Geological setting, distribution, potential resources and prospects for exploitation of SMS deposits

Georgy Cherkashov

VNIIOkeangeologia

St. Petersburg, Russia

Member of Legal and Technical Commission, International Seabed Authority

Outline

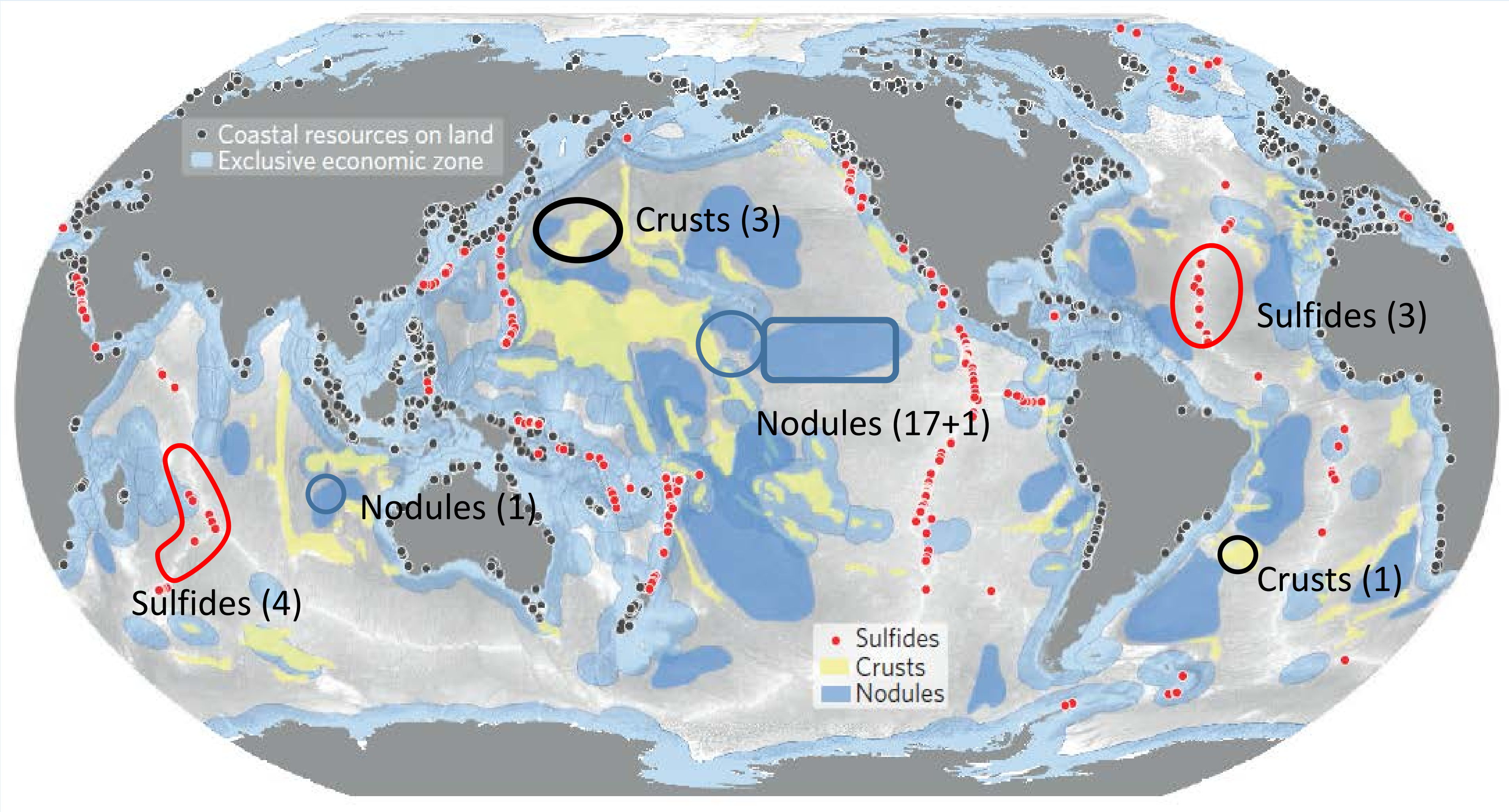
- Introduction
- Distribution of SMS deposits along Northern Mid-Atlantic Ridge
- Resource estimation of SMS deposits
- Prospects for exploitation
- Conclusions

Introduction

Key geological parameters for the setting of SMS deposits and environmental characteristics at the Mid-Ocean Ridges

- Water depth
- Bathymetry/bottom relief, slopes degree/mass wasting prosecces (landslides)
- Spreading rate and type of accretion: symmetrical or asymmetrical
- Type of hosted rocks: sediments/basalts/ultramafics
- Sedimentation rate
- Intensity of tectonic, volcanic and hydrothermal processes

Global distribution of seabed minerals and areas under contract with ISA



Hannington et al, 2017 with add.

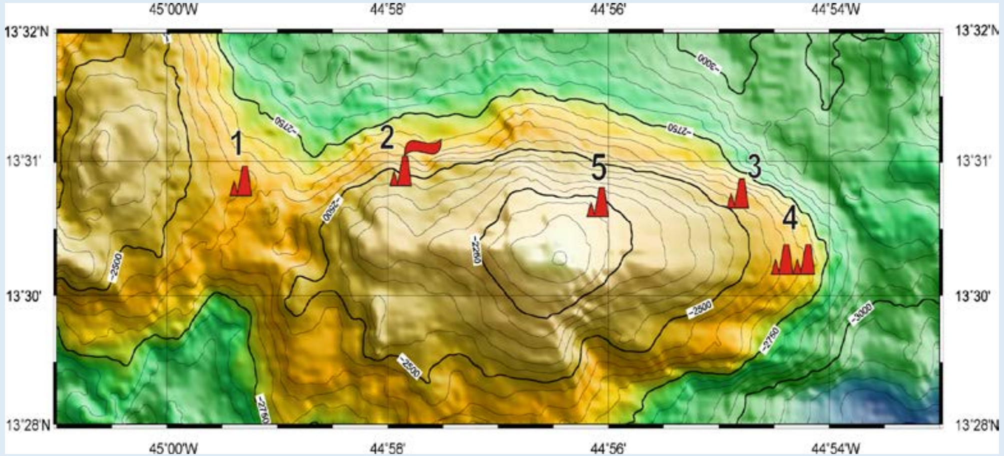
Geological setting, major/minor components and global resources of deep-sea mineral deposits

