Prospects and Status of Exploration for Polymetallic Sulphides

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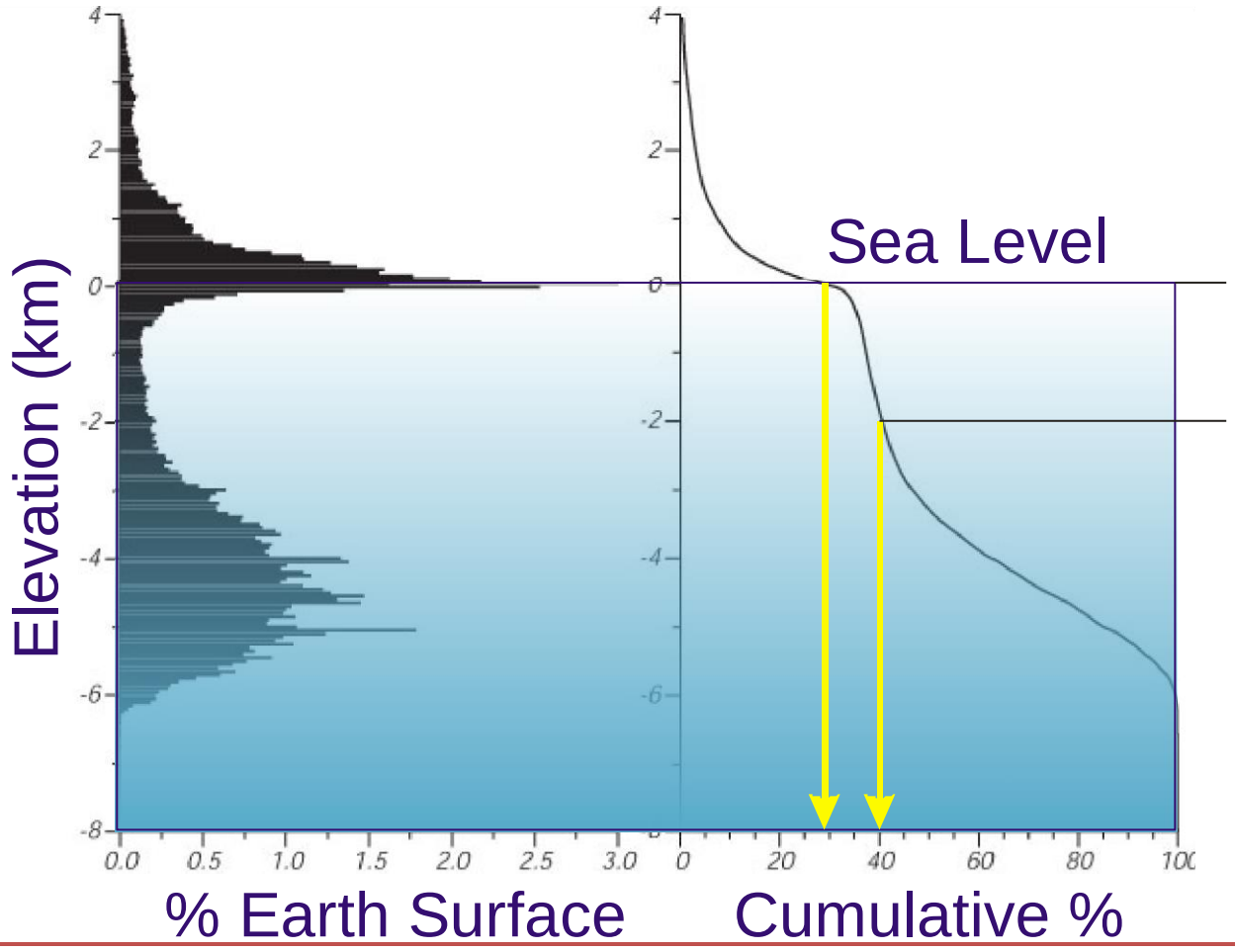
Outline

- 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
- Conclusive remarks

MARINE MINERALS: THE FUTURE OF SUPPLY

EARTH'S HYPSOMETRIC CURVE



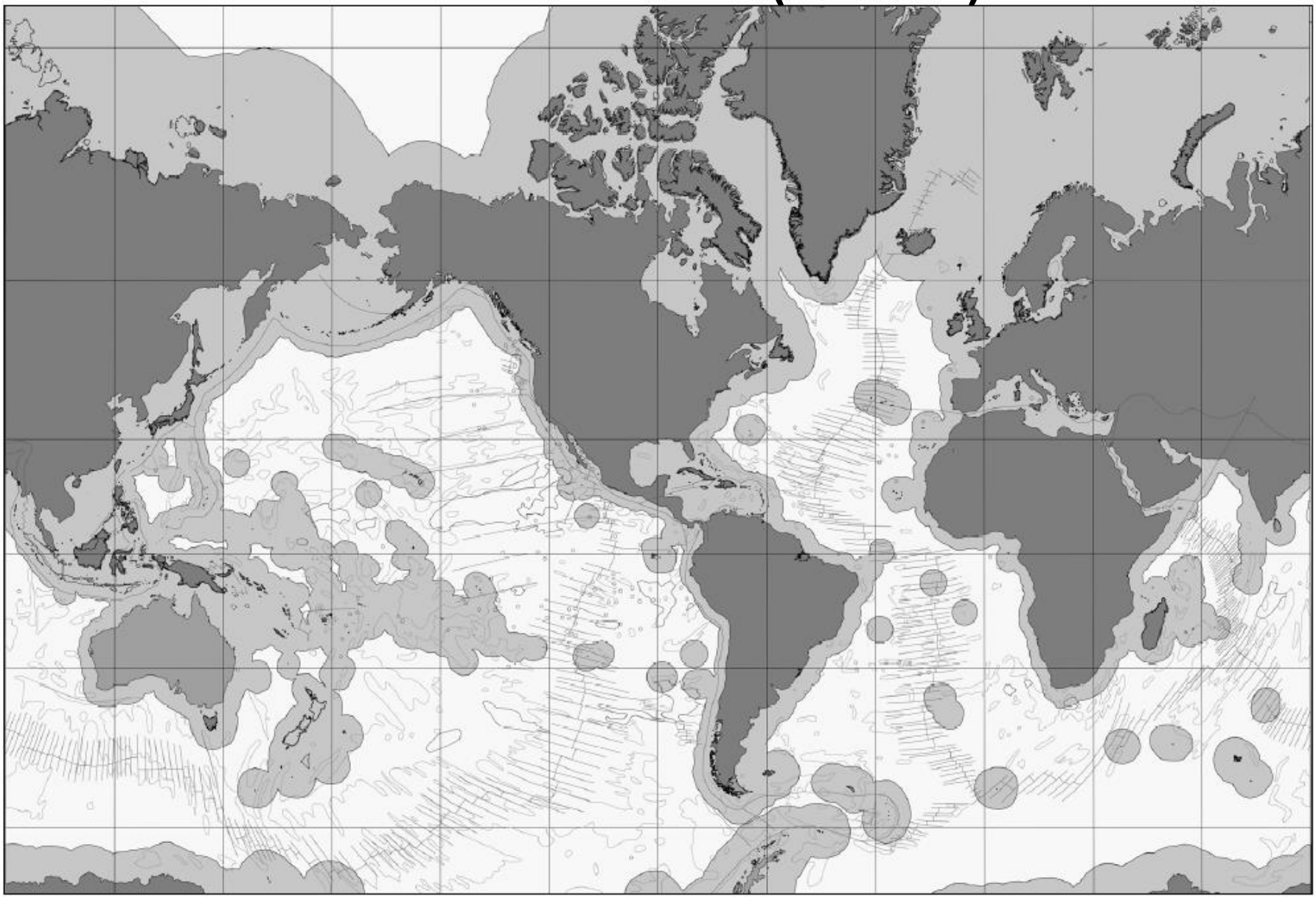
71% below Sea Level

60% below 2,000 m

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

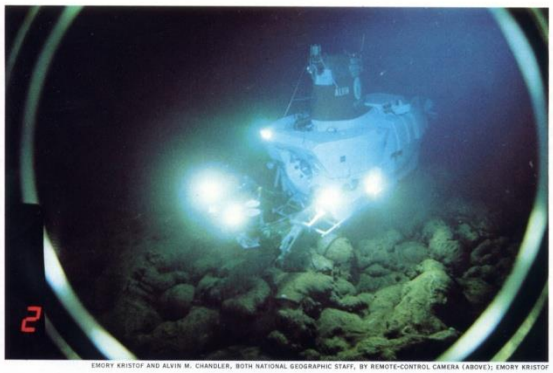
In the EEZ

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

In the Area & EEZ

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

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.

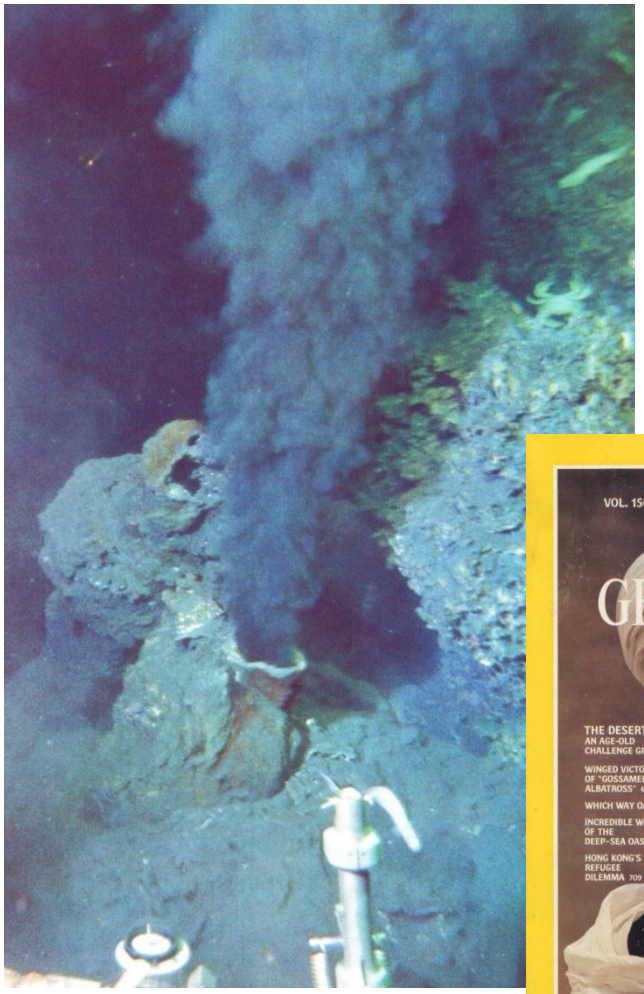
But along those few miles in the past six years, scientists in tiny submarines such as *Alvin* (***above***) have found, in those utterly dark nether depths of the sea, animals and mineral factories unlike any seen before.

