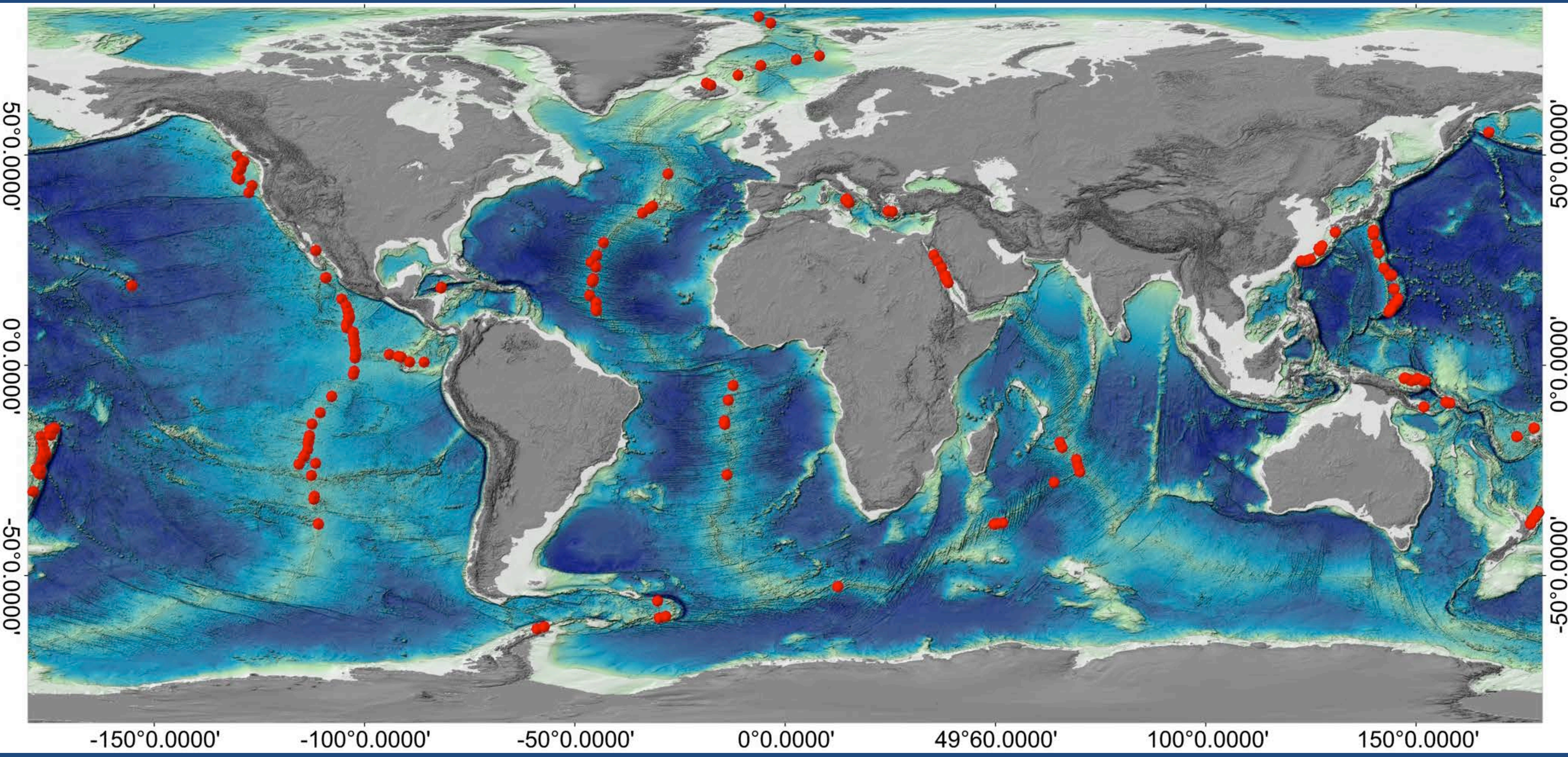


November 1979

1979: East Pacific Rise 21°N;
water depth: 2600 m; exit temperature: 350°C

Global distribution & Geological setting of SMS

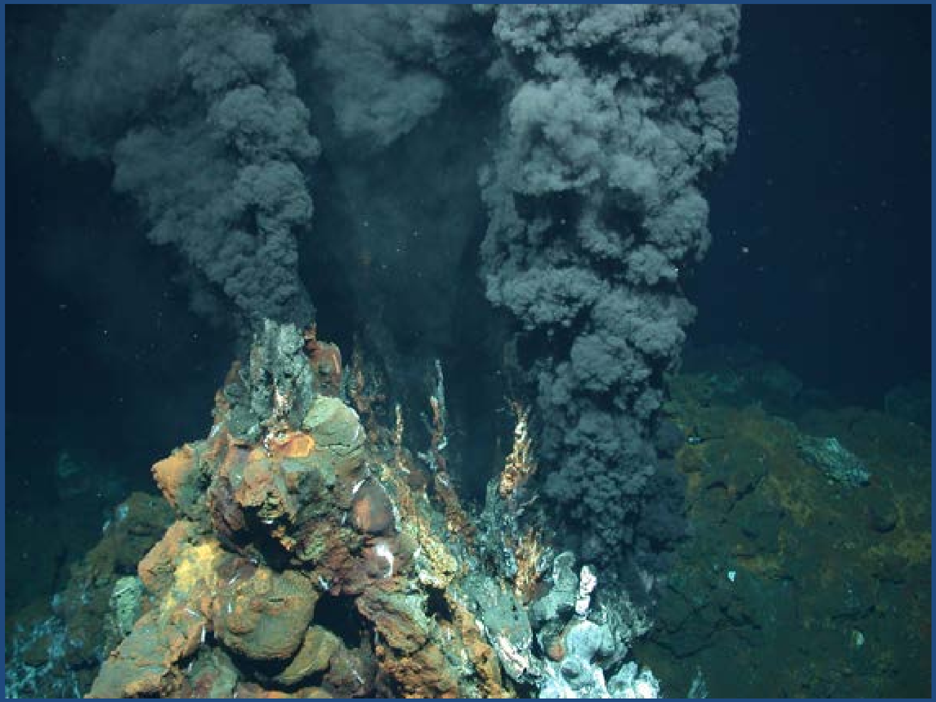
Global distribution of seafloor hydrothermal systems in the world ocean



Basic Facts (Petersen, 2009)

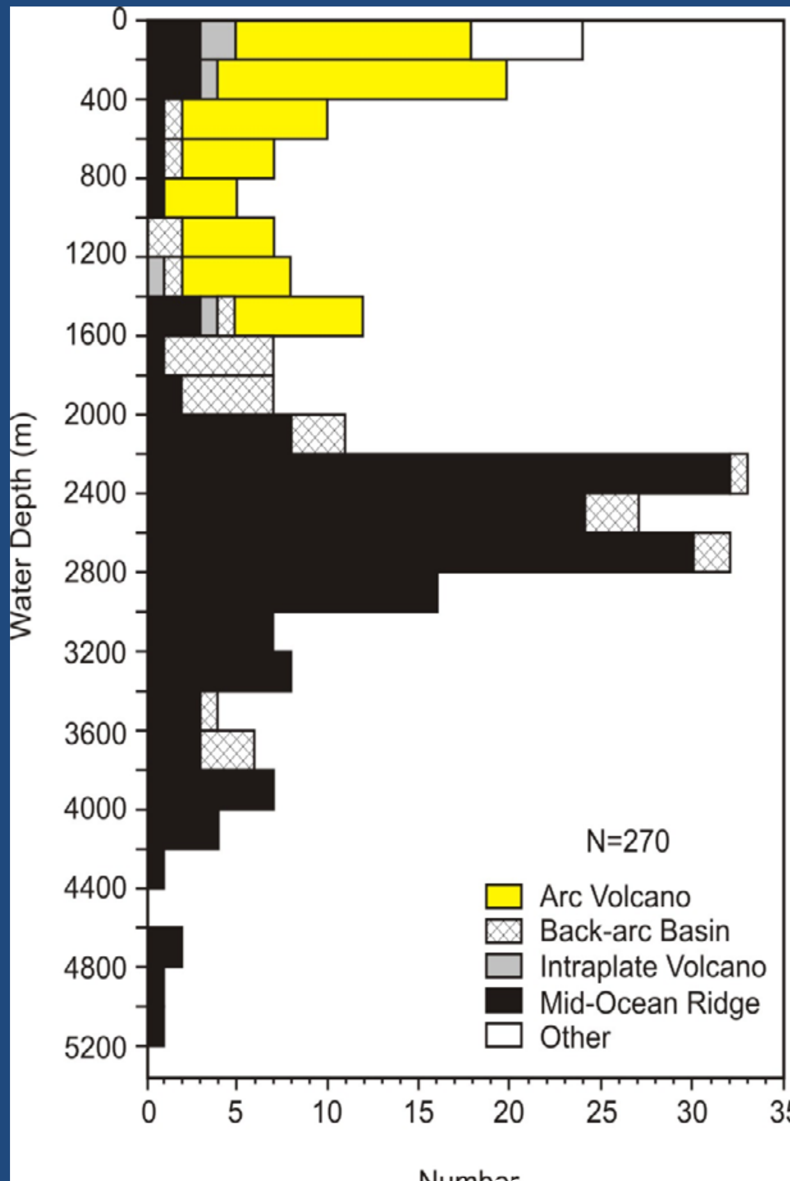
- >350 known sites of hydrothermal activity
- 215 sites of polymetallic sulfide deposits
- 150 sites of high-temperature hydrothermal activity (black smokers)

- 59% at mid-ocean ridges (55,000 km)
- 25% in back-arc environments (22,000 km)
- 15% on submarine volcanic arcs
- <1% on intraplate volcanoes



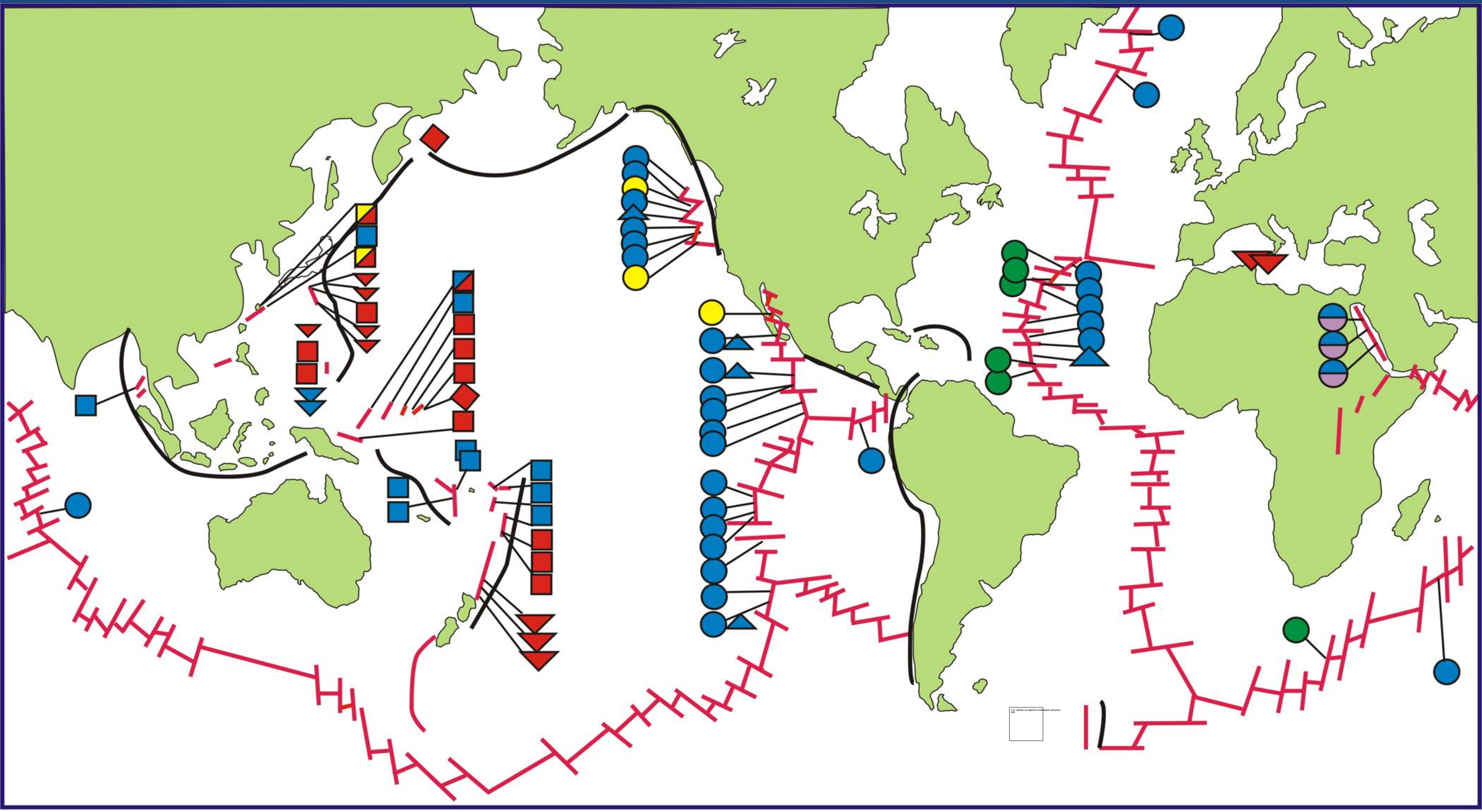
415°C, Turtle Pits

Water depth distribution of the SMS



Hannington et al., 2006

Geological setting of the SMS
(Updated from Fouquet, IFREMER, 1998, 2002)