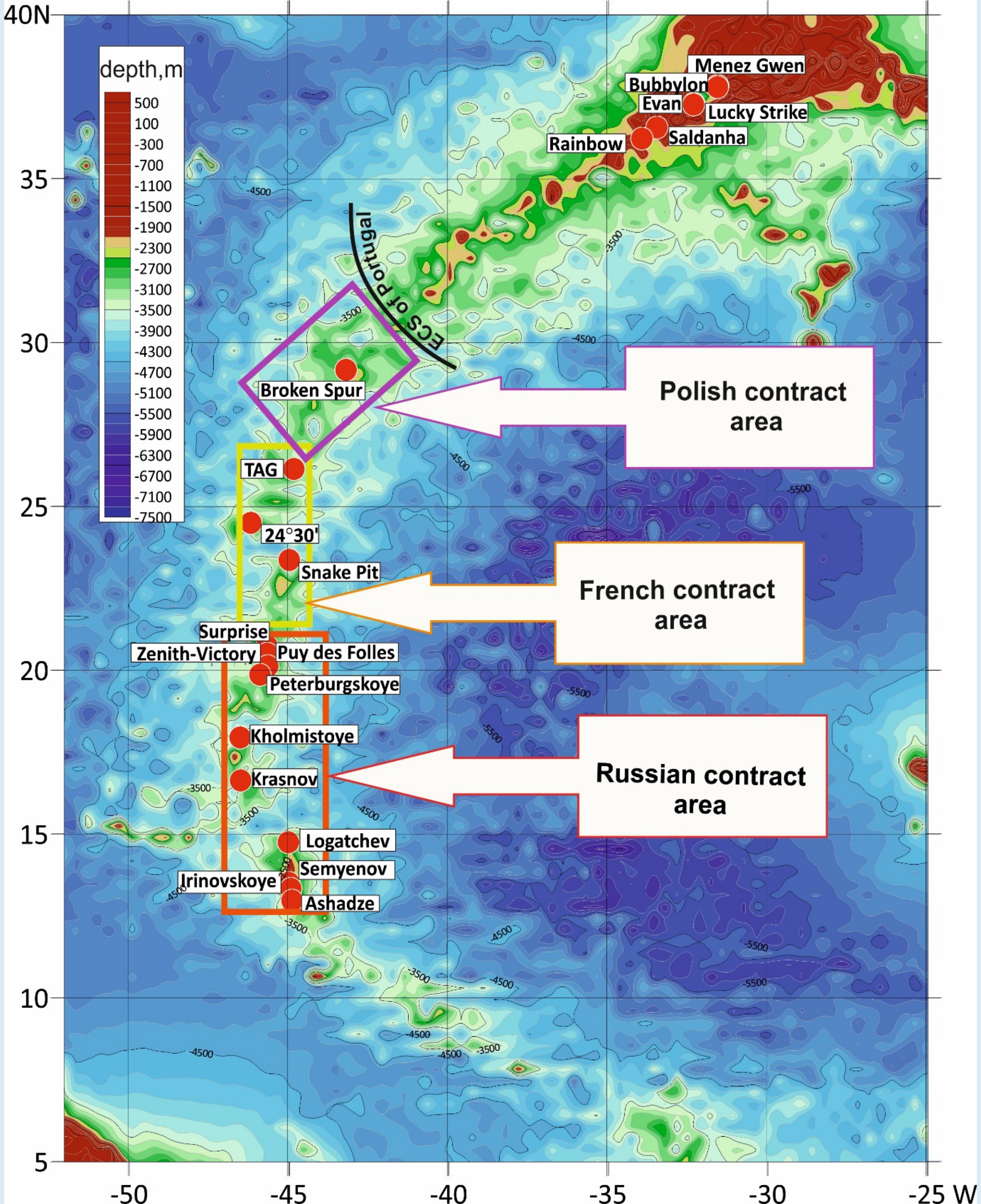
	Nodules	Crusts	SMS
Geological setting	Abyssal basins	Seamounts	**Mid-ocean ridges Island arc systems**
Major components	Mn, Ni, Co, Cu	Co, Mn, Cu, (REE)	**Cu, Zn, Pb, Au, Ag**
Minor components/ Byproducts	Mo, Li, REE, Tl, Zr, Ti, Ge	Te, Mo, Bi, W, Ti, Pt, V, Nb, Y	**Se, Te, Ge, Bi, As, Cd, Ga, Tl, In**
Grade distribution	Homogeneous on regional scale	Homogeneous on regional scale	**Very heterogeneous on regional and local scale**
Global resources, mln t (Reference)	38 900 (Sergeev et al., 2017)	35 100 (Halbach et al., 2017)	**4 000**
Resources in "Prime zones", mln t (Reference)	21 100 (CCZ) (Hein et al., 2013)	7 533 (NPPCZ) (Hein et al., 2013)	**300 (NAEZ)**

CCZ – Clarion-Clipperton Zone
NPPCZ – North Pacific Prime Crust Zone
NAEZ – North Atlantic Equatorial Zone

Distribution of SMS deposits along Northern Mid-Atlantic Ridge

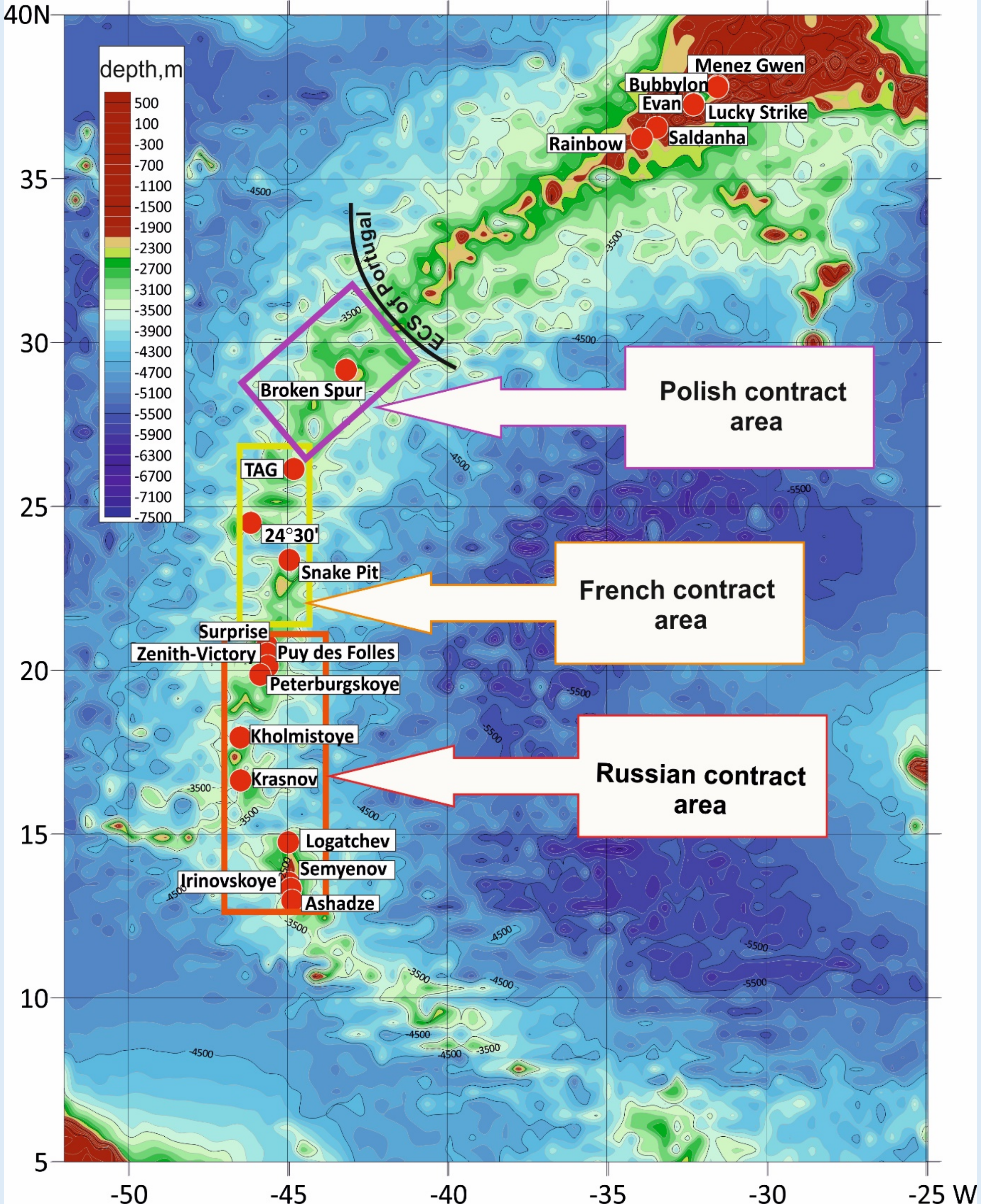
- 20 seafloor massive sulfide sites are currently detected between Azores and 13°N
- Distance between separate sites considerably variable (from 10 to 100 km and more): uneven distribution
- Clustering of mounds/fields are typical for the SMS deposits