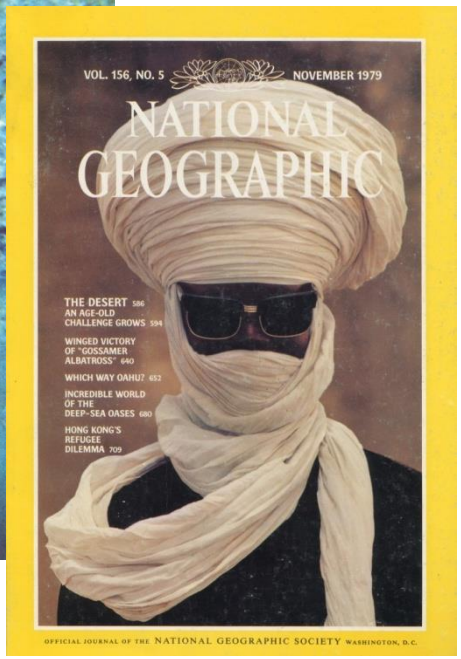
In 1979 the latest in a series of expeditions went out into the Pacific to study spreading centers of the ocean floor. These are places where the thin, rigid plates that form the hard crust of our planet are pulling apart, separating as much as eight inches a year. In the cracks molten magma wells up,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

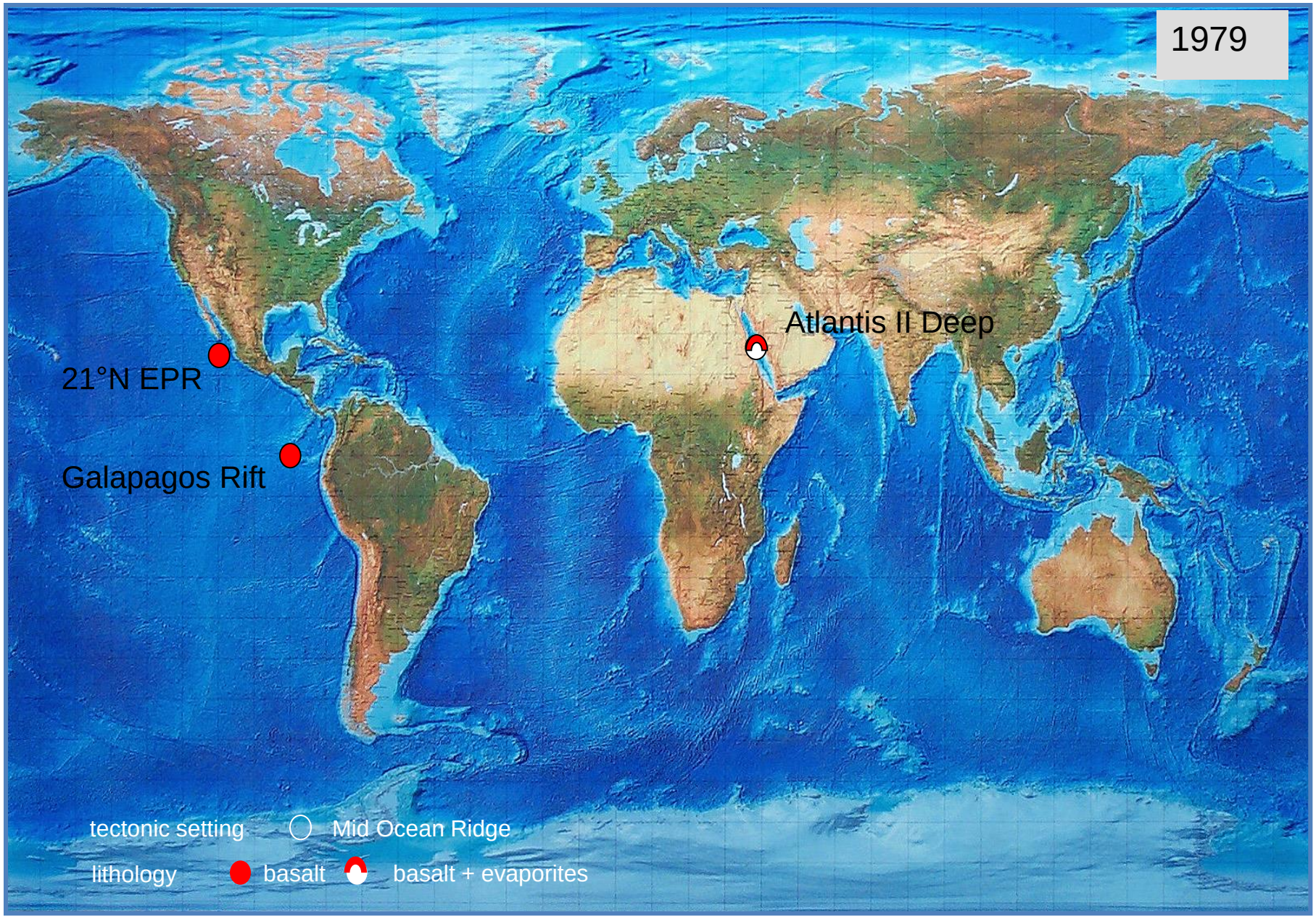
680

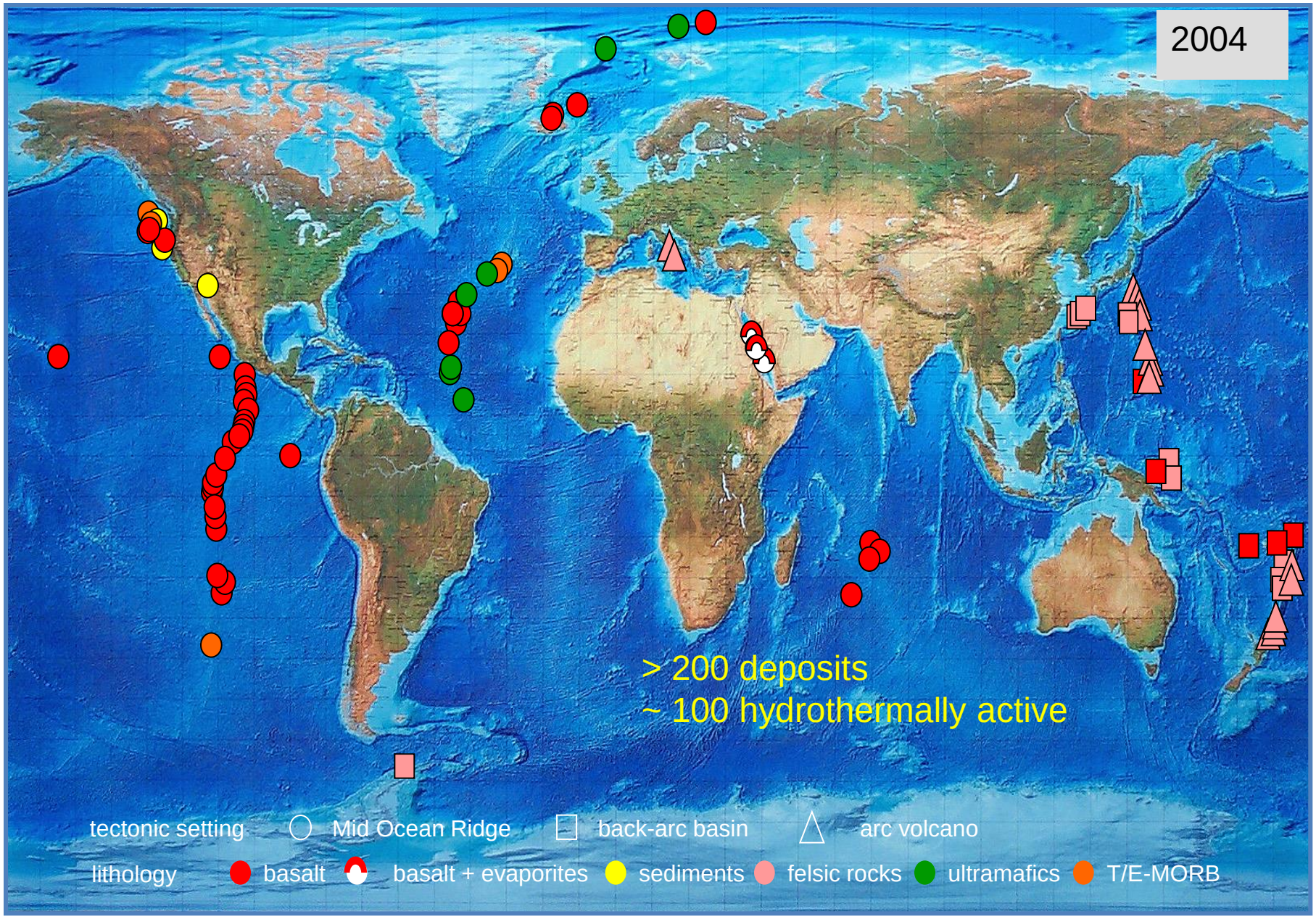




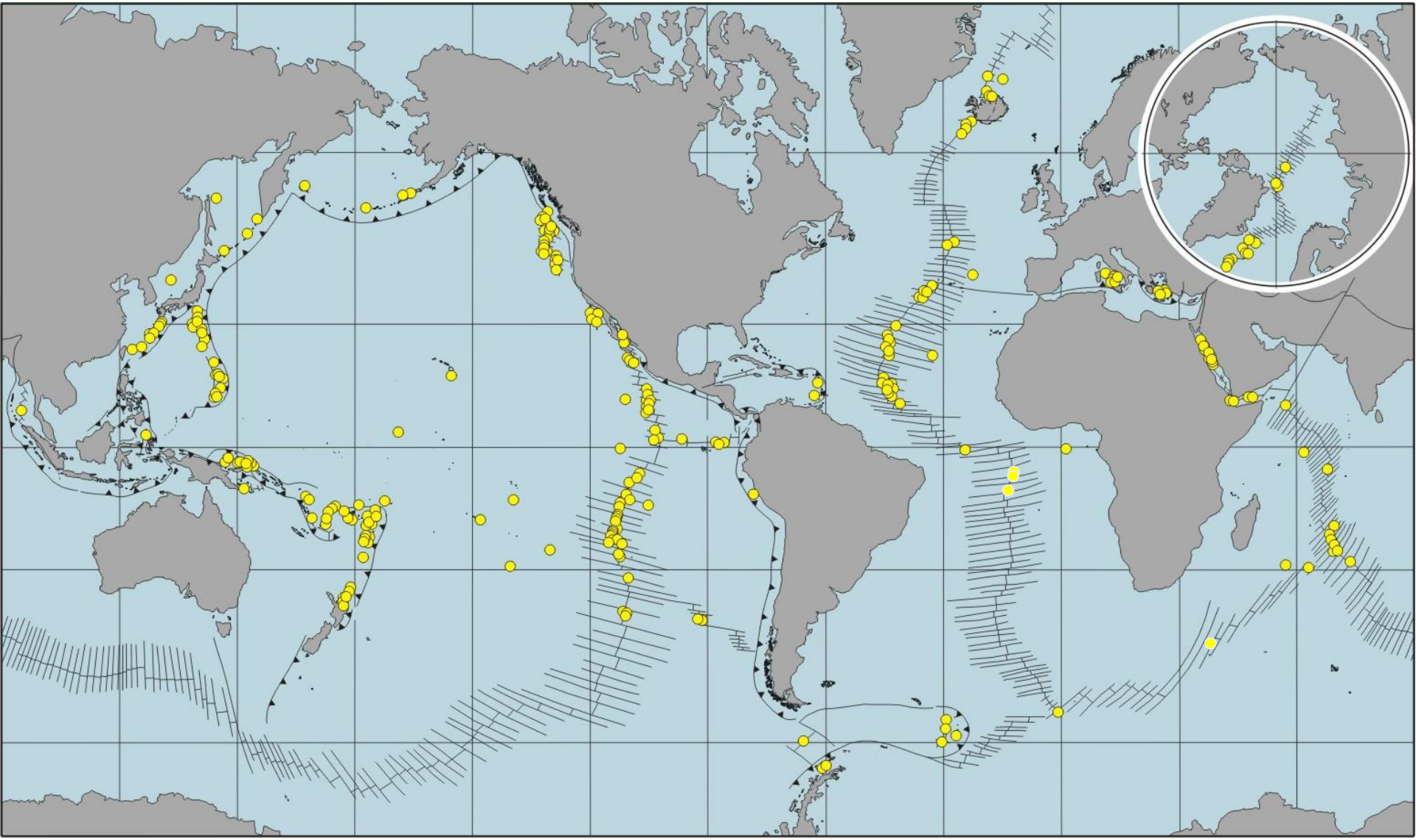
November 1979

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


1979
Atlantis II Deep
21°N EPR
Galapagos Rift