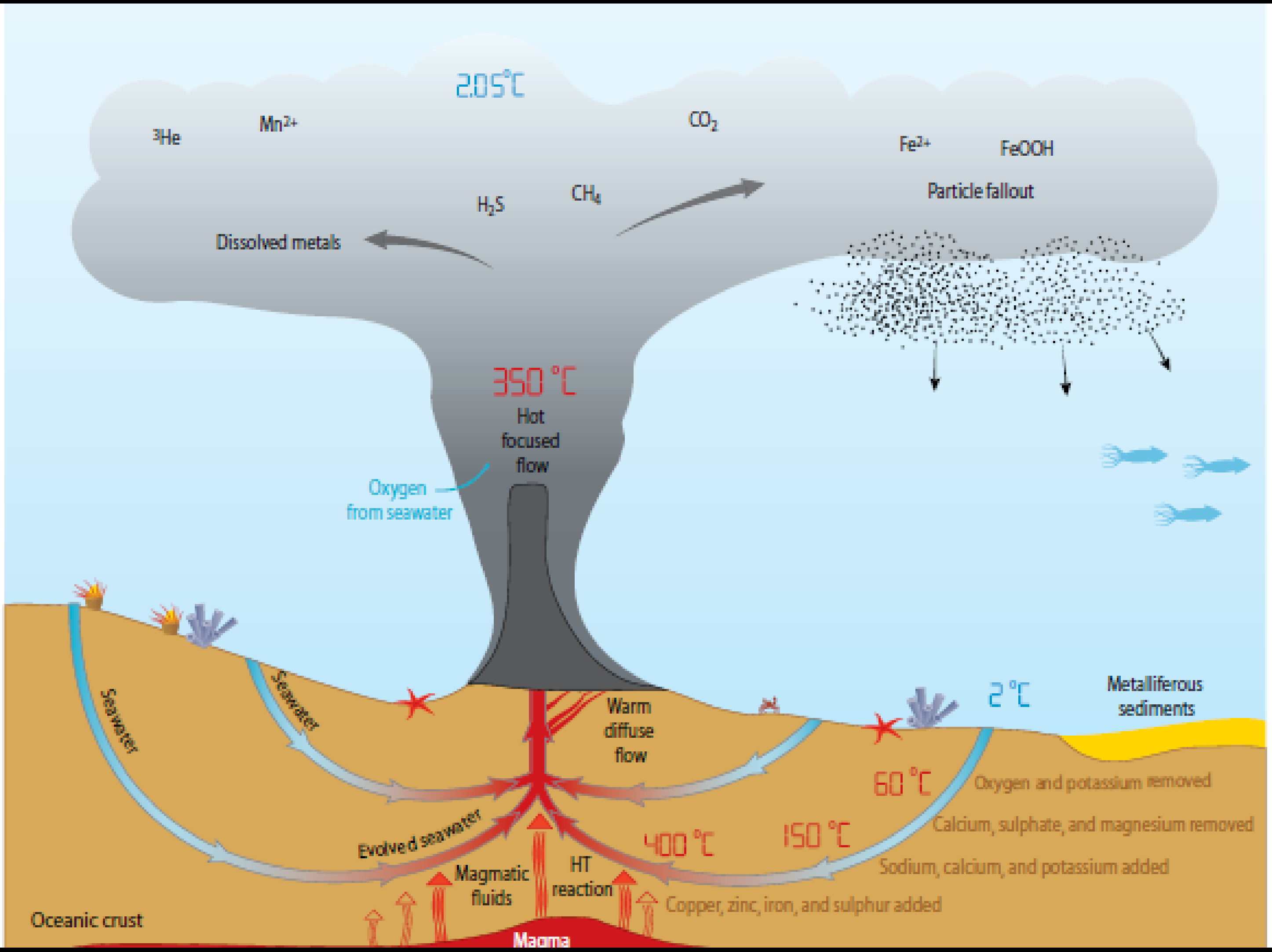


Host Rocks → Basalt, Sediment-Basalt, Felsic Volcanics, Ultramafic, Evaporites

Tectonic Setting → Ridge, Seamount, Back Arc Basin, Volcanic Arc, Fore Arc

Formation, Size & Morphology

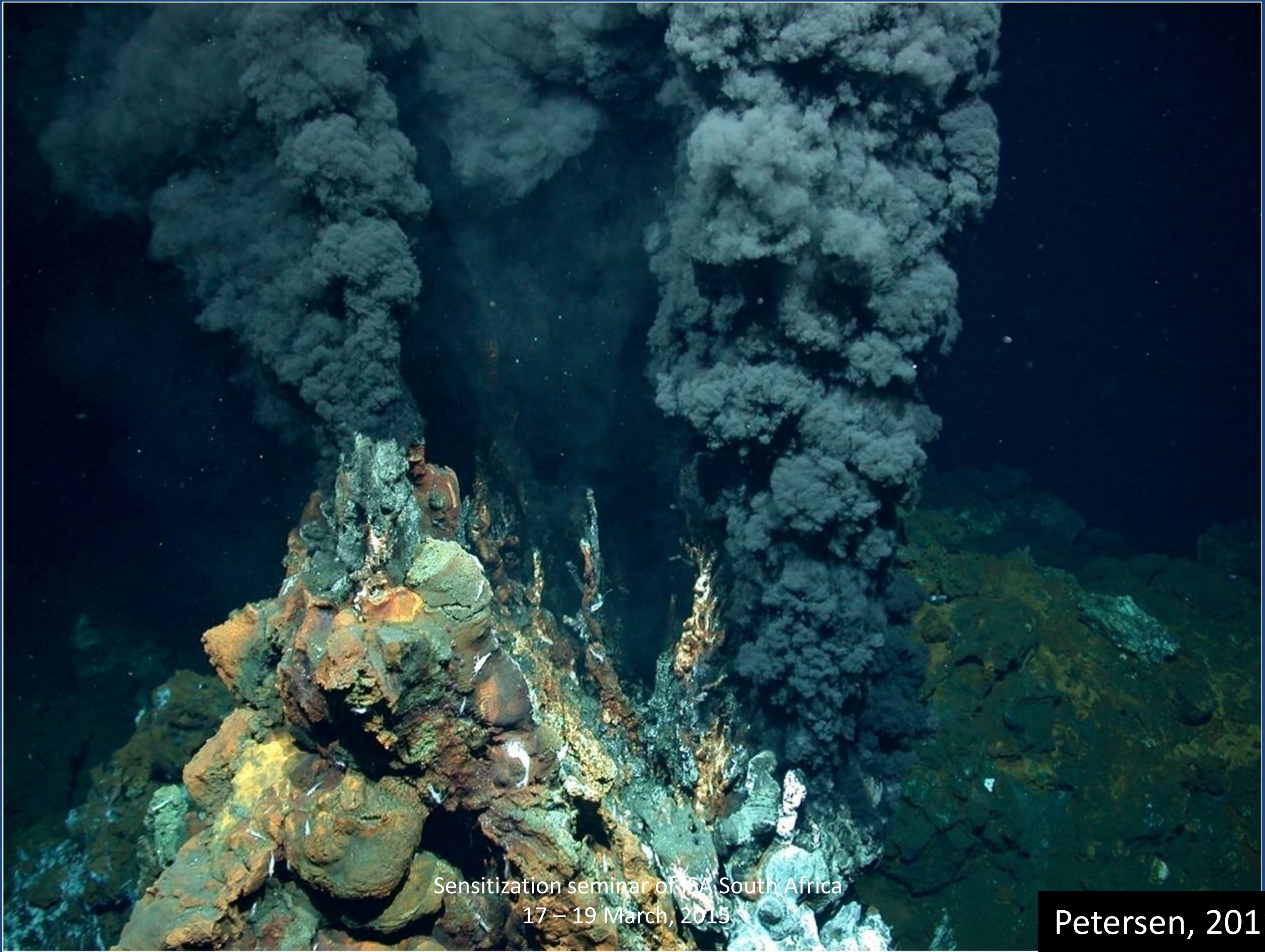
Formation of the oceanic hydrothermal system



SPC (2013). *Deep Sea Minerals: Sea-Floor Massive Sulphides, a physical,biological, environmental, and technical review. Baker, E., and Beaudoin,*Y. (Eds.) Vol. 1A, Secretariat of the Pacific Community

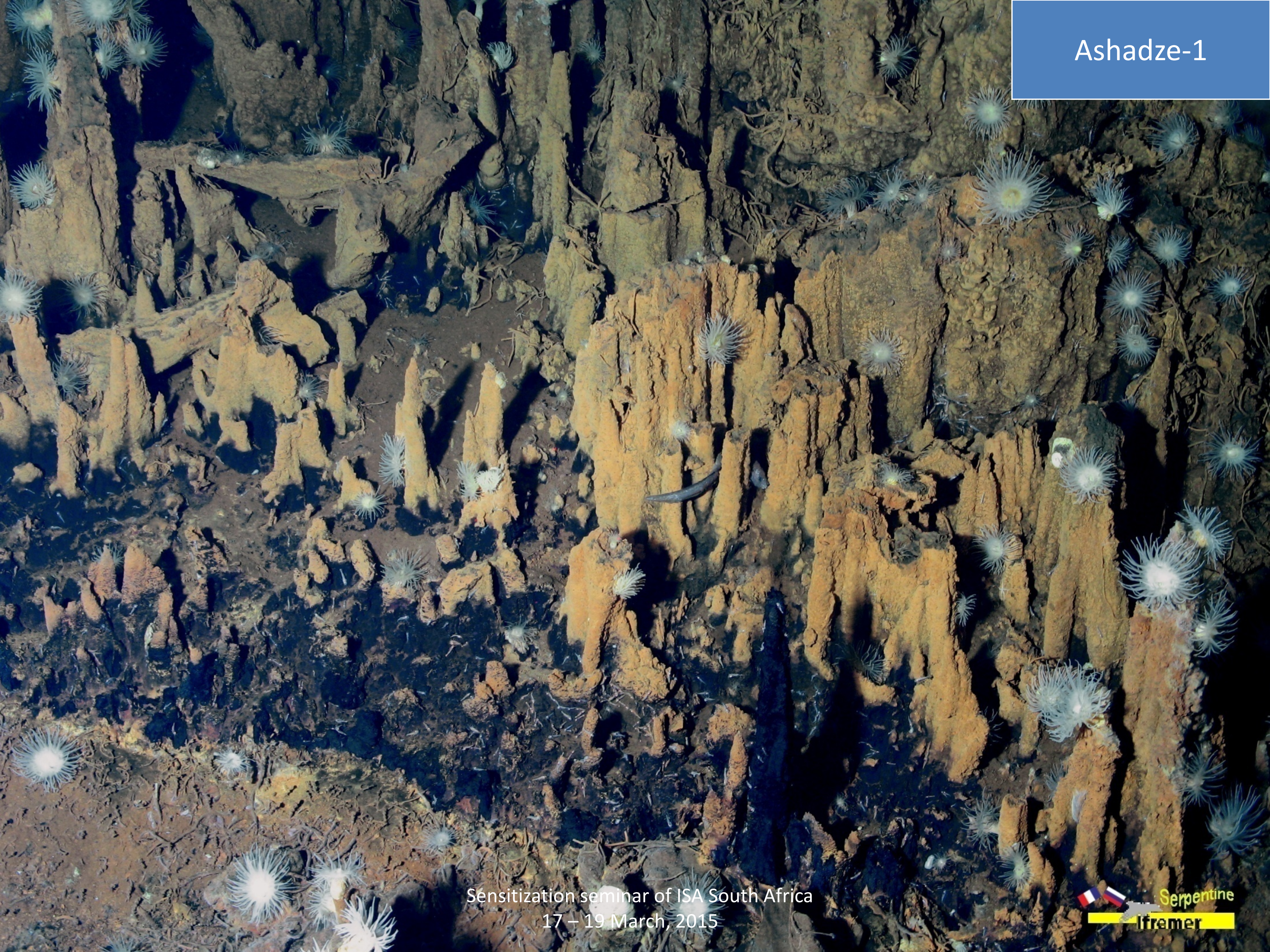
«Black smokers»