Distribution of SMS deposits along Northern Mid-Atlantic Ridge: <u>Uncertainties</u>

- There were no systematic studies of hydrothermal vents/SMS distribution along MAR before 2011 when the Regulations of SMS exploration were issued
- All sites to the North from 21°N were discovered ”by chance” before 2000
- There were very few detailed (polygon) studies (TAG, Logatchev, Lucky Strike)
- All known sites is ~ 20-30% from predicted which are remained to be discovered (Beaulieu et al., 2015)

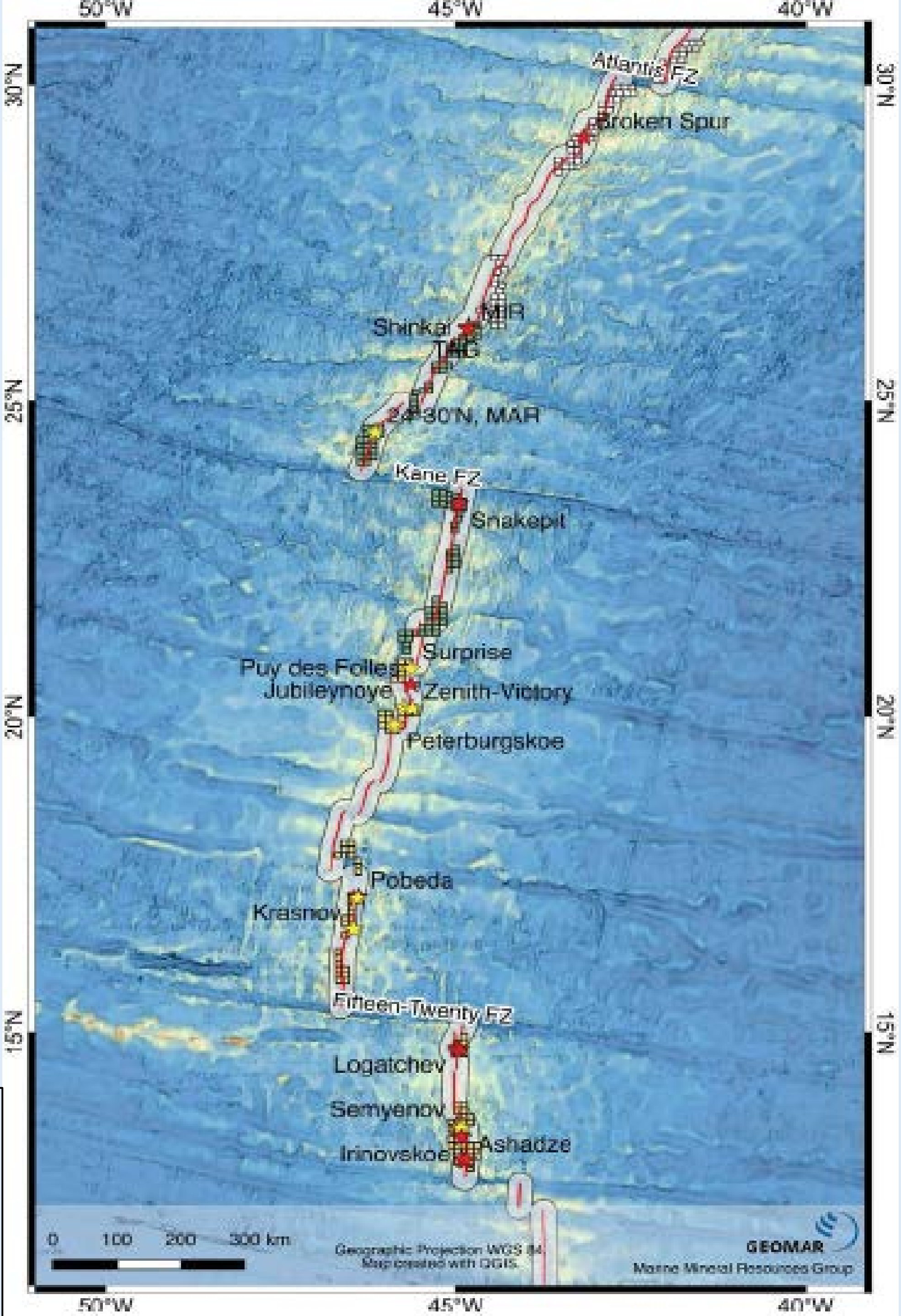


Distribution of SMS deposits and exploration blocks along Northern Mid-Atlantic Ridge

Map showing a 20-km corridor in the central Atlantic

Status of Contract Exploration Programs:

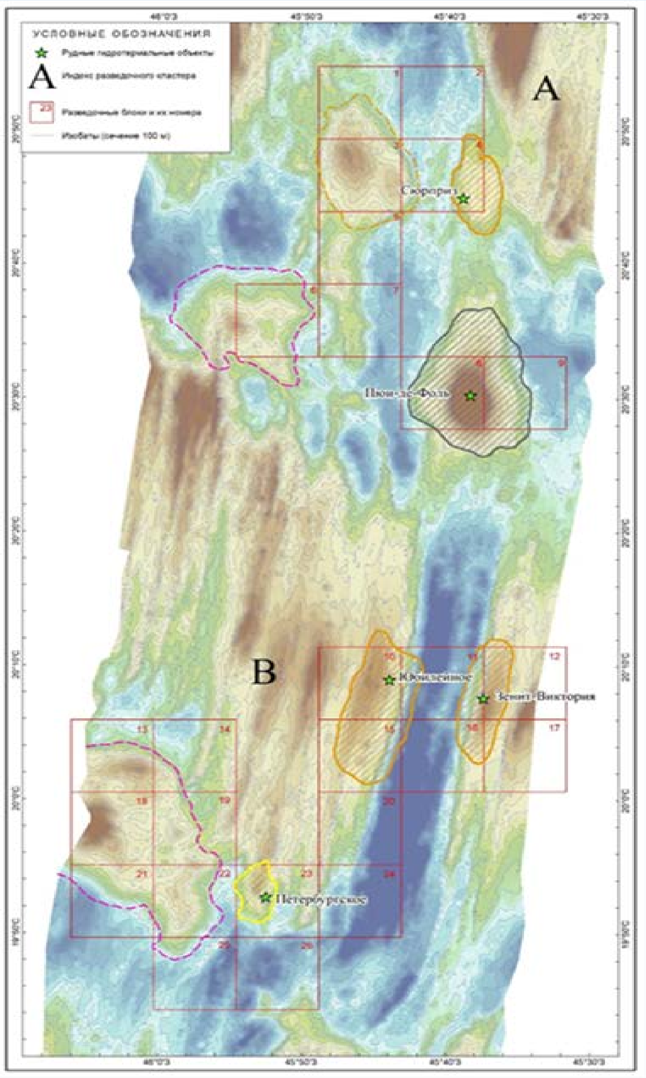
- Polish exploration program is not started yet
- There is very limited data for French Exploration Area (FEA): ~ 20 targets (plumes) within FEA were detected (E.Pelletier, 2018)
- Russian exploration program is far from the end
- Relinguishment procedure is coming!

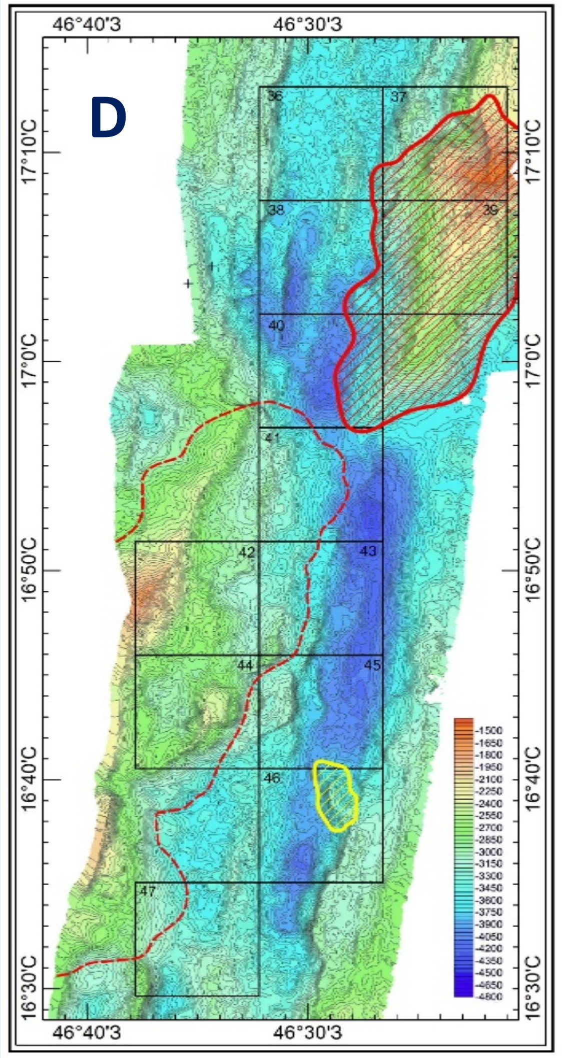


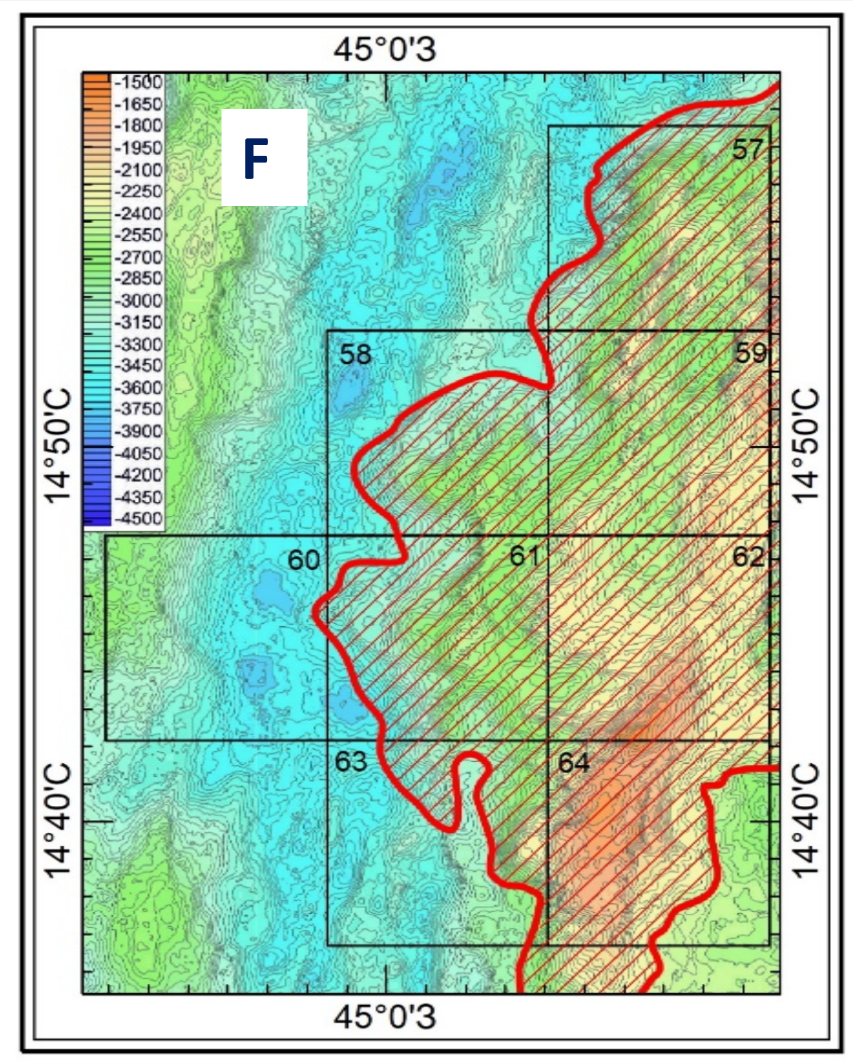
Current exploration contract blocks for Russia (green), France (yellow), and Poland (white).
The locations of known active (red stars) and inactive vent fields (yellows stars).