tectonic setting
Mid Ocean Ridge
lithology
basalt
basalt + evaporites


2004
> 200 deposits
~ 100 hydrothermally active
tectonic setting
Mid Ocean Ridge
back-arc basin
arc volcano
lithology
basalt
basalt + evaporites
sediments
felsic rocks
ultramafics
T/E-MORB

Distribution of seafloor hydrothermal systems in the Ocean

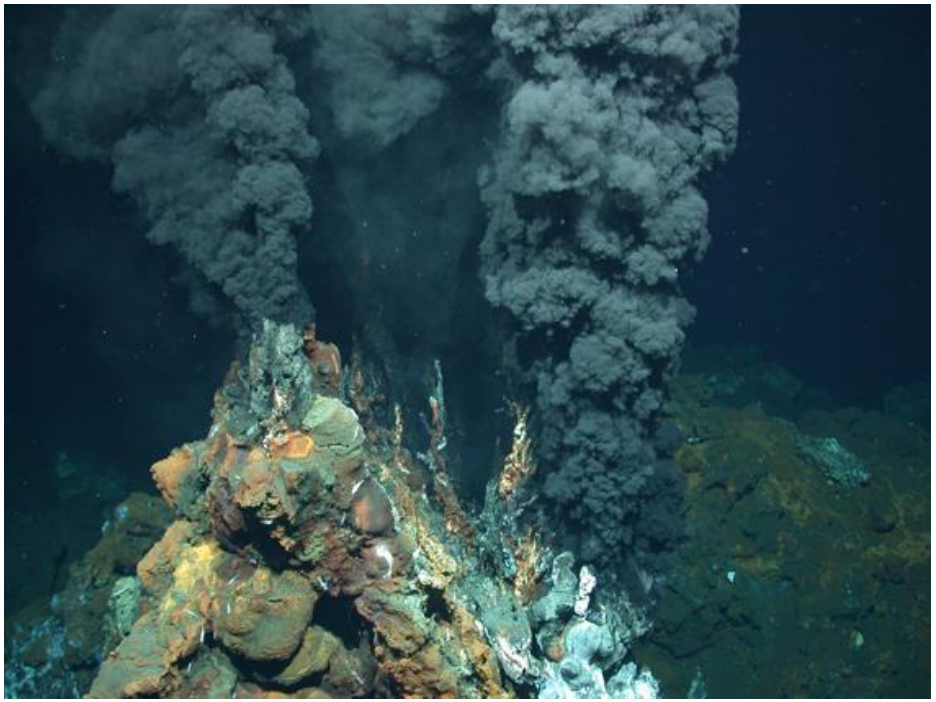


Hannington, de Ronde and Petersen, 2005

Basic Facts (Petersen, 2009)

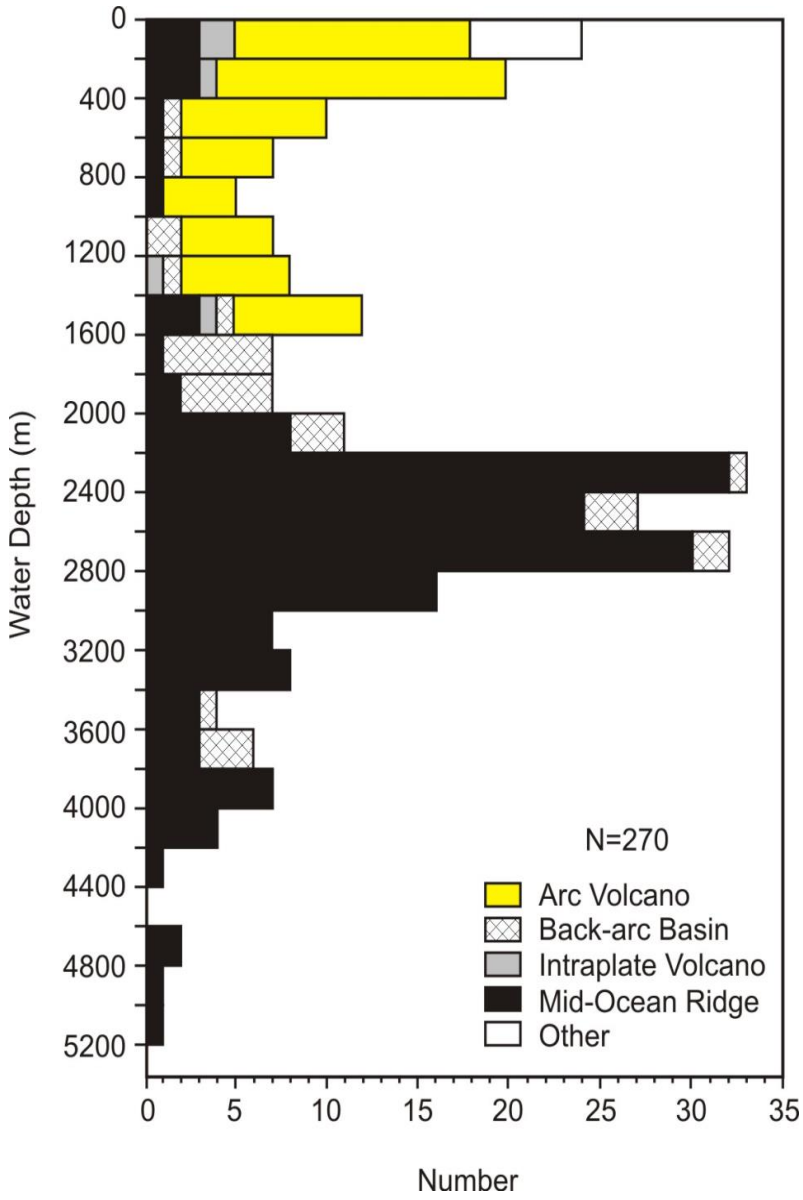
- >350 known sites of hydrothermal activity
- 215 sites of polymetallic sulfide deposits
- 150 sites of high-temperature hydrothermal activity (black smokers)