Hot(>350°C) metal-rich fluid discharging at the seabottom

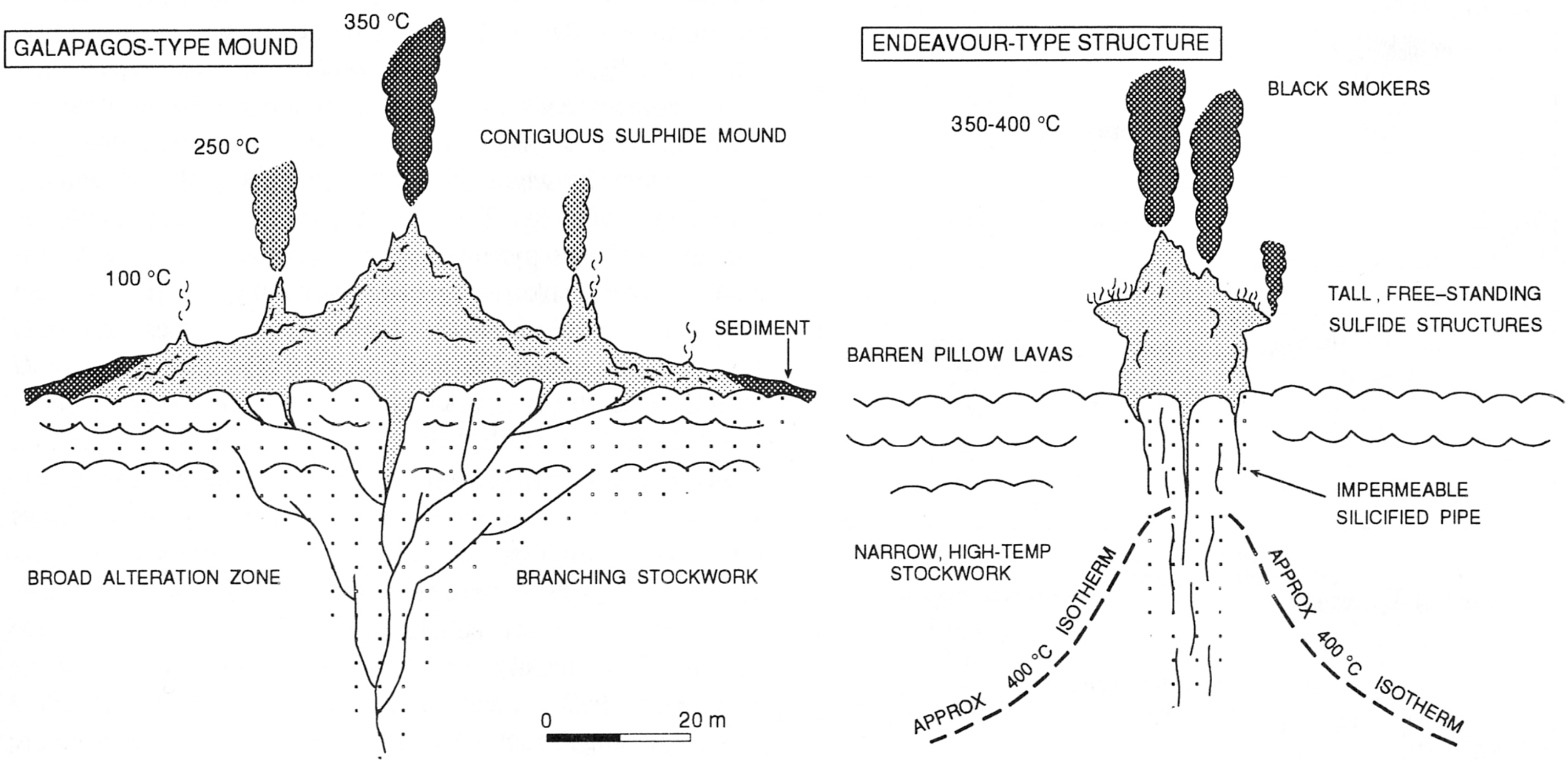


Petersen, 2011

Ashadze-1

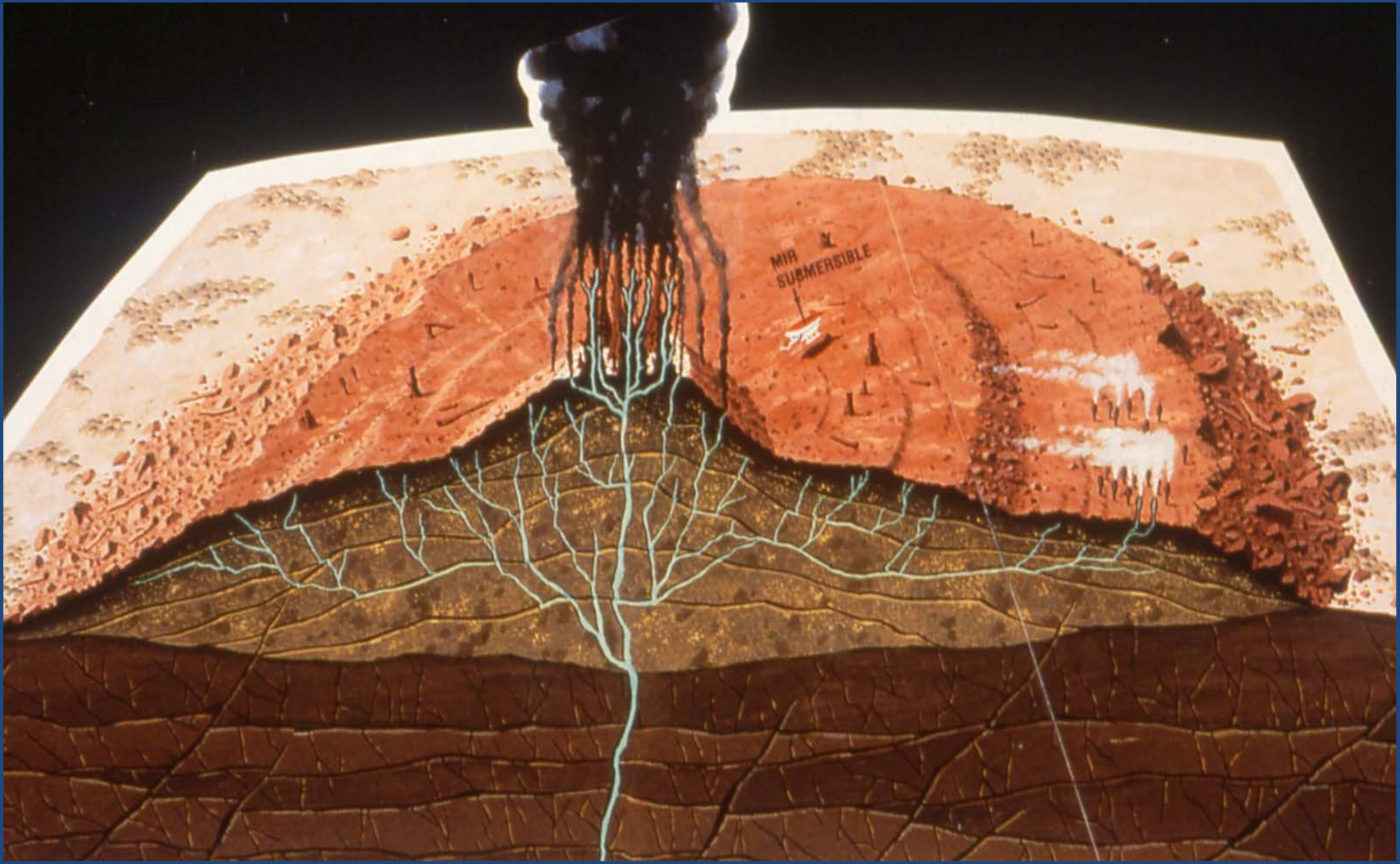


Seafloor Massive Sulfides (SMS) on the surface (typical)

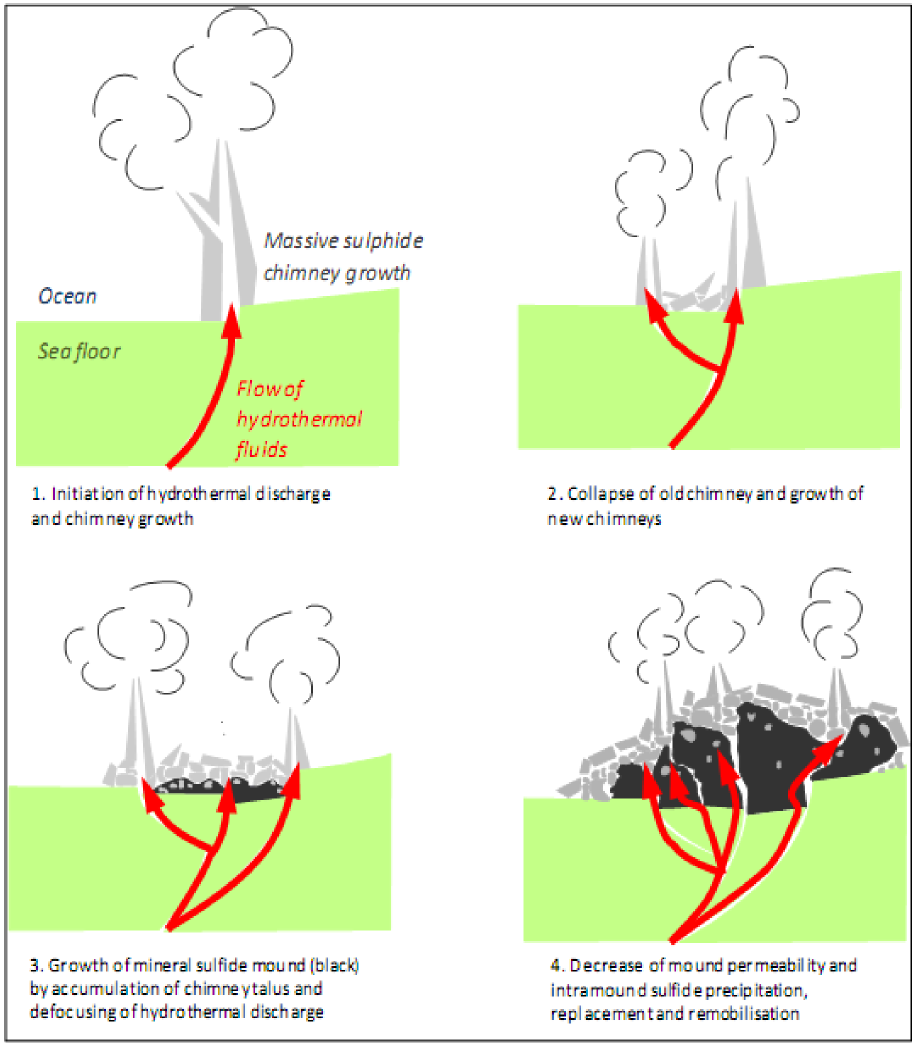


(from Hannington, Petersen et al., 1995)

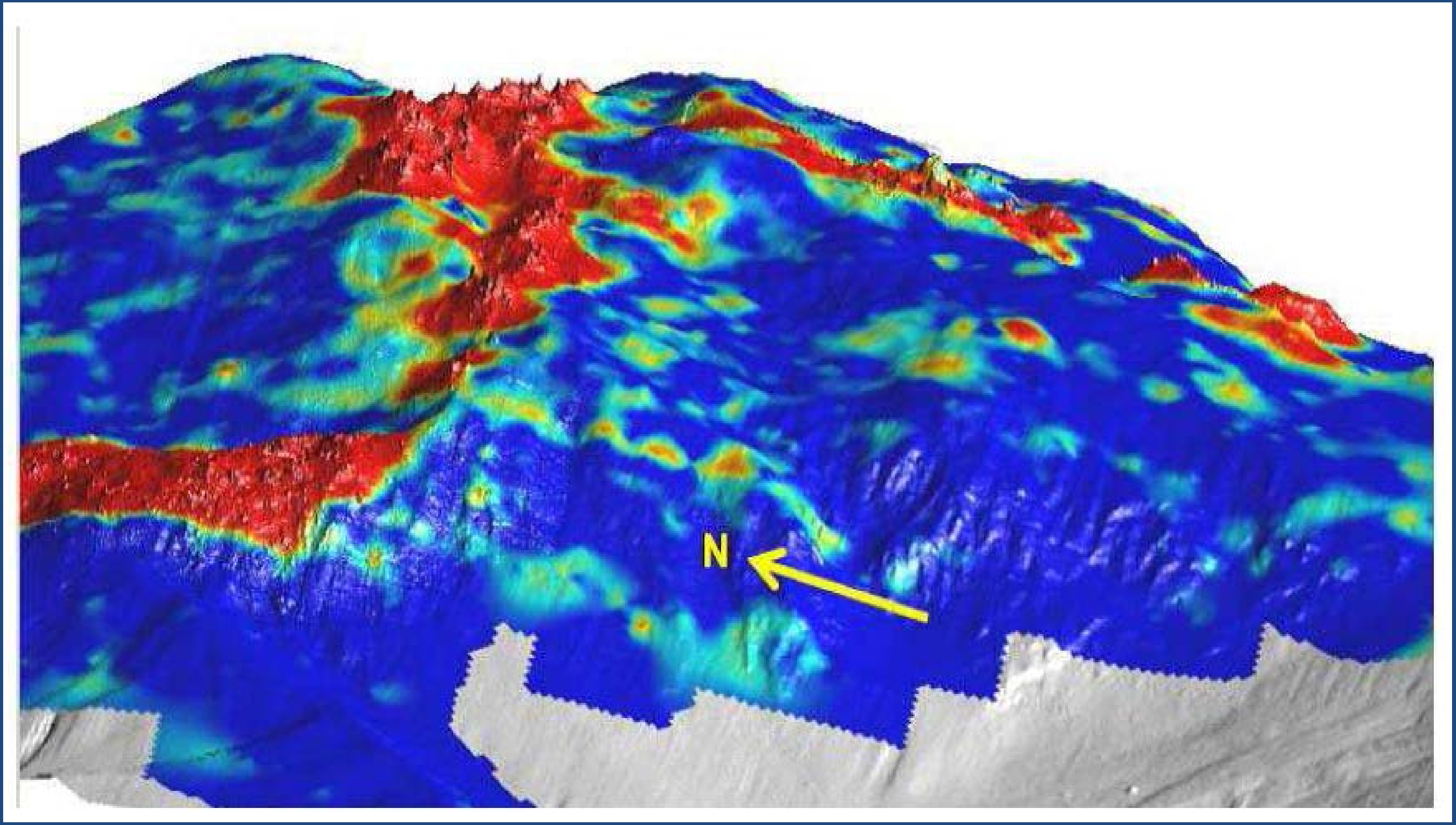
Active Mound, TAG field



Development of SMS mounds on the seafloor



Solwara 1 SMS deposit topographical model – red shading denotes the recovery areas