Petersen et al. 2017

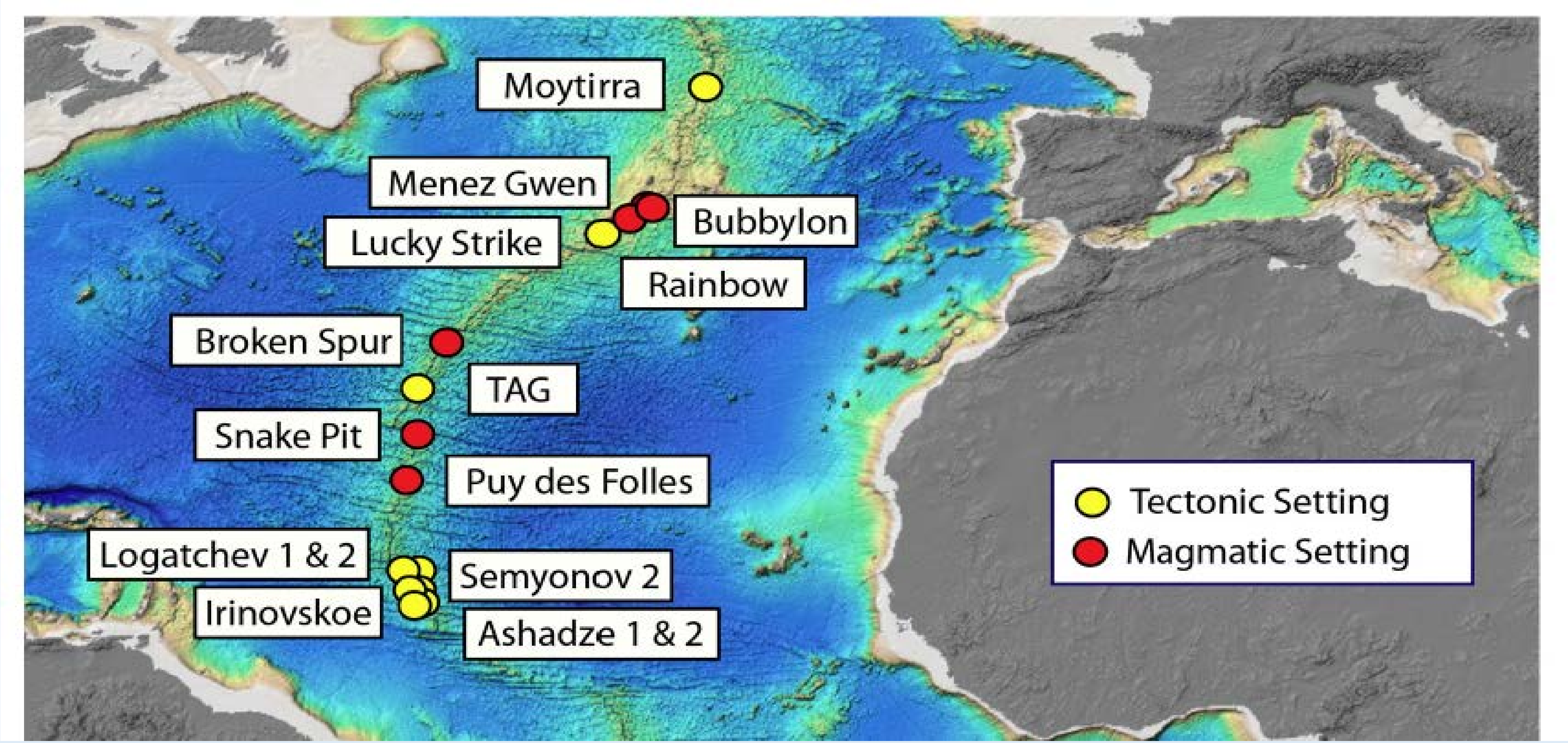
Project of the first relinquishment for contract area at the MAR







Distribution of two types of SMS deposits along the Mid-Atlantic Ridge



German et al., 2016

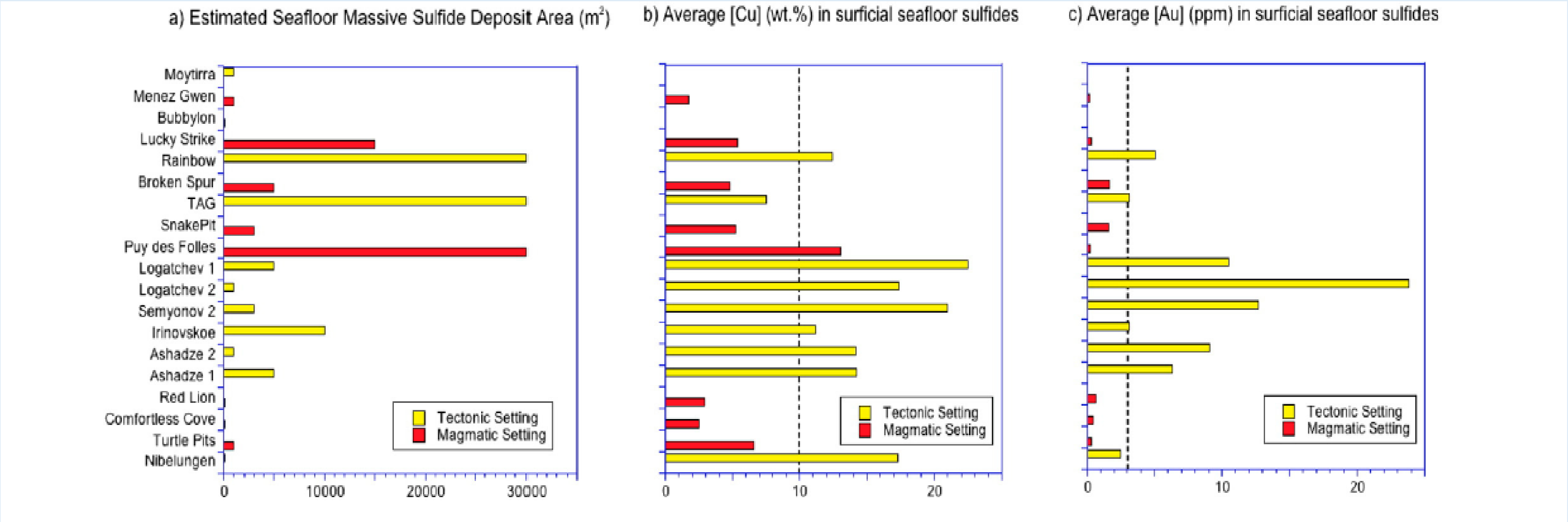
Characteristics of SMS deposits at the Northern Equatorial MAR