- 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

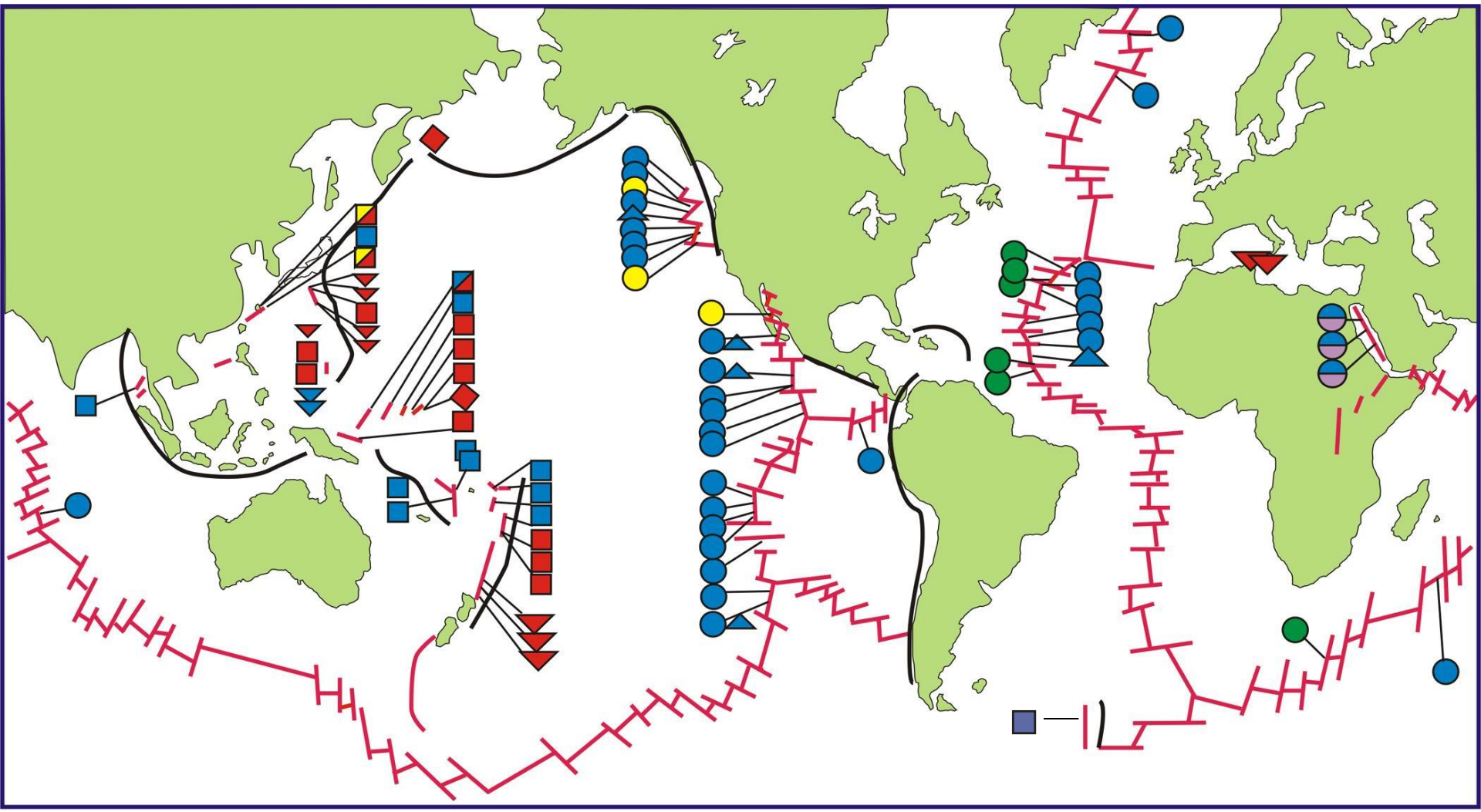
Water depth distribution of the SMS



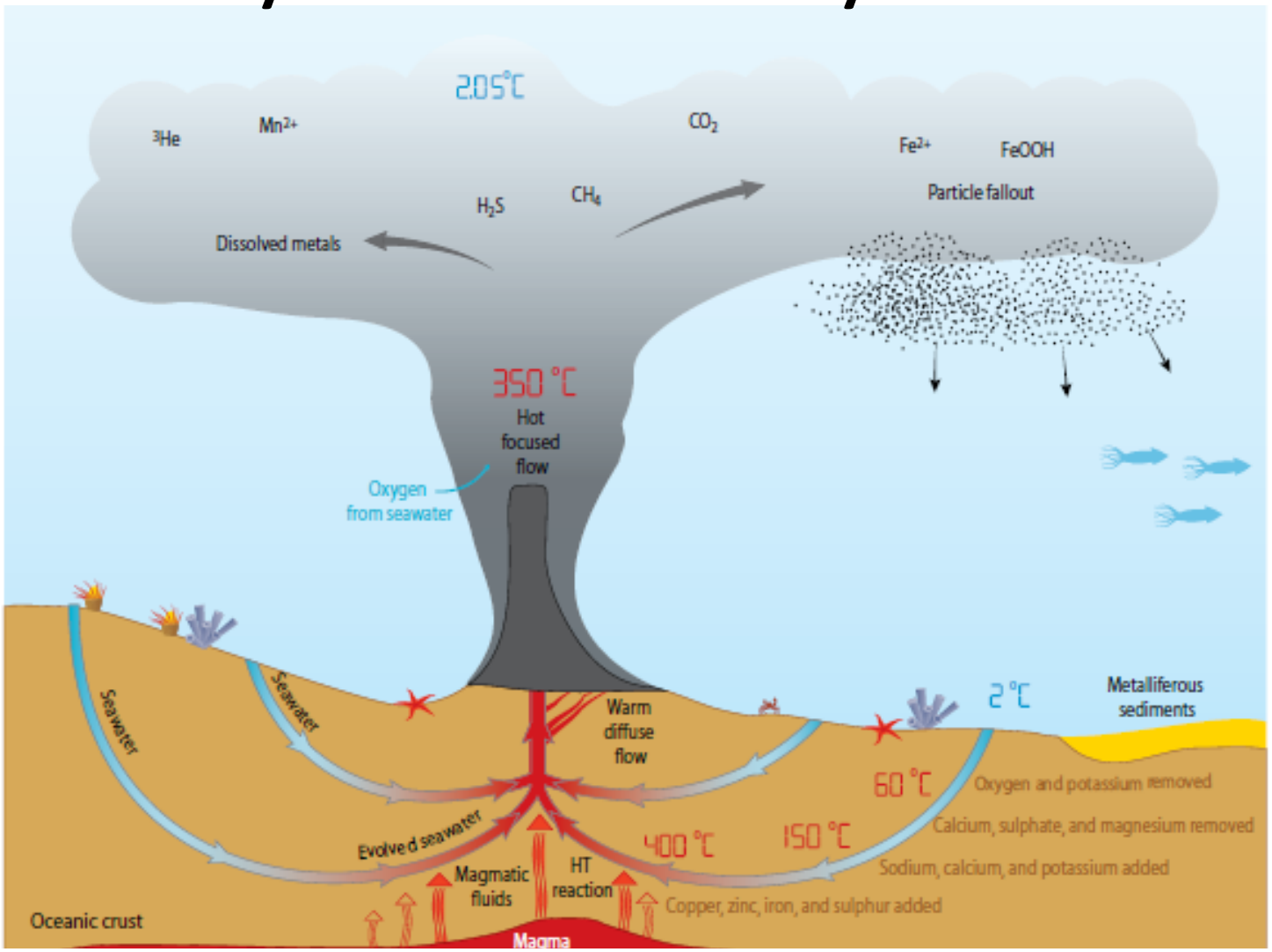
Hannington et al., 2006

Geological setting of the SMS

(Updated from Fouquet, IFREMER, 1998, 2002)



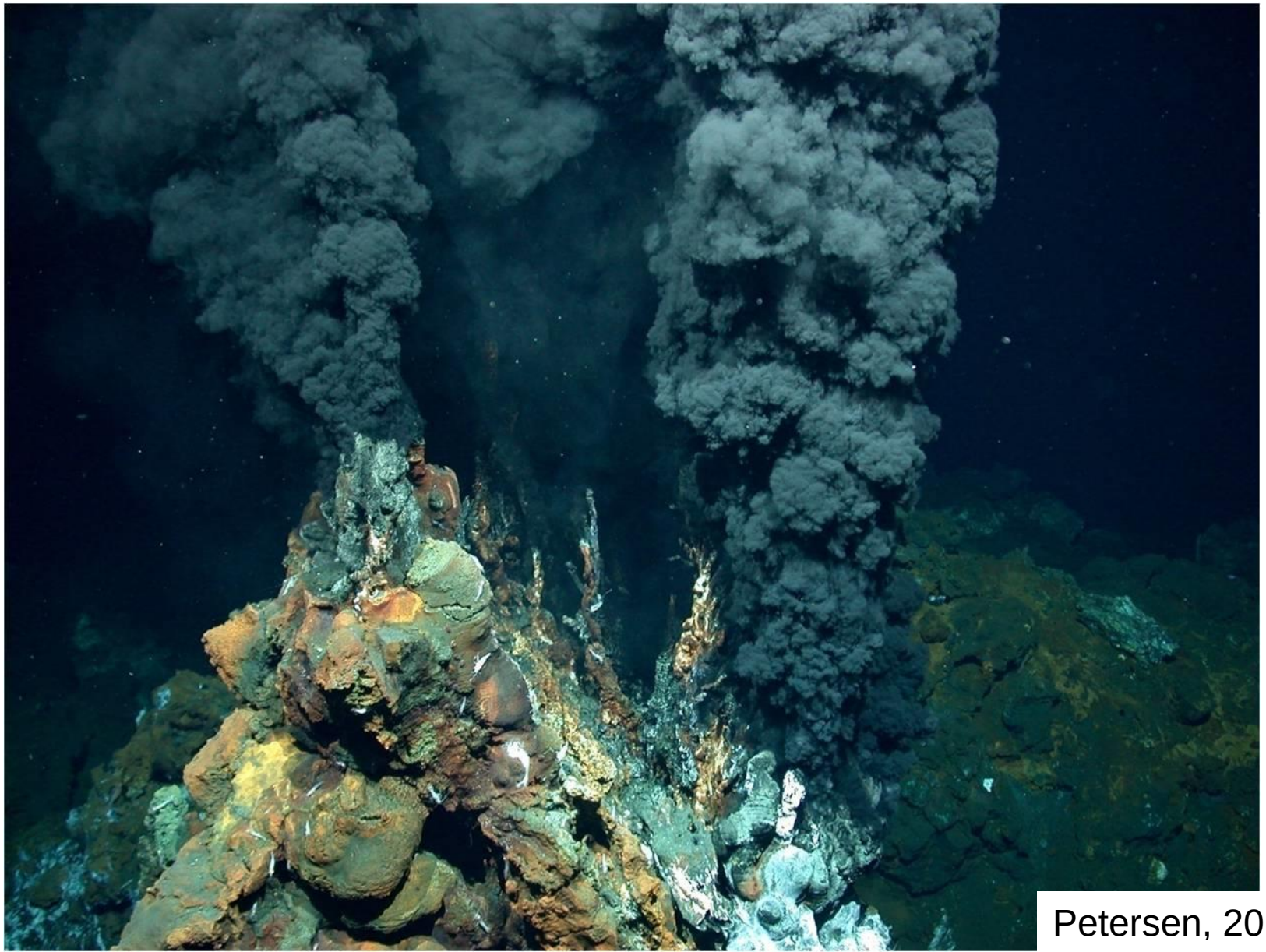
Formation of the oceanic hydrothermal system