«Coalesced mounds with apron of disintegrated ore material»

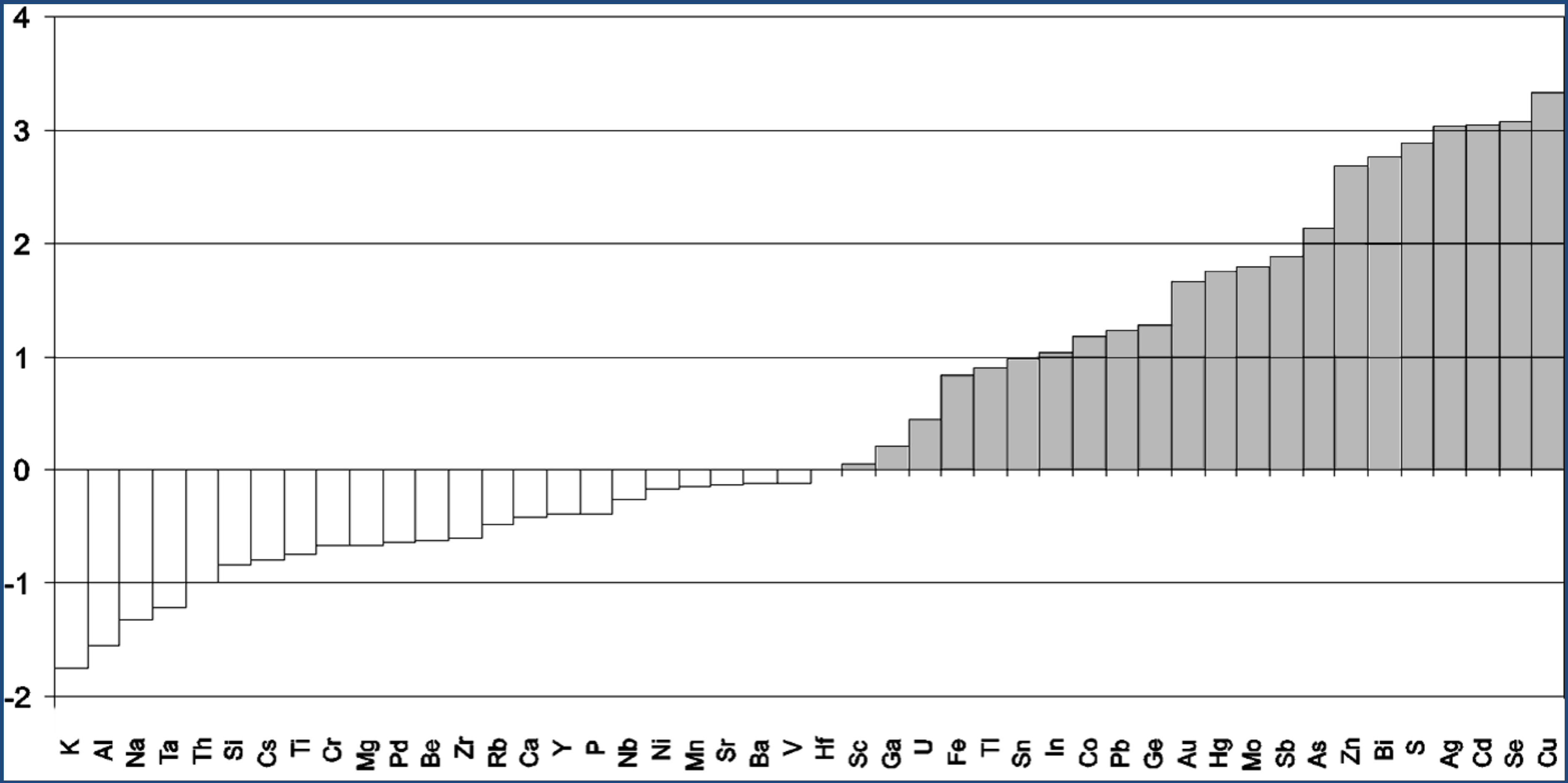
SMS composition

Vertical section through a small copper- and zinc-rich high temperature chimney.
(Y.Fouquet, IFREMER)

Sample of SMS (700 kg)

Fragment of Cu-sulfide chimney onboard

Metal Grades (e.g. rare-metals) & Resources



Metal concentrations in SMS related to the mean value in the Earth crust

Metals of economic interest in SMS

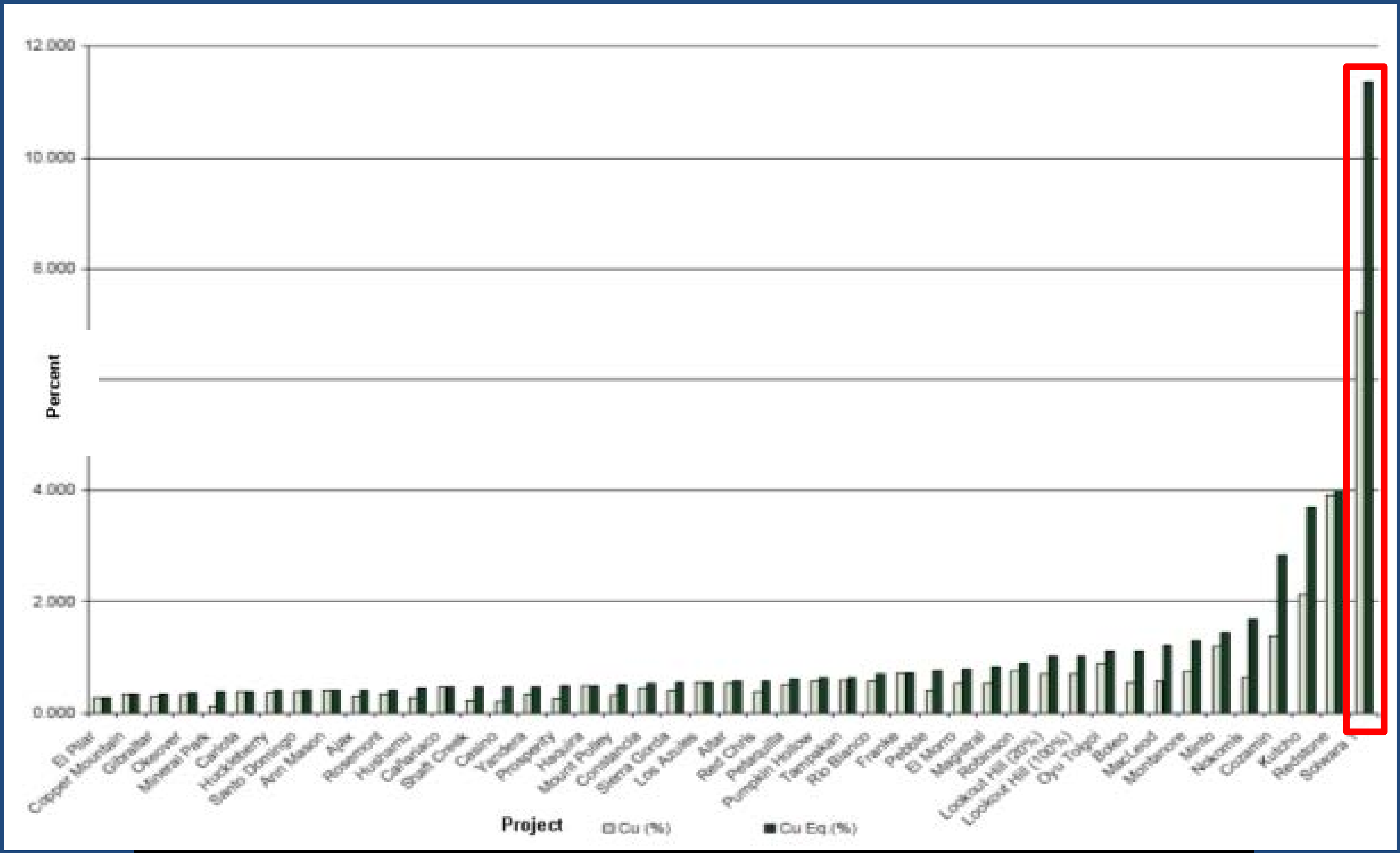
- Major

Cu, Zn, Pb, Au, Ag, (Co)

- Rare (byproducts)

Cd, Se, Ge, Ga, Mo, Te, In

Copper grade comparisons of SMS (Solwara 1) with onshore projects

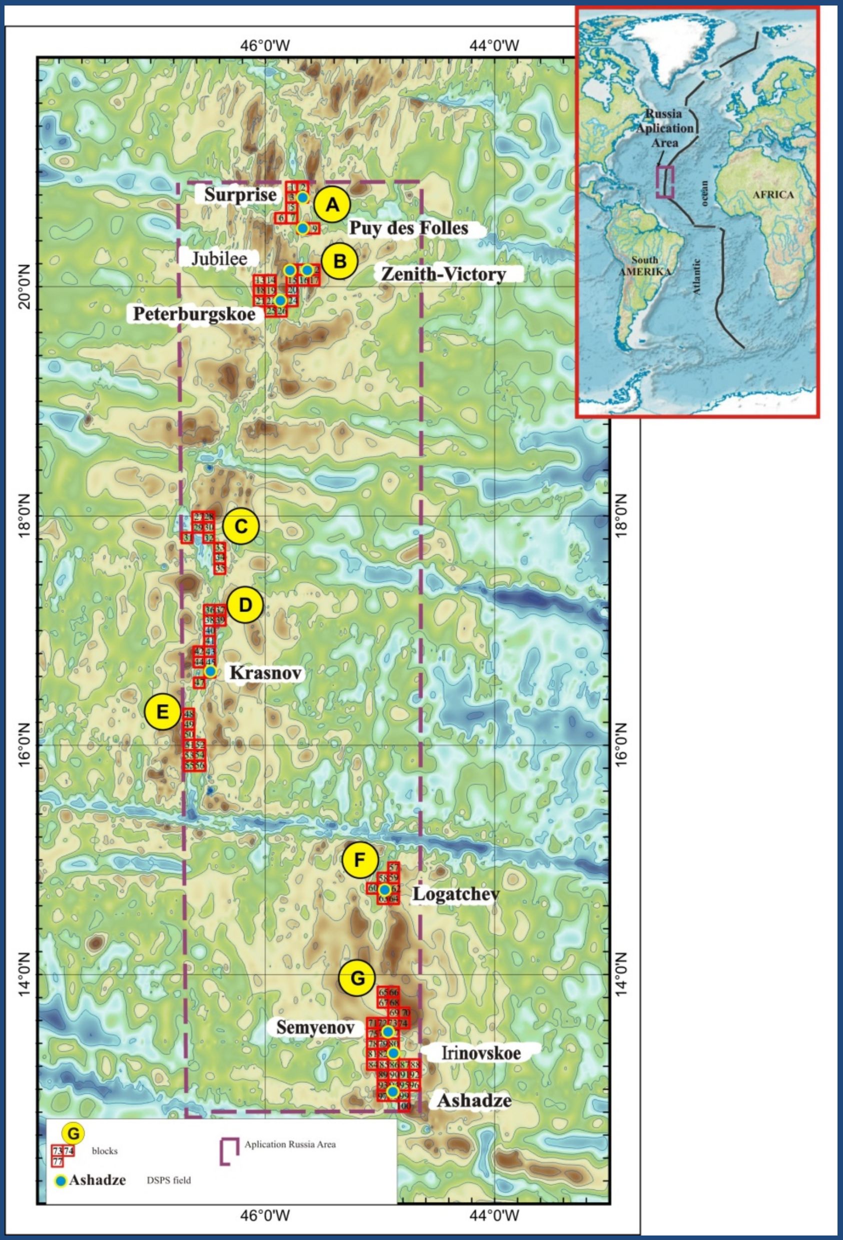


Courtesy of Craig Miller, TD Securities, Mar 2010, Nautilus Minerals NI 43-101 resource