			Water depth, m		Area, m^2	Cu,%	Zn,%
Menez Gwen	37°50′N	31°31′W	830	Magmatic	<1,000	1.75	0.13
Bubbylon	37°48′N	31°32′W	1000	Magmatic	<100	tbd	tbd
Lucky Strike	37°17′N	32°16′W	1700	Magmatic	≥15,000	5.37	0.30
Rainbow	36°14′N	33°54′W	2300	Tectonic	30,000	12.43	5.10
Broken Spur	29°10′N	43°10′W	3100	Magmatic	5,000	4.78	1.64
TAG	26°08′N	44°49′W	3670	Tectonic	30,000	7.51	3.15
Snake Pit	23°22′N	44°57′W	3490	Magmatic	3,000	5.18	1.58
Puy des Folles	20°30′N	45°39′W	1960	Magmatic	30,000	13.07	0.23
Logatchev 1	14°45′N	44°58′W	2990	Tectonic	5,000	22.51	10.47
Logatchev 2	14°43′N	44°56′W	2700	Tectonic	1,000	17.39	23.80
Semyonov 2	13°31′N	44°58′W	2420	Tectonic	3,000	21.00	12.71
Irinovskoe	13°20′N	44°54′W	2770	Tectonic	10,000	11.20	3.14
Ashadze 2	12°59′N	44°54′W	3260	Tectonic	1,000	14.14	9.10
Ashadze 1	12°58′N	44°52′W	4088	Tectonic	5,000	14.21	6.30

Distance between deposits varies from tens to hundred km

German et al., 2016

Resources and grades of metals in SMS deposits in tectonic and magmatic setting

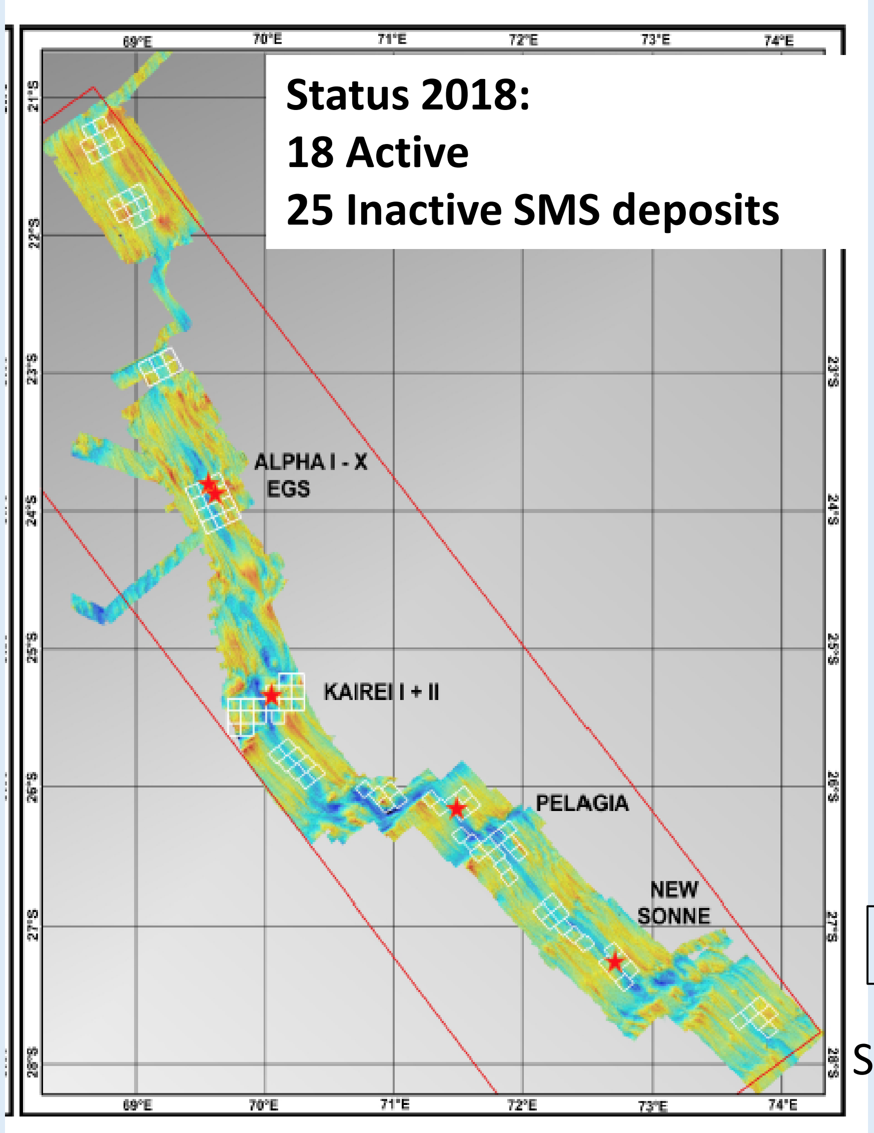


Ultramafic hosted/**tectonic** SMS deposits have much higher area and Cu&Au grades than basalt hosted/**magmatic** SMS deposits