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

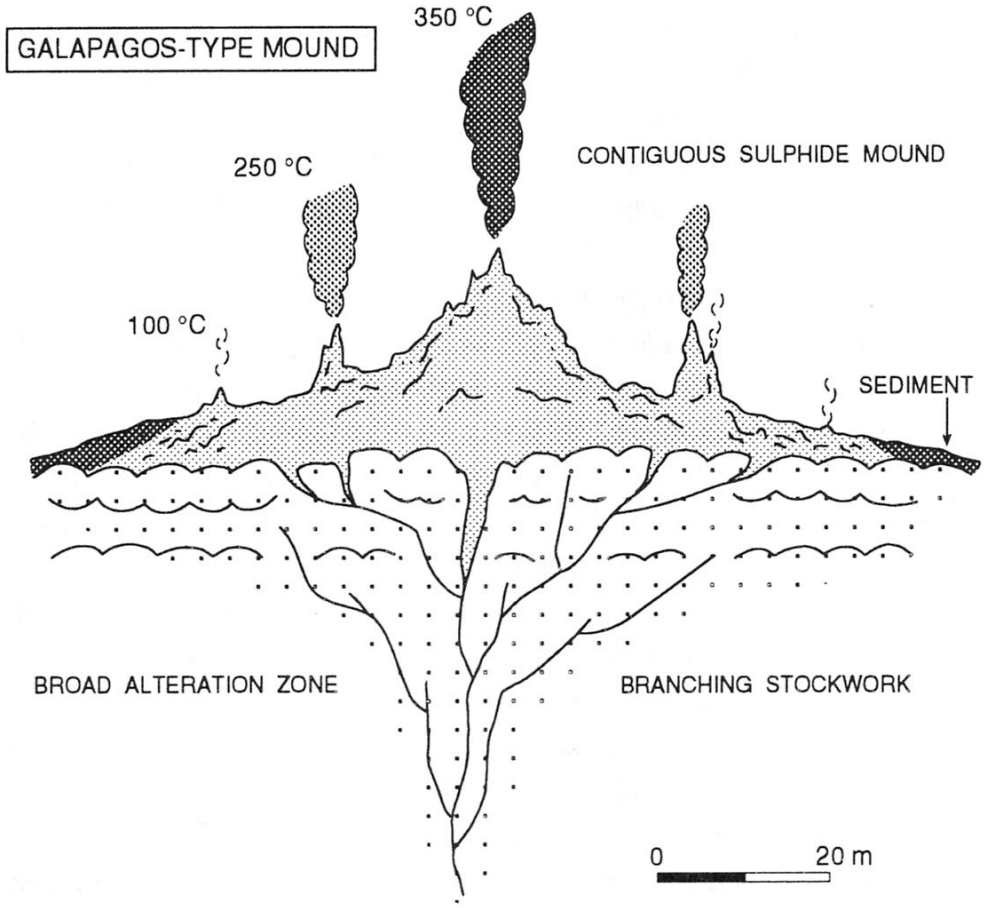
«Black smokers»

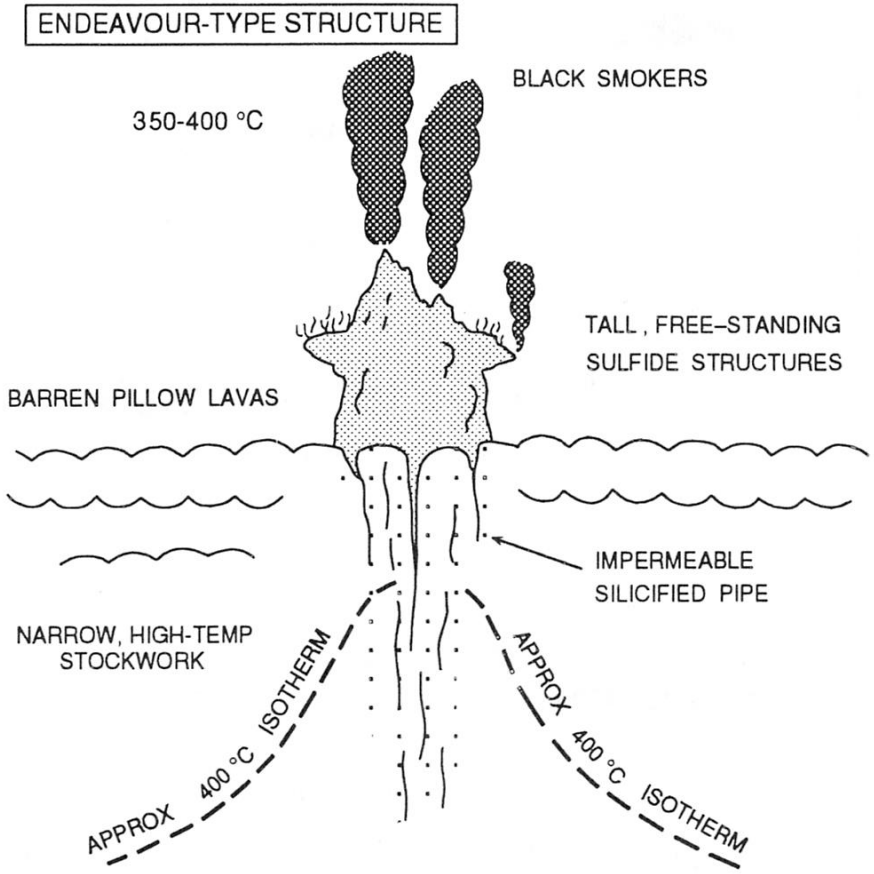
Hot(>350°C) metal-rich fluid discharging at the seabottom



Petersen, 2011

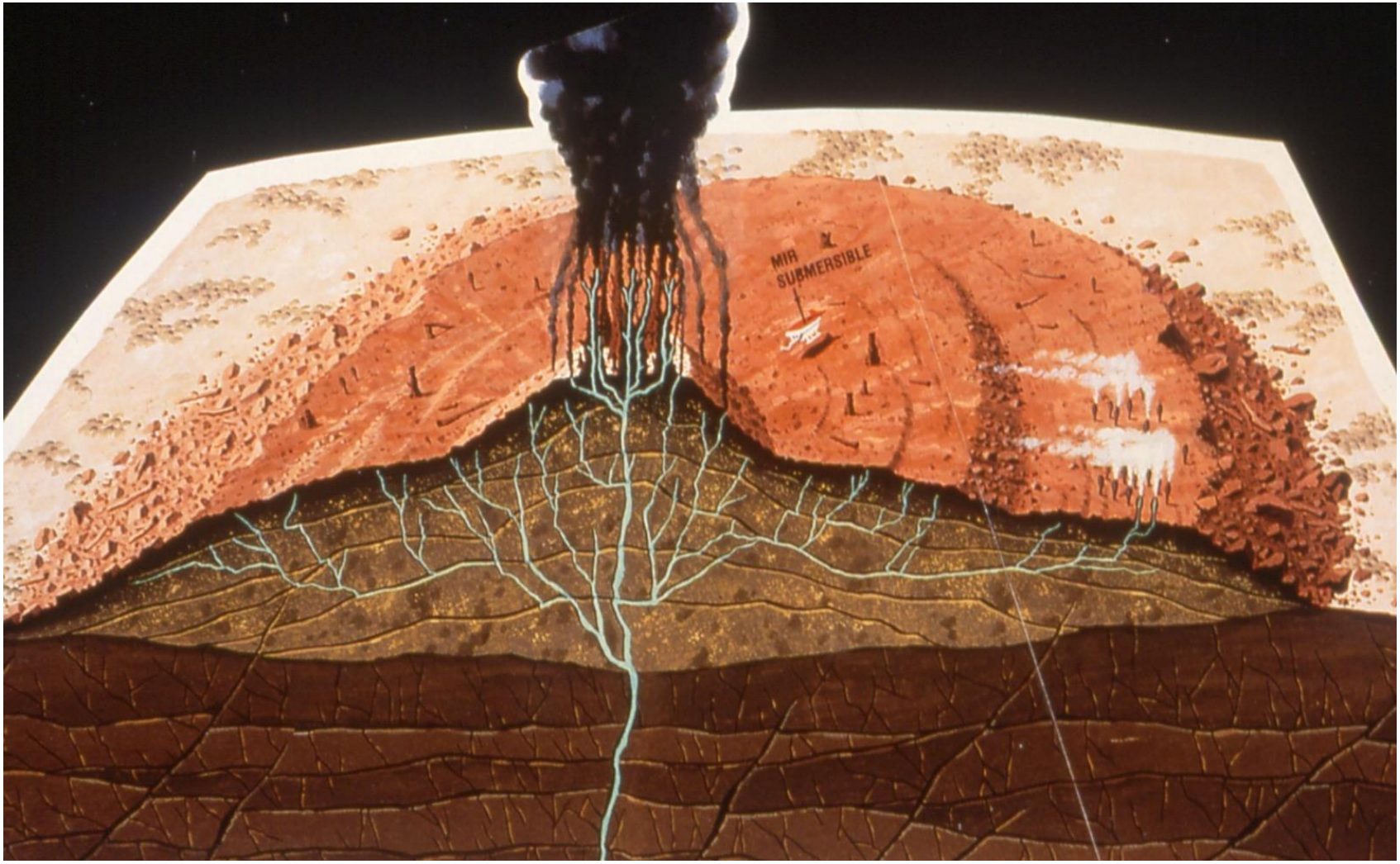
Seafloor Massive Sulfides (SMS) on the surface (typical)