Russian licensed area at the Mid-Atlantic Ridge

SMS deposit, year of discovery

- **Logatchev**, 1994
- **Puy des Folles**, 1997, 2008
- **Ashadze**, 2003, 2005, 2007
- **Krasnov**, 2004, 2006
- **Semyenov**, 2007, 2009
- **Zenith – Victory**, 2008, 2010
- **Irinovskoe**, 2009, 2011
- **Peterburgskoe**, 2010
- **Jubilee, 2012**
- **Surprise, 2012**



Major metals concentration in MAR SMS

	Ashadze-1 (U/B)	Ashadze-2 (U/B)	Logatchev-1 (U/B)	Logatchev-2 (U/B)	Krasnov (B)	Semyenov (U/B&B)	Puy des Folles (B)
Fe %	27.86	32.08	21.80	18.00	41.01	34.30	31.02
Cu %	10.52	17.70	33.19	22.40	1.74	2.48	13.07
Zn %	17.64	0.83	4.30	16.00	0.69	2.39	2.41
Au ppm	3.5	11.1	14.0	43.0	0.76	3.6	0.23
Ag ppm	87.7	7.8	56.0	4.2	26.0	53.3	27.5
Co ppm	1975	1148	539	90	488	285	845
Ni ppm	163	22	75	90	2	21	b.l.
N	97	51	124	9	144	21	19

U/B – ultrabasic hosted SMS; B – basalt hosted SMS

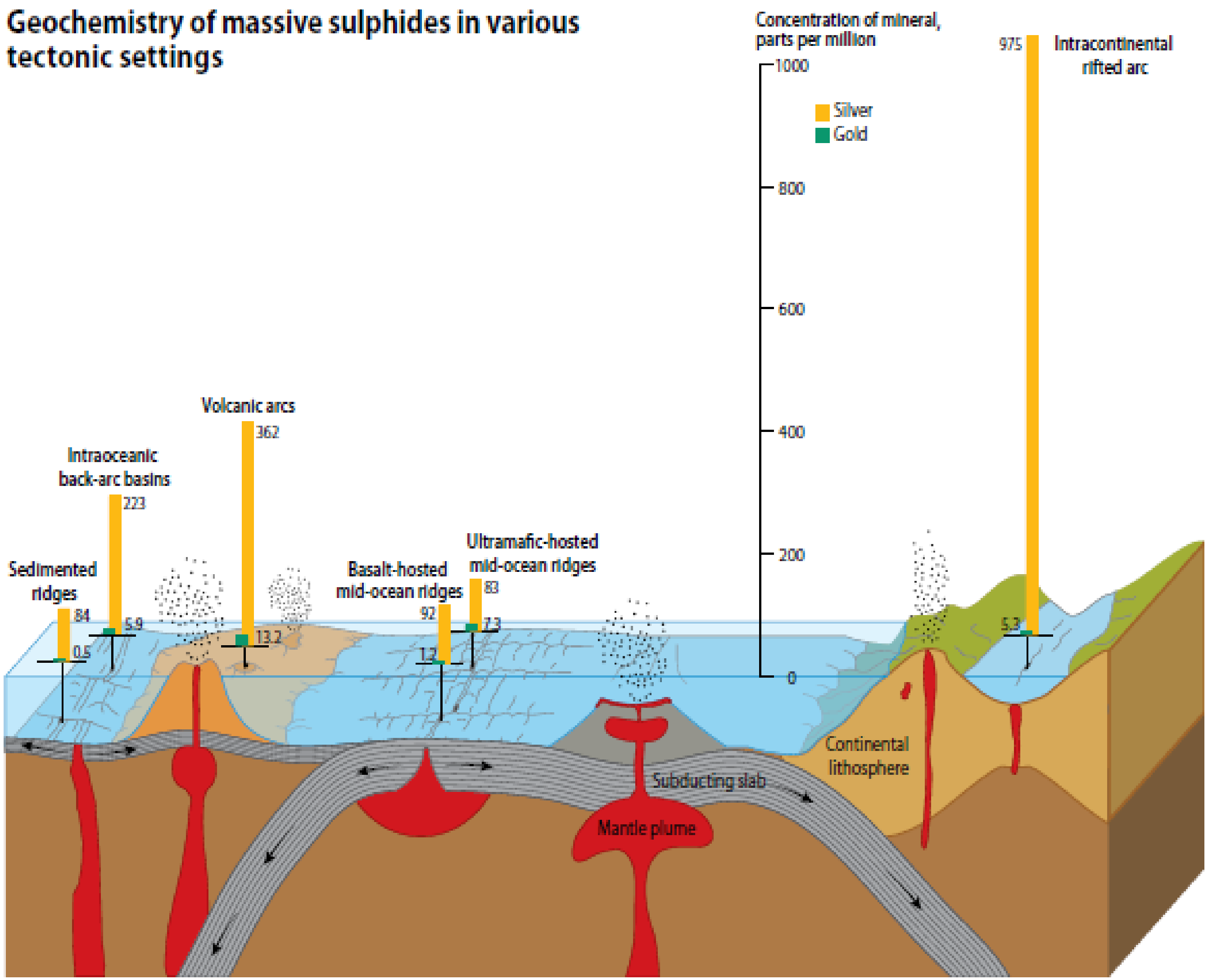


Figure 6. Concentrations of gold and silver in sea-floor massive sulphides formed in different geological settings (Source: GEOMAR)

SPC (2013). *Deep Sea Minerals: Sea-Floor Massive Sulphides, a physical,biological, environmental, and technical review. Baker, E., and Beaudoin,*Y. (Eds.) Vol. 1A, Secretariat of the Pacific Community

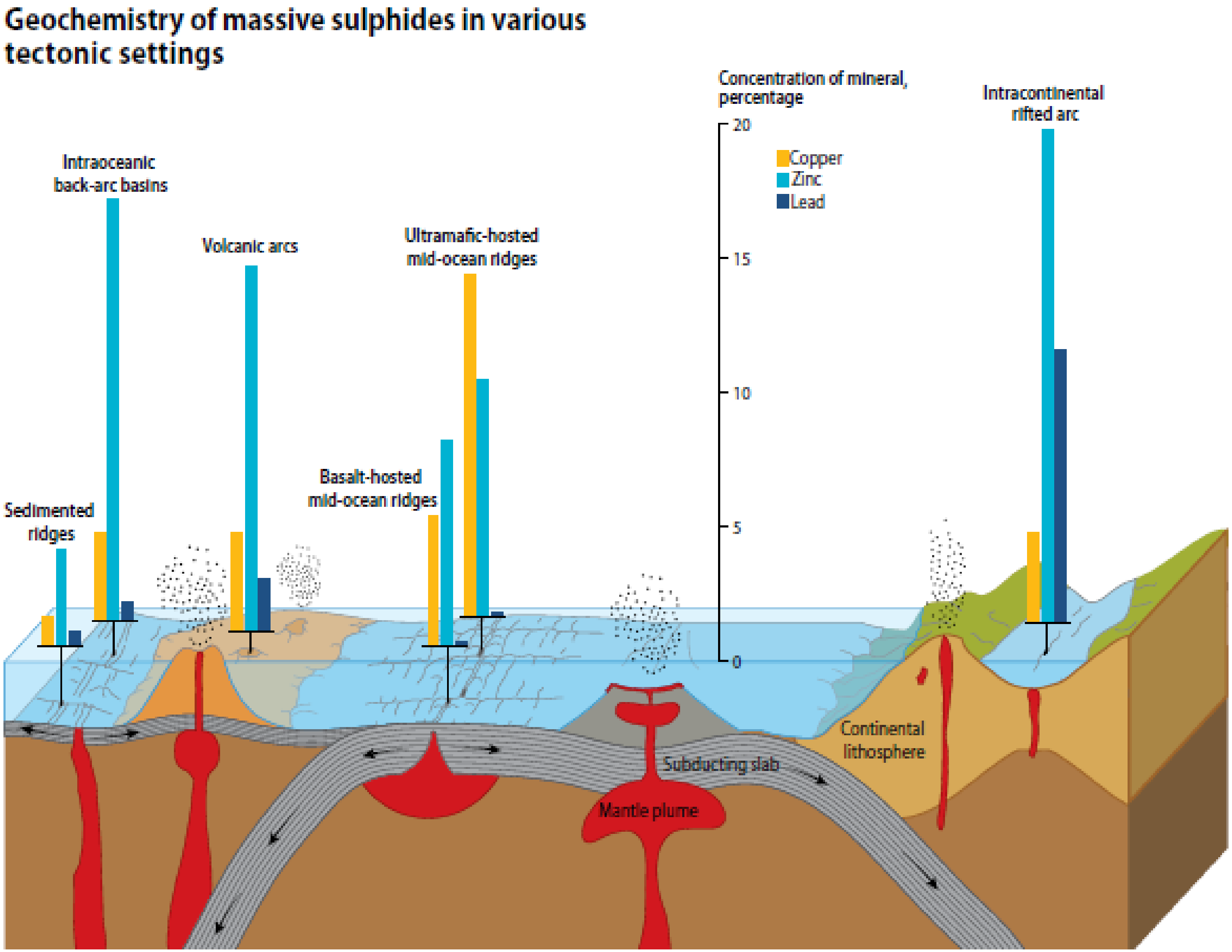


Figure 5. Concentrations of copper, zinc, and lead in sea-floor massive sulphides formed in different geological settings (Source: GEOMAR)

SPC (2013). *Deep Sea Minerals: Sea-Floor Massive Sulphides, a physical,biological, environmental, and technical review. Baker, E., and Beaudoin,*Y. (Eds.) Vol. 1A, Secretariat of the Pacific Community

Resources

- Estimates of single SMS deposit range from n x 10^3 tonnes to n x 10^6 tonnes ore masses. This is comparable with onshore massive VMS deposits.
- Estimates of the oceanwide metal potential of seafloor hydrothermal systems range from 530 x 10^9 tonnes Cu+Zn (Cathles, 2011) to 3 x 10^9 tonnes Cu+Zn (Hannington et al., 2010).

Parameters of the massive sulfide deposits (northern equatorial MAR)

Deposit (A – active I – inactive)	Latitude (N)	Water depth (meters)	Estimated size parameters of deposit		
			Square km^2	Thickness m	Est.resources mln. tonnes
Ashadze-1 (A)	12° 58.5'	4200	0.058	10	1.74
Ashadze-2 (A)	12° 59.5'	3250	0.106	20	5.70
13° 20' N (I)	13° 20'	2600	0.110	?	?
Semyenov (I/A)	13° 31'	2400-2600		5	42.00
Logatchev-1 (A)	14° 45'	3100	0.032	15	1.75
Logatchev-2 (A)	14° 43'	2720	0.007	10	0.25
Krasnov (I)	16° 38'	3700-3750	0.161	25	13.95
Zenith-Victoria (I)	20° 08'	2370-2390	0.495	8	11.00
Puy des Folles (?)	20°30.5'	1940 - 2000	0.858	4	10.00
TAG (ActiveMound) (Hannington et al., 1998)	26° 08'	3670	0.031	40-50	4.0
Solwara-1 (www.nautilusminerals.com)		1200		< 20	1.2

Active & Inactive SMS: environmental issues

Principal types of SMS

- by geological setting:

• on the surface of seafloor (mostly)

• subseafloor (proposed)

- by association with hydrothermal activity:

• active

• inactive (preferential)