German et al., 2016

Statistics of **SMS** deposits in the Atlantic and Indian oceans

Indian ocean, German Exploration Area



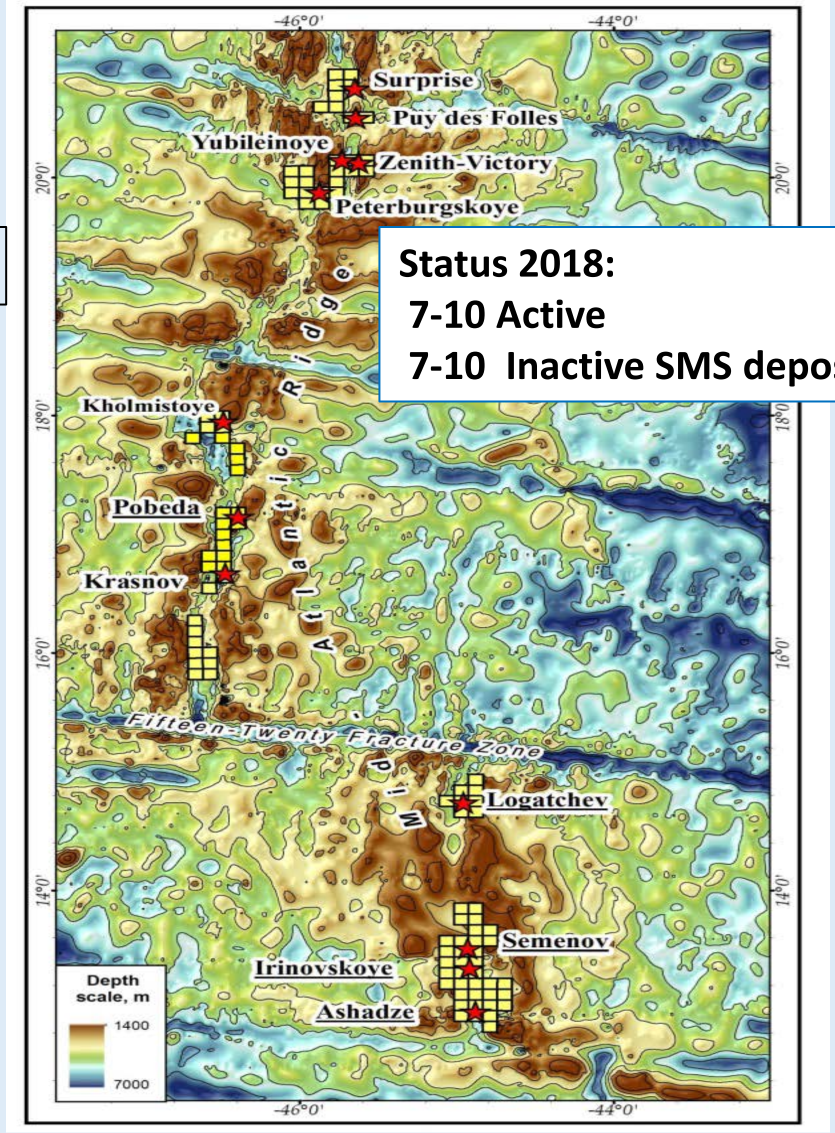
Status 2018:
18 Active
25 Inactive SMS deposits

No data

Schwarz-Schampera et al, 2018

Atlantic Ocean, Russian Exploration Area

~ 100 mln. t.

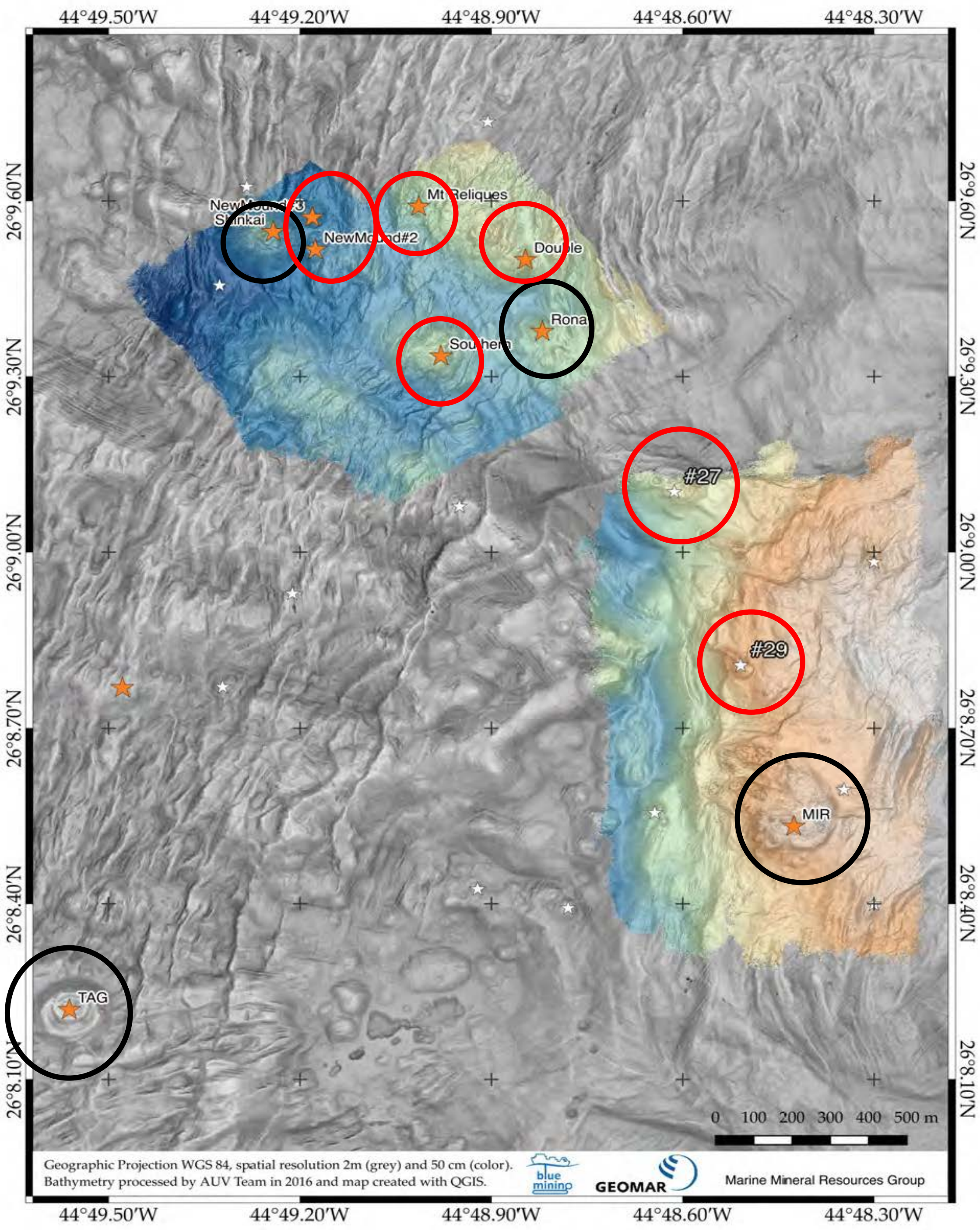


Status 2018:
7-10 Active
7-10 Inactive SMS deposits

<u>Resource estimation</u> depends on some factors:

1. Using of new technology and increase of exploration scale
2. Morphology of SMS deposits and continuation (or not) of the ore body/massive sulfides below “paleo-seafloor”
3. Amount of low-temperature/non-sulfide minerals within ore body
4. Zonality of ore body (including ”zone refining” results in enrichment of Cu and Zn in outer part of deposit and in diluting of Cu and Zn in inner part)

I. New technology: AUV with different sensors – high resolution echo-sounder, SP, magnetometer7



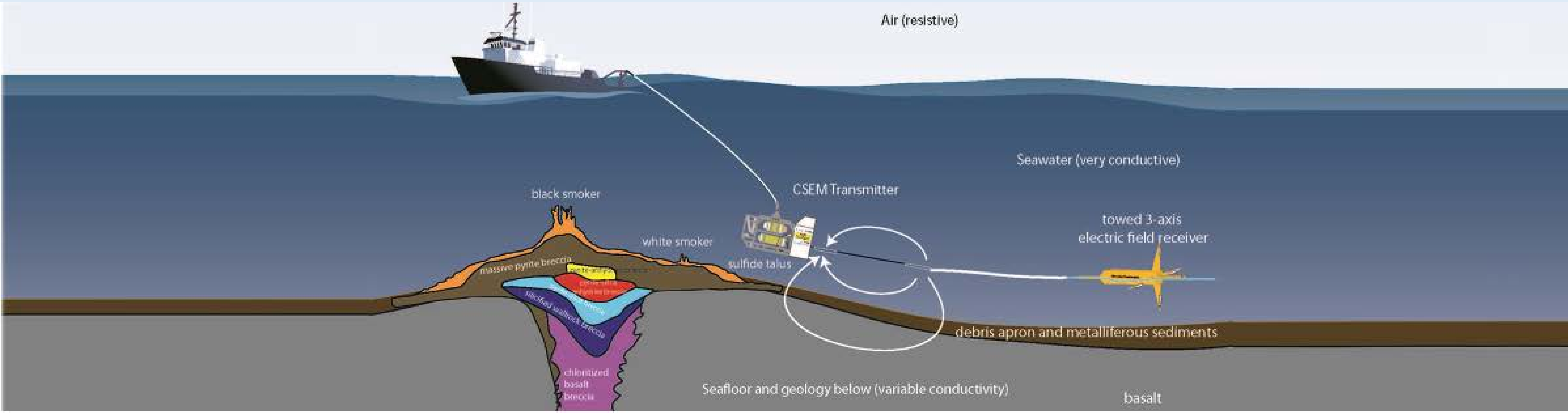
New technology: Results of detailed study using high-resolution AUV-based bathymetry at the TAG Area

7 new hydrothermal mounds have been discovered

Resources increased from 10 mln. t. to 75 mln.t.

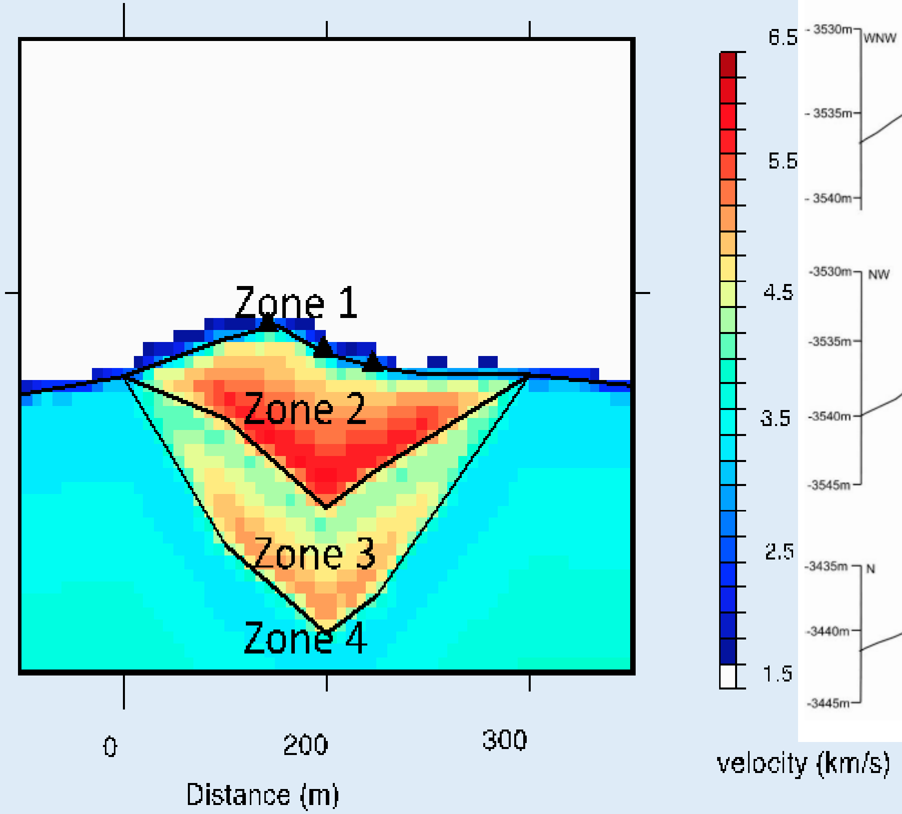
Blue Mining, 2018
Murton et al., 2018

Deep-towing system for detection of SMS deposit

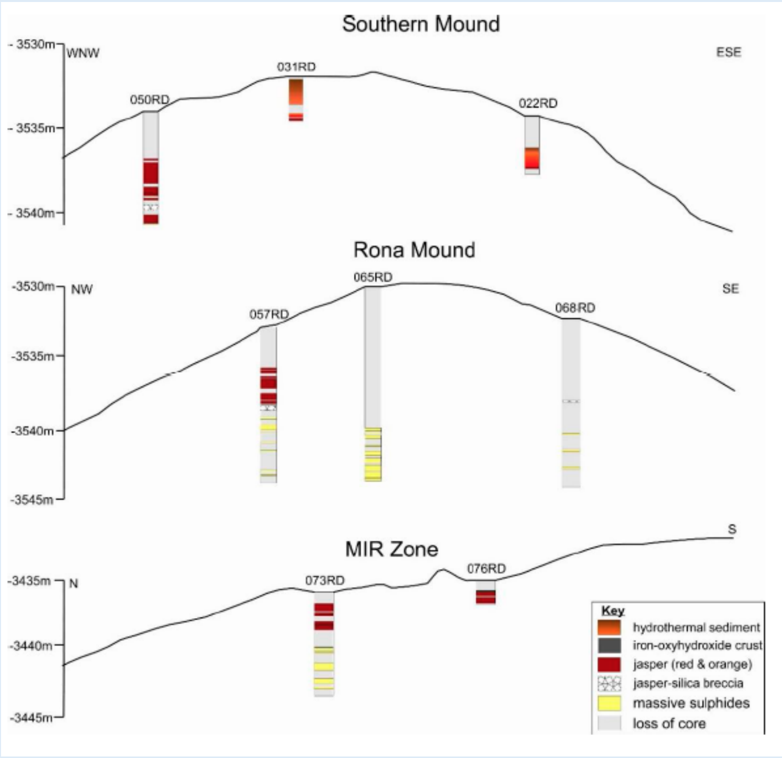


Comprehensive approach (with use seismic and conductivity) allows to propose increasing resource estimation in 3.7 times taking into account massive sulfides below paleo sea-floor