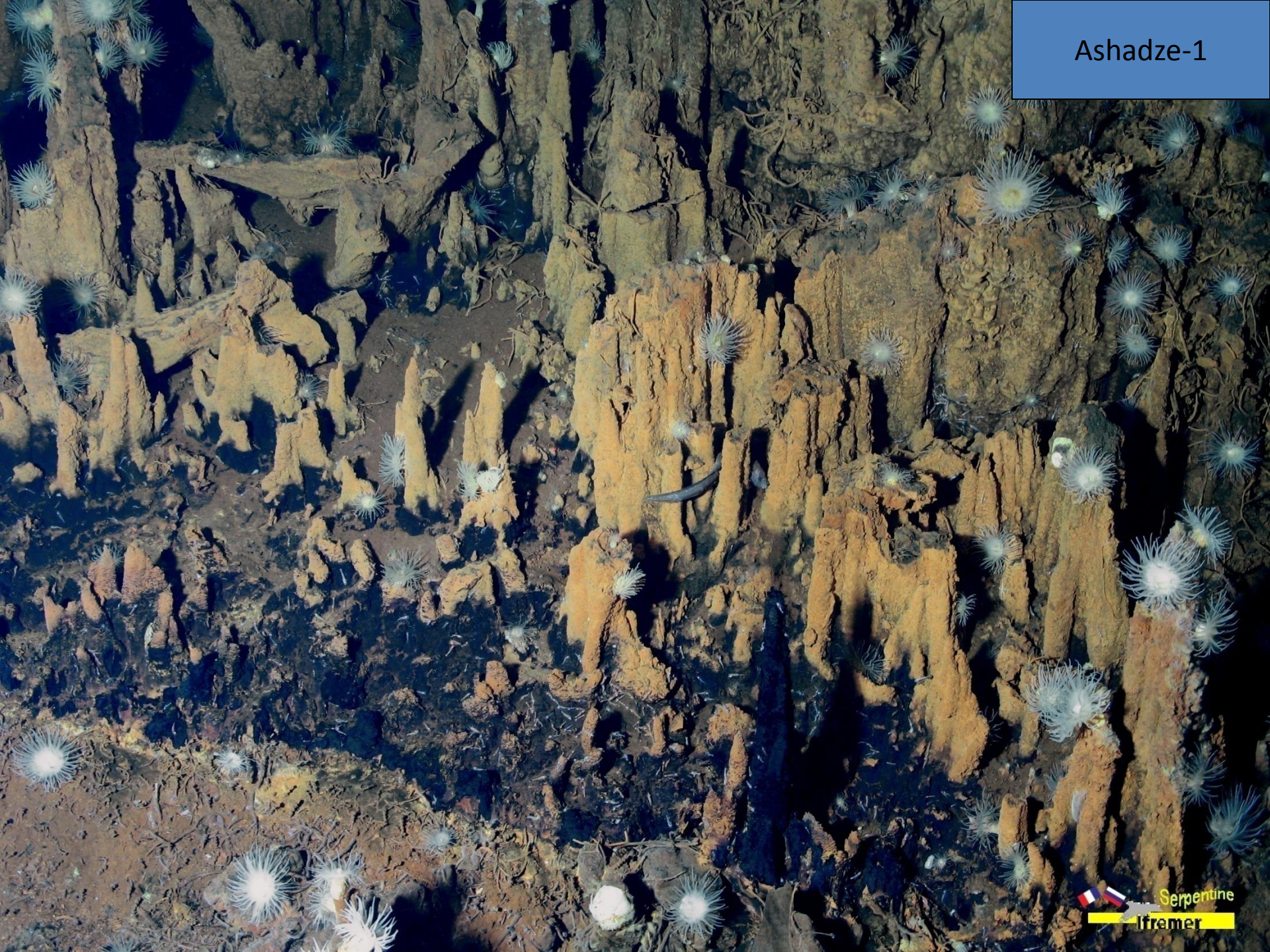




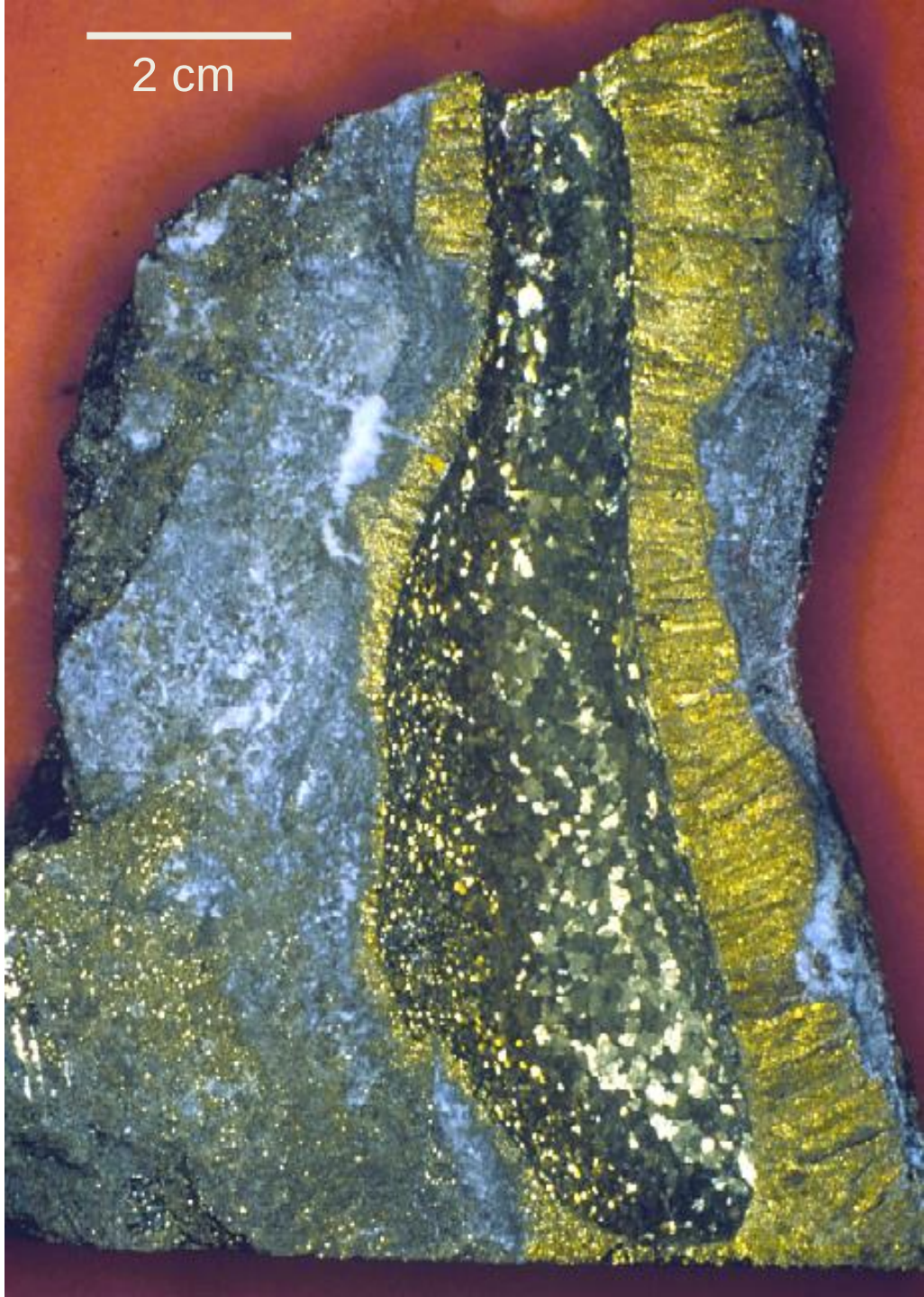
(from Hannington, Petersen et al., 1995)