Active hydrothermal site

Active site

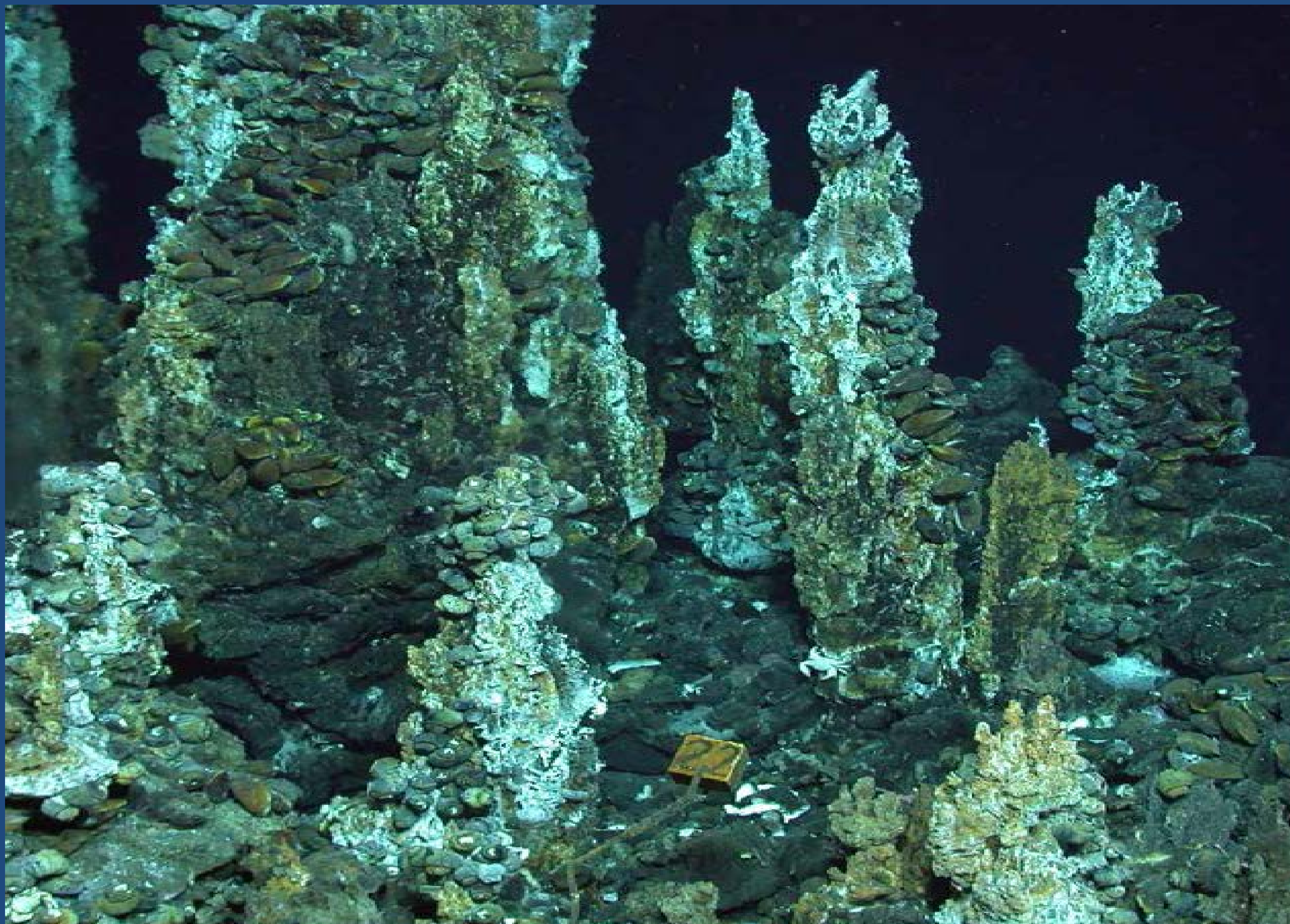
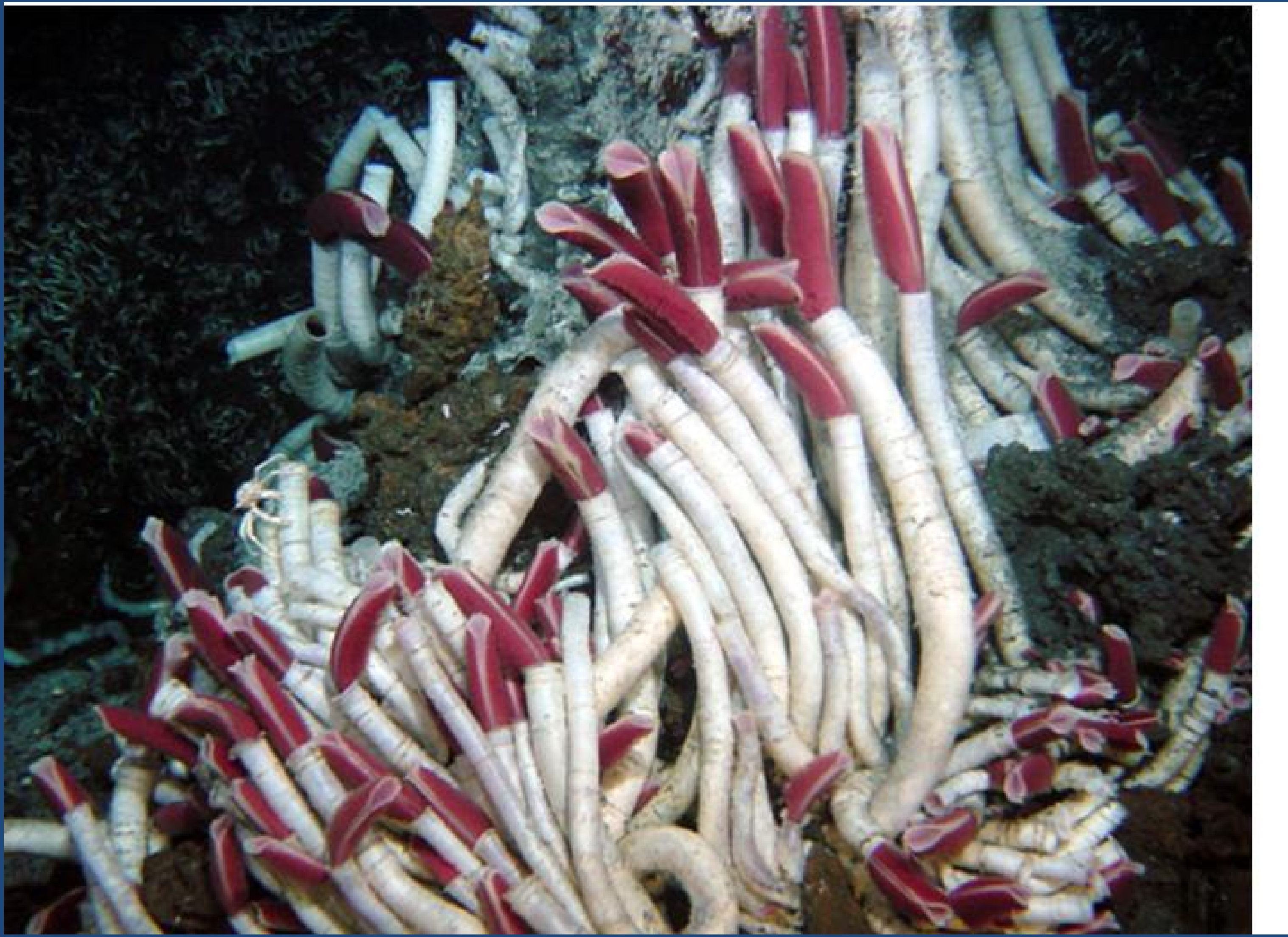
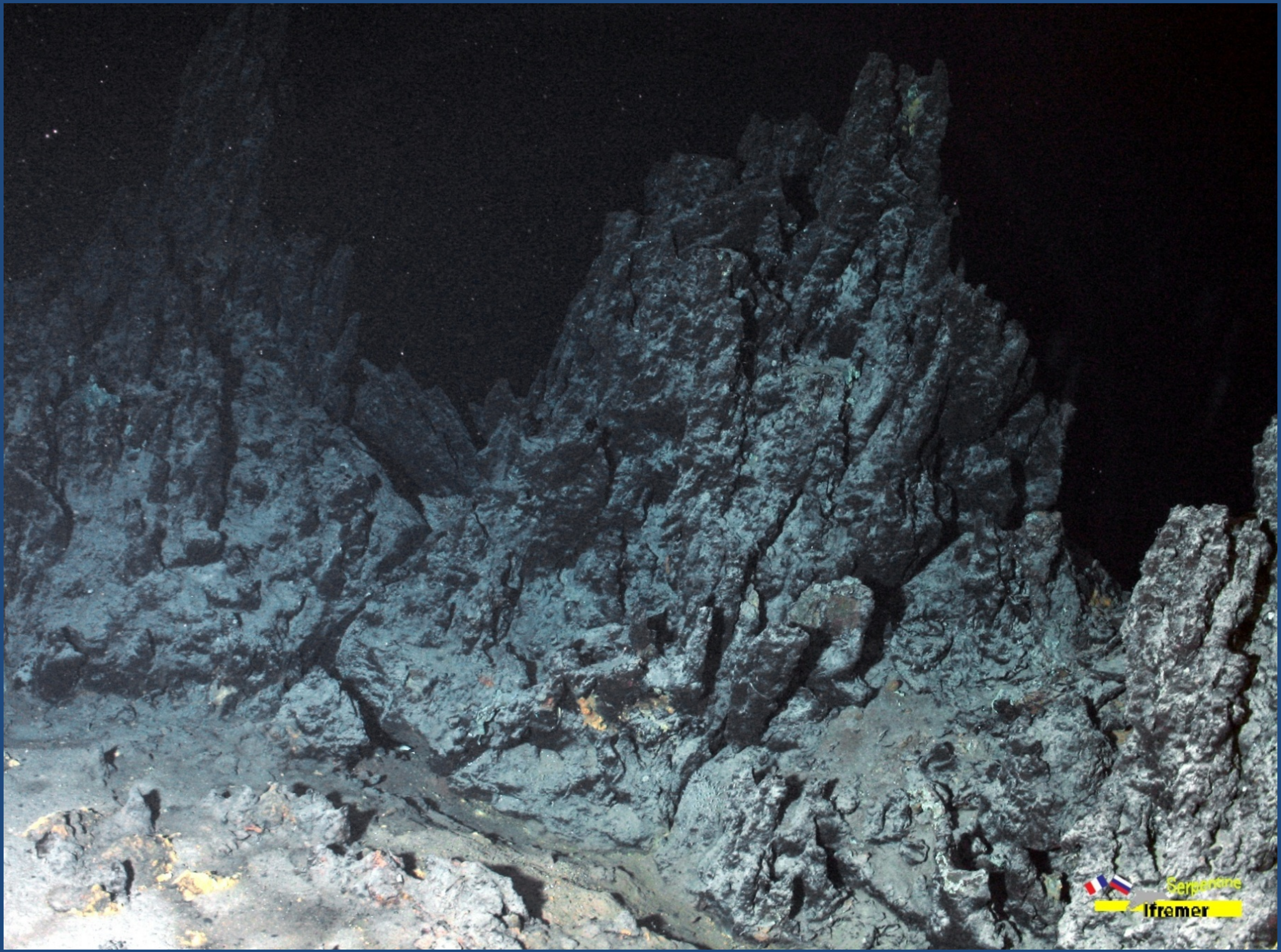


Photo courtesy of Chuck Fisher.

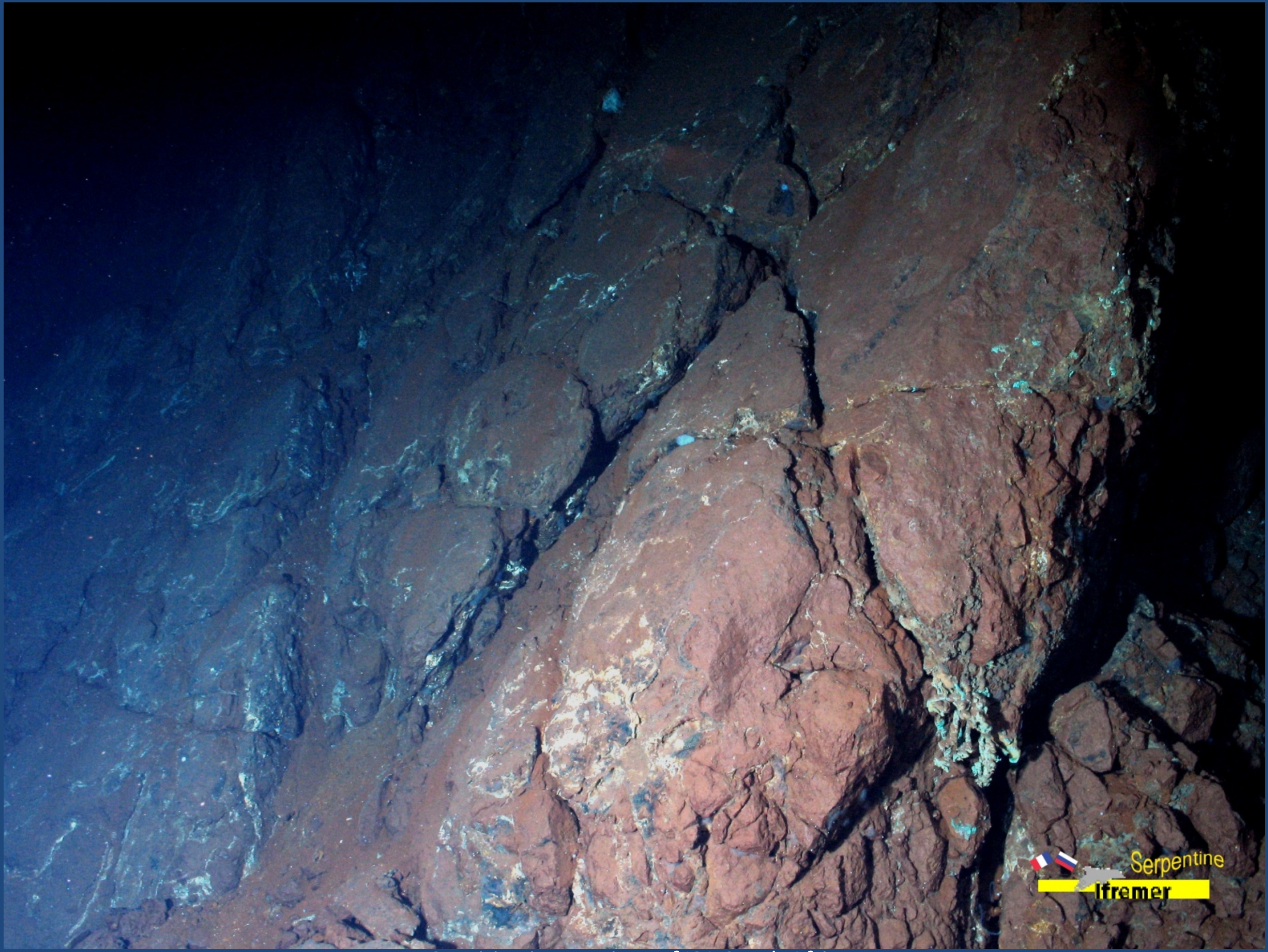
Hydrothermal community at the active site