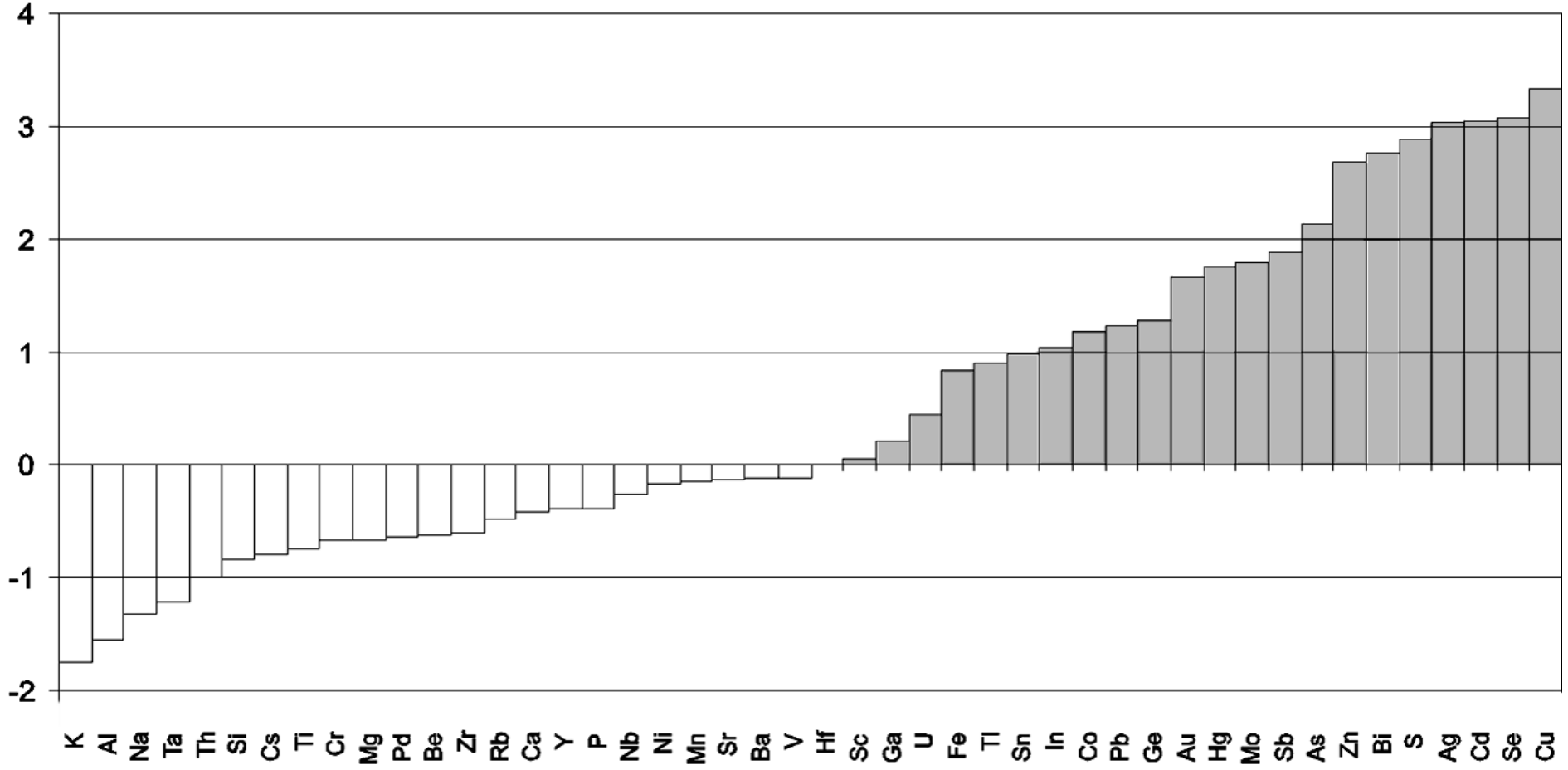
Active Mound, TAG field




Ashadze-1
Serpentine
Ifremer

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





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

Metals of economic interest in SMS

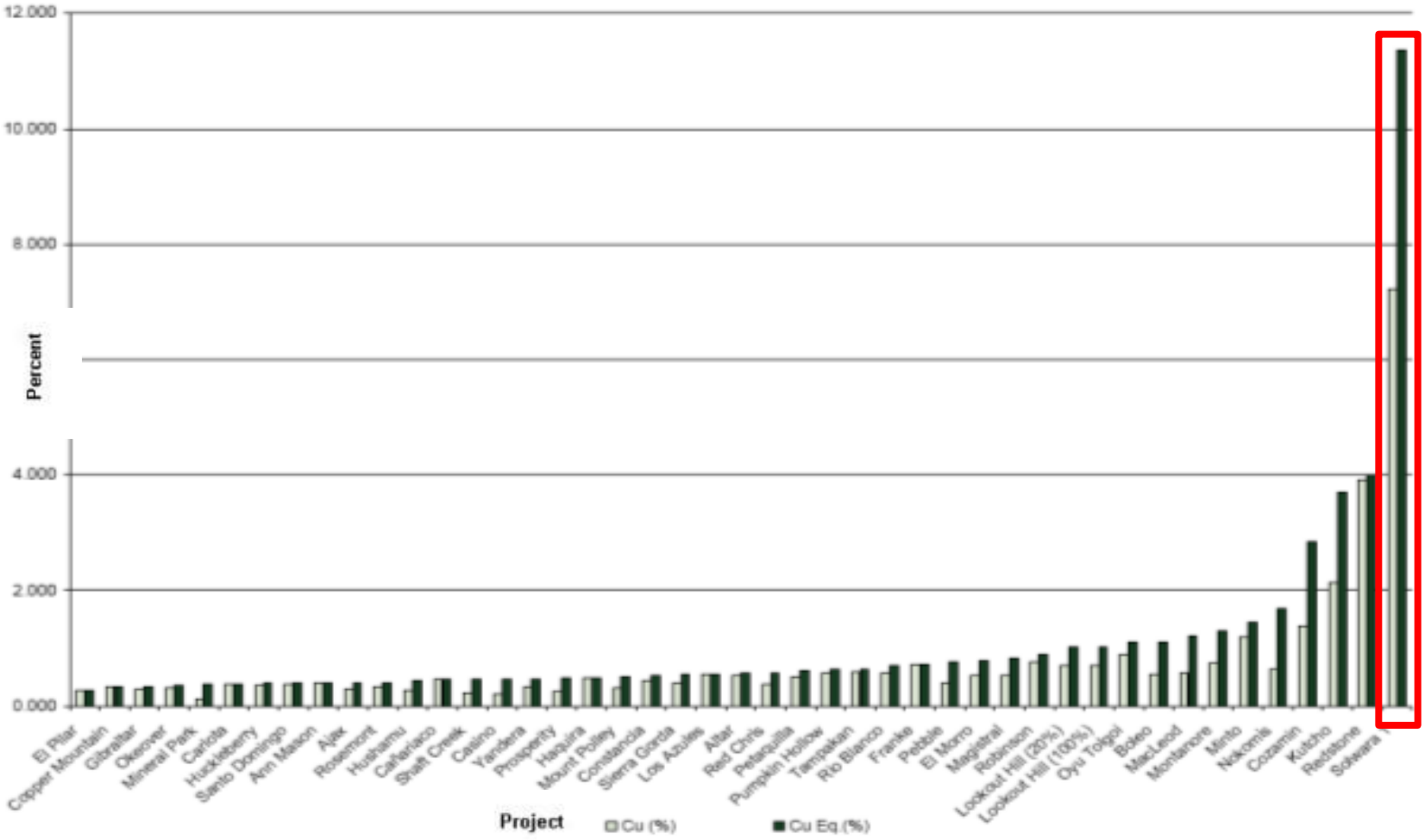
- Major

Cu, Zn, Au, Ag, (Pb)

- Rare

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

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

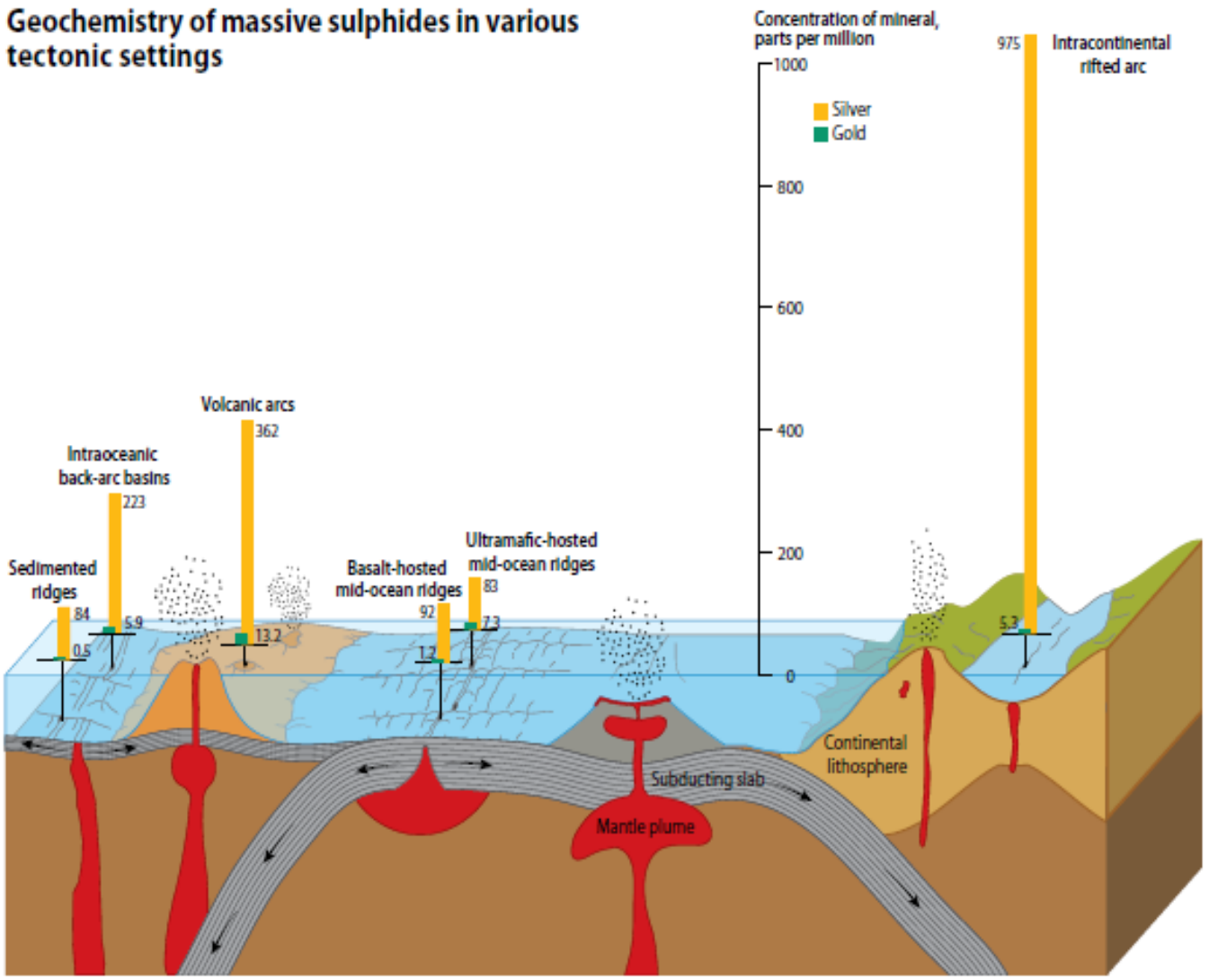


Figure 6. Concentrations of gold and silver in sea-floor massive sulphides formed in different geological settings (Source: GEOMAR)

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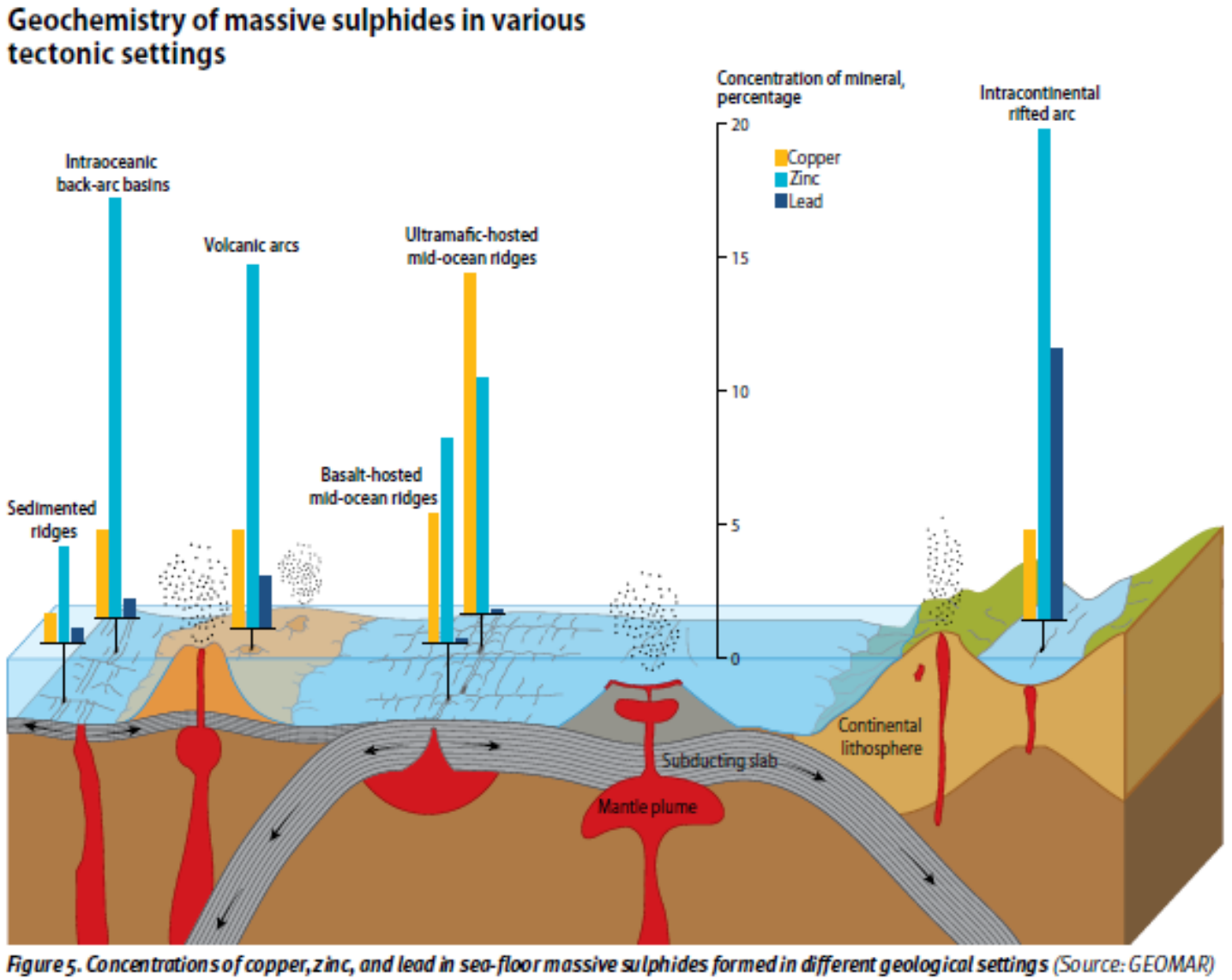