Inactive chimney



Oxidized SMS at the inactive site



Exploration methods & Exploitation approaches

Exploration studies for SMS deposits

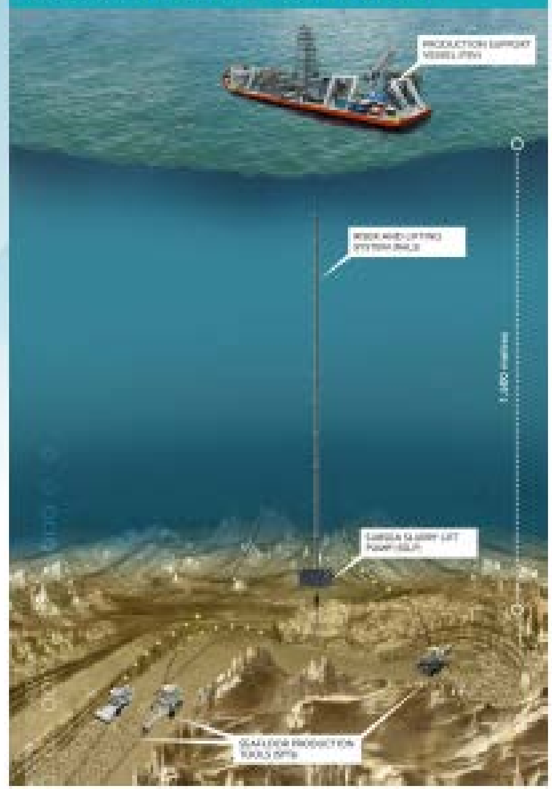
Exploration for sulfide deposits

- ❑ Specific techniques to locate active deposits.
  - ❑ Geological setting
  - ❑ Chemical tracers in the water column
  - ❑ Physical tracers in the water column
- ❑ Few techniques for locating inactive deposits
  - ❑ Chemical and mineral tracers in the sediments
  - ❑ Near seafloor electric measurements
- ❑ Evaluation of deposits
  - ❑ Near seafloor electric measurements
  - ❑ Drilling operation

Seafloor Production: what is it?

NAUTILUS Minerals

Seafloor Production System



Using existing technology from the offshore oil and gas sector, combined with rock cutting and materials handling technologies used in land-based operations

- Production Support Vessel
  - Operational base. Power supply and dewatering plant
- Riser and Lifting System
  - Pumps material to the surface
- Seafloor Production Tools
  - Three remotely operated machines, cutting and collecting material

Sensitization seminar of ISA South Africa
17 – 19 March, 2015

Seafloor Production Tools (all being commissioned)

NAUTILUS Minerals

Auxiliary Cutter

Length:	15.8 m
Width:	6.0 m
Height:	7.6 m
Boom swing:	11.6 m
Boom cutting:	+4 -1.0 m
Weight:	250 Te

Bulk Cutter

Length:	14.2 m
Width:	4.2 m
Height:	6.8 m
Cutter Width:	4.2 m
Cutting Height:	+4 -0.5 m
Weight:	310 Te

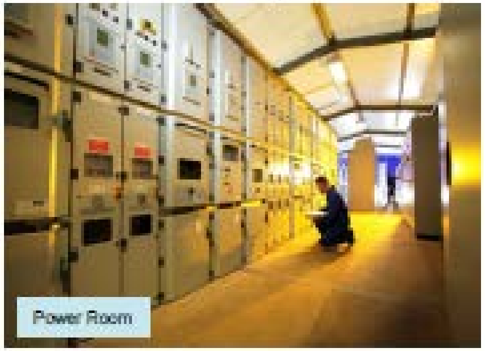
Collecting Machine

Length:	16.5 m
Width:	6.0 m
Height:	7.6 m
Collection Range – height:	-2 m +6 m
Collection Range – Width:	± 4 m
Weight:	200 Te

Current status of Seafloor Equipment build

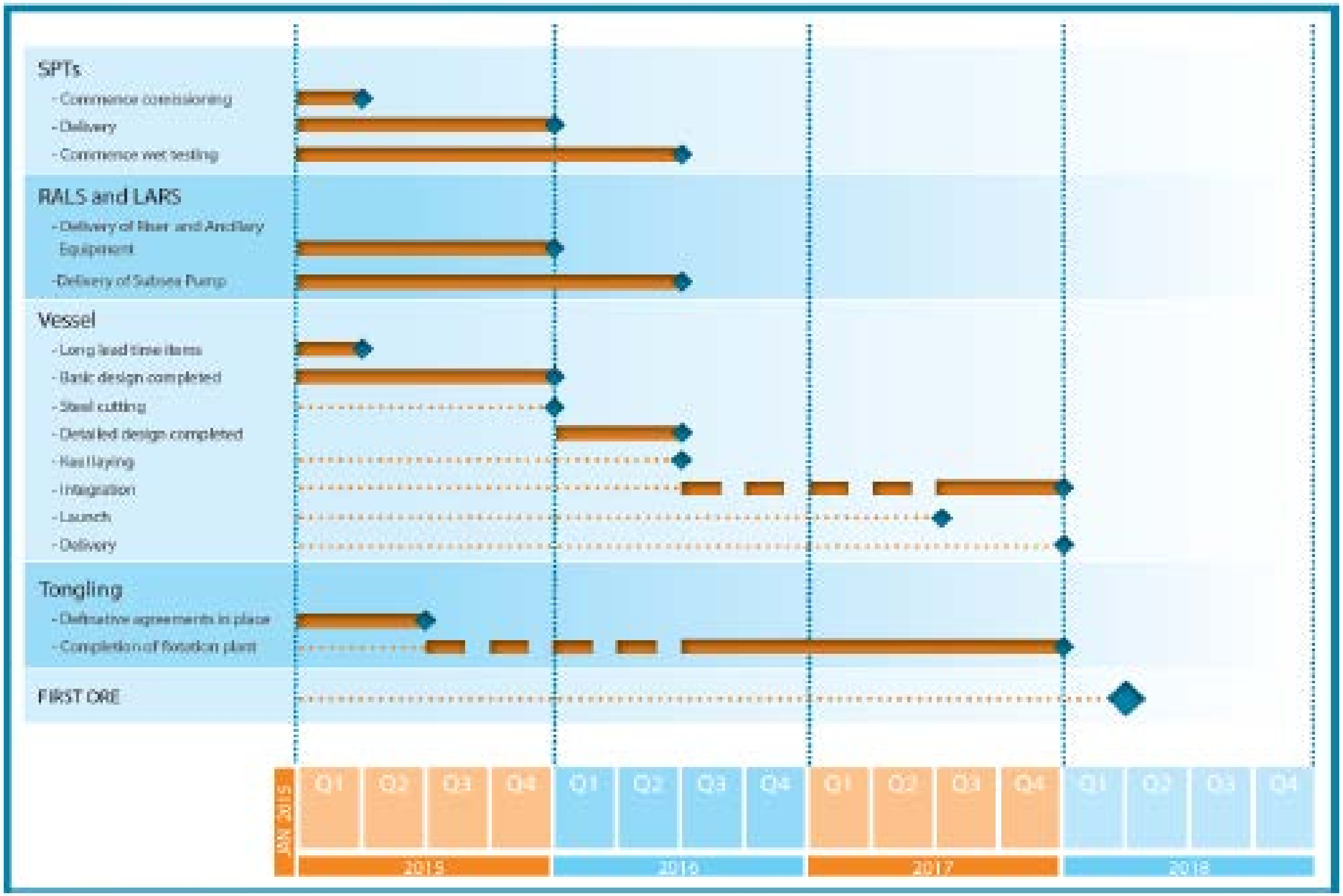
NAUTILUS Minerals

- Seafloor Production Tools (SPTs)
  - BC, CM and AC undergoing commissioning
  - Delivery expected by Q4 2015
  - Extensive wet testing planned 2016
- Riser and Ancillary Equipment
  - >50% complete with delivery expected by Q4 2015
- Pump
  - > 50% complete with delivery expected by mid 2016



Timeline to Production

NAUTILUS Minerals



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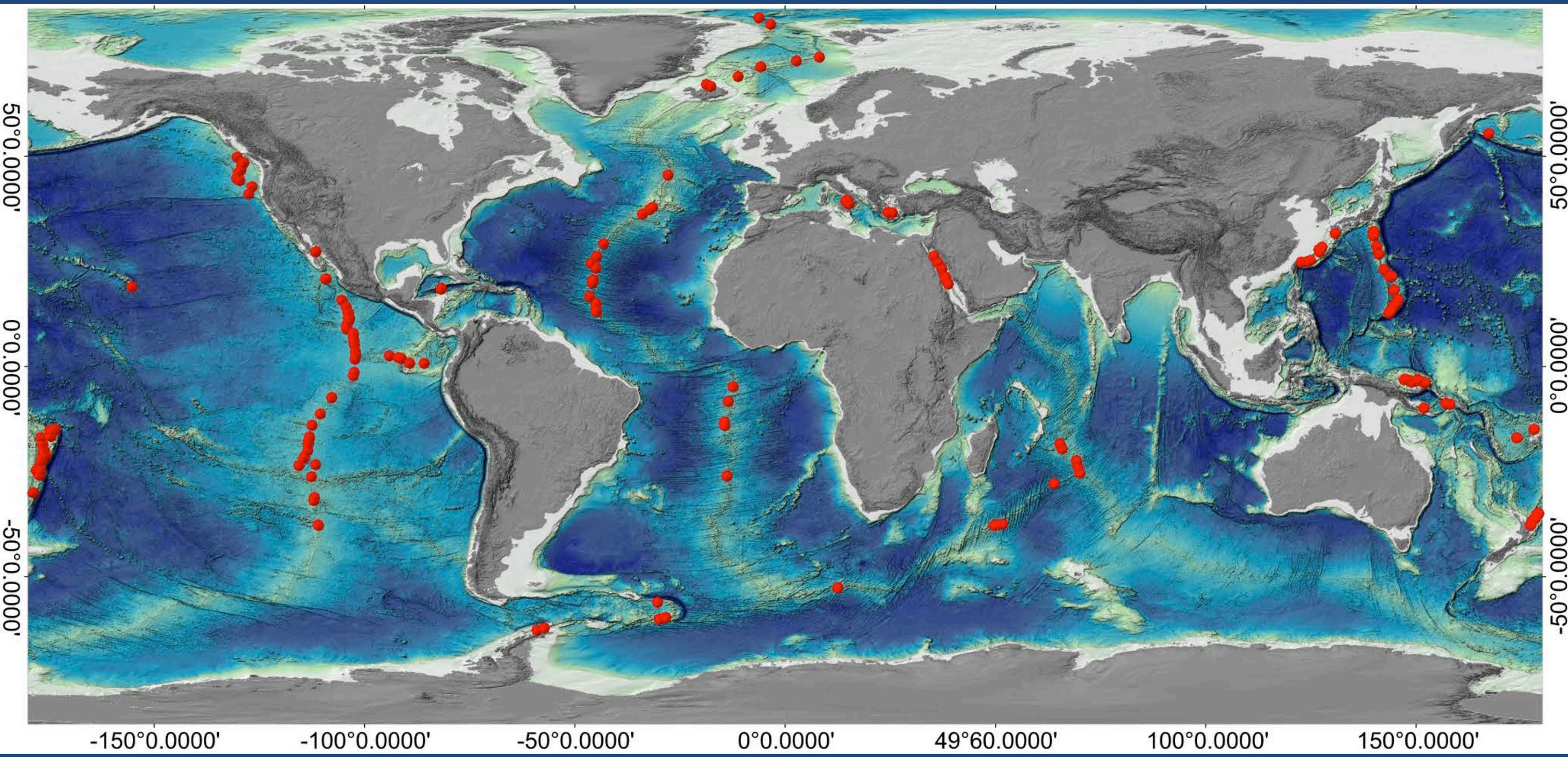
distribution of seafloor hydrothermal systems in the world ocean



Peteresen, 2013

Russian licensed area at the Mid-Atlantic Ridge

SMS deposit, year of discovery

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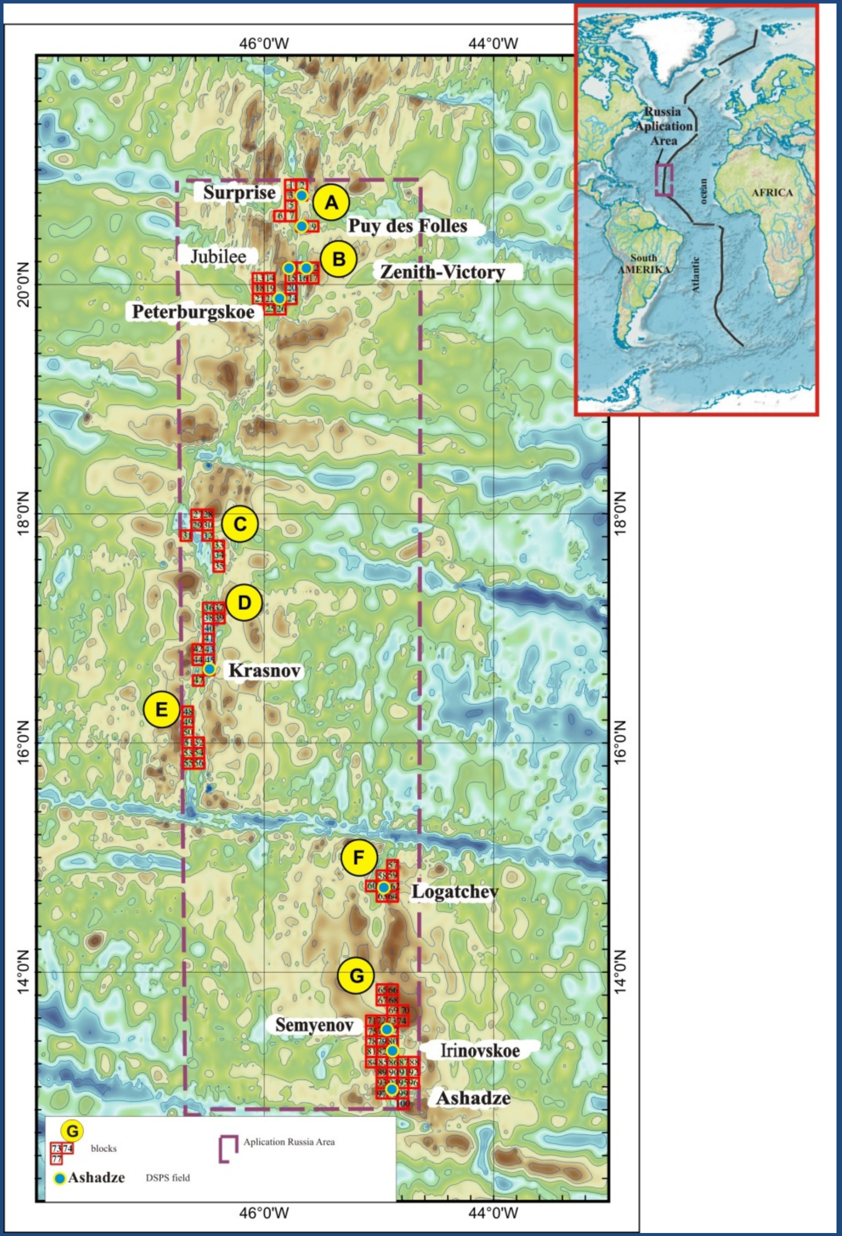
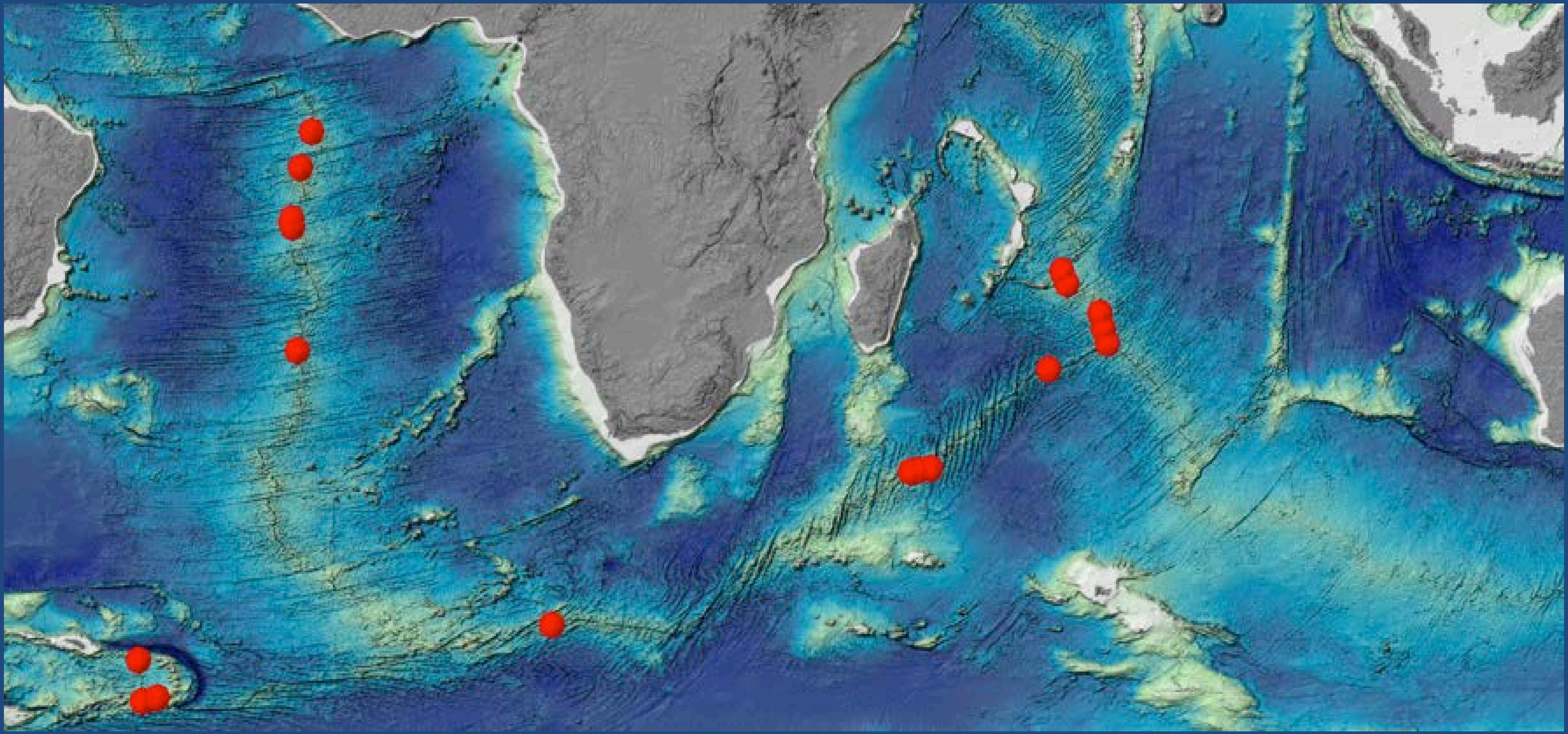
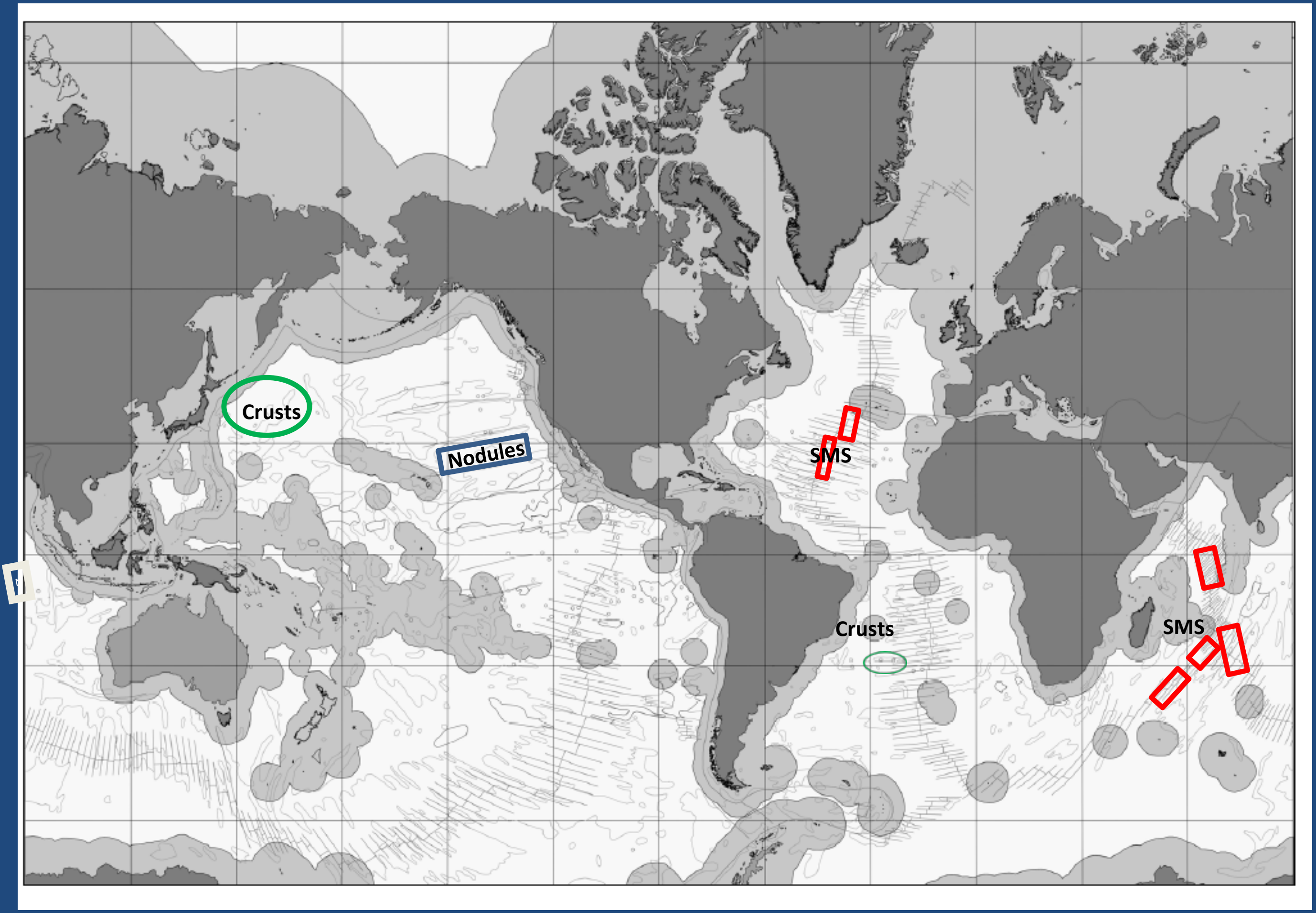


Distribution of seafloor hydrothermal systems in South Atlantic and Indian ocean



Images of hydrothermal activity in the Central Indian Ocean (source WHOI)

Exclusive economic zones & application areas



Contractor/Applicant	Nodules	Crusts	Massive Sulfides
China, COMRA	2001, 2015 (A)	2014	**2011**
Russia, YMG, MNR	2001	2015	**2012**
Japan, DORD, JOGMEC	2001	2014	
India,	2001		**2013 (A)**
France, IFREMER	2001		**2014**
Korea, KIOST	2001		**2014**
InterOceanMetal	2001		
Germany, BGR	2006		**2013 (A)**
United Kingdom, UKSRL	2013 (A)		
Belgium, GSR	2013		
Tonga, TOML	2012		
Kiribati, MARAWA	2015		
Nauru, NORI	2011		
Cook Island, CIIC	2014 (A)		
Singapore, Ocean Mineral	2015		
Brasil, CPRM		2014 (A)	

Concluding 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.
- Available exploration methods are sufficiently efficient for prospecting SMS deposits
- Due to limited data available resource estimates of SMS have a wide range and could be revised after further exploration studies.
- Feasibility of cost-effective production of SMS has been elaborated not for the Area, but for the exclusive economic zones (EEZ) of the island States in South-West Pacific
- The first commercial mining of SMS is expected in the EEZ (2018?). Development of the mining production systems is close to completion.

Concluding remarks

- ISA effectively administers activities related to the SMS exploration.
- ISA pays particular attention to the environmental aspects of mineral exploration and to the training of specialists from developing countries.
- The interest in this type of marine minerals is growing. In less than four years after the adoption of the Regulations, four contracts for SMS exploration in the Atlantic and Indian oceans have already been signed, and two new applications approved by ISA Council.
- New areas for SMS application is still available in the Atlantic and Indian oceans