Figure 5. Concentrations of copper, zinc, and lead in sea-floor massive sulphides formed in different geological settings (Source: GEOMAR)

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Rare metals enriched in SMS using in Hi-tech and Green technologies

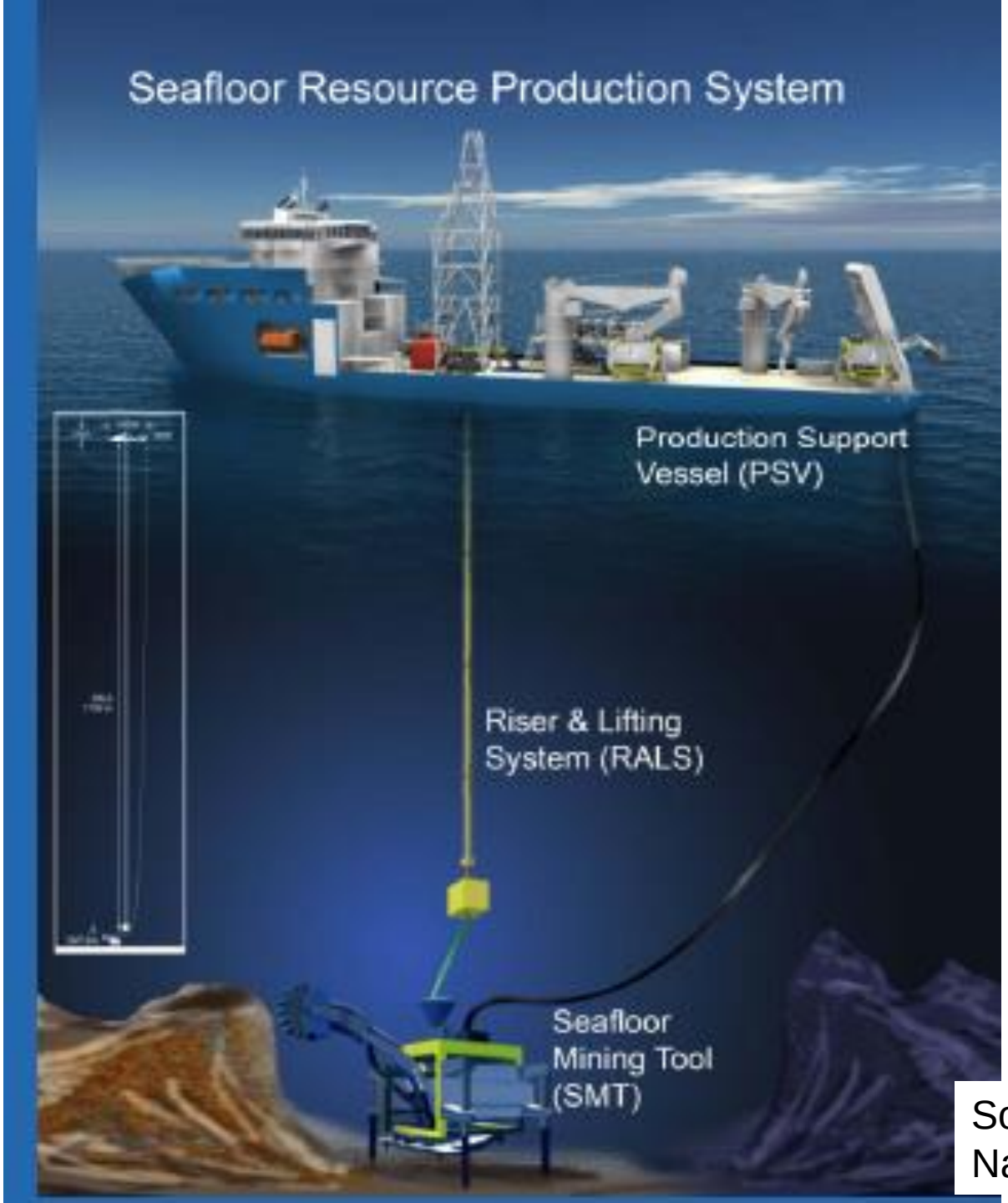
Mo, Ga, Ge, Co, Au

Se, Te, Cd, Bi, In

Exploration studies for SMS deposits

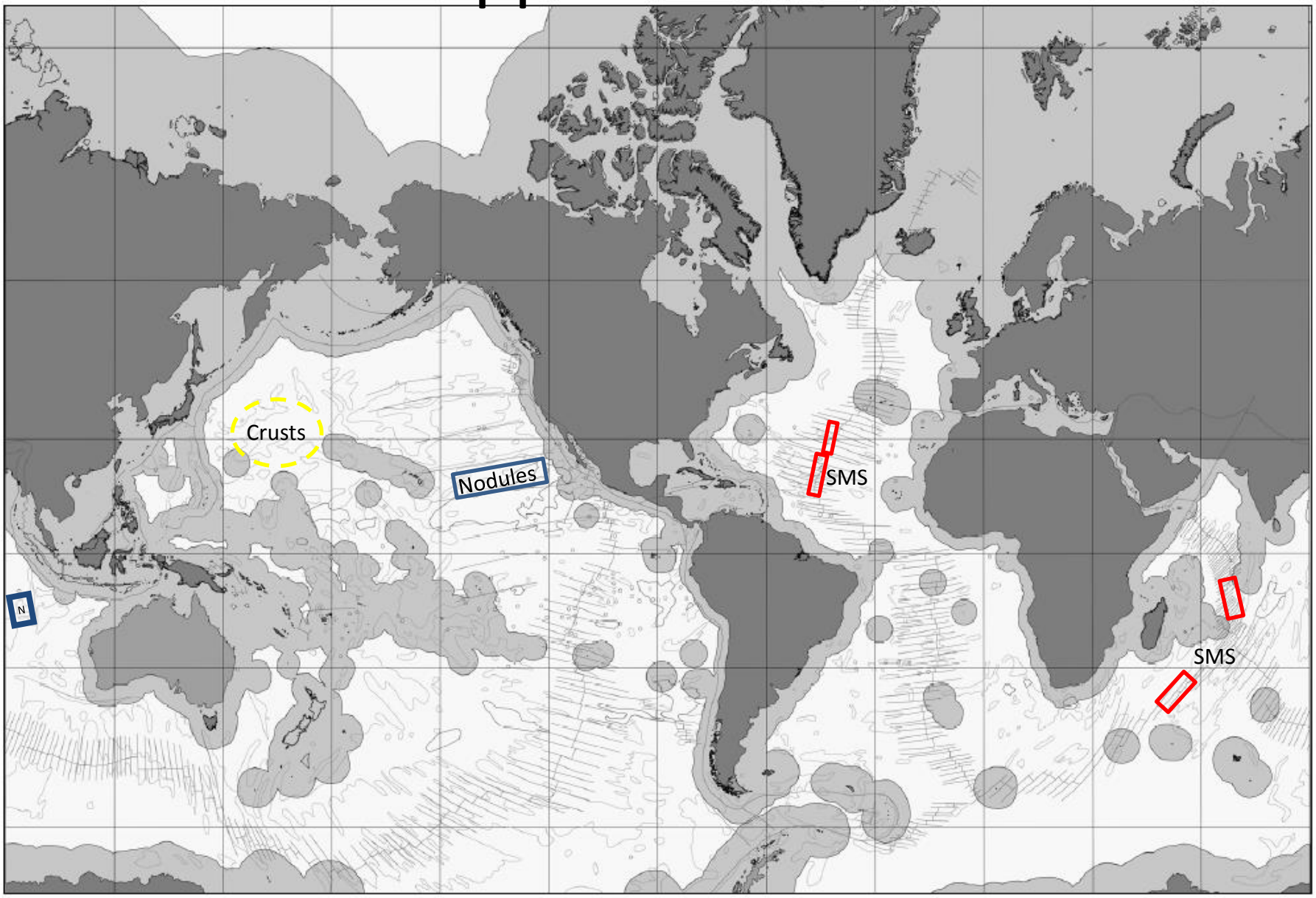
Exploration for sulfide deposits

- 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



Source:
Nautilus Minerals

Exclusive economic zones & application areas



Contractors/Apllicants with ISA

Contractors/Applicants	Nodules	Crusts	Massive Sulfides
China	2001	2012	**2011**
Russia	2001	2013 (A)	**2012**
Japan	2001	2012	
India	2001		**2013 (A)**
France	2001		**2012**
Korea	2001		**2012**
InterOceanMetal	2001		
Germany	2006		**2013 (A)**
United Kingdom	2012		
Belgium	2012		
Tonga	2012		
Kiribati	2012		
Nauru	2012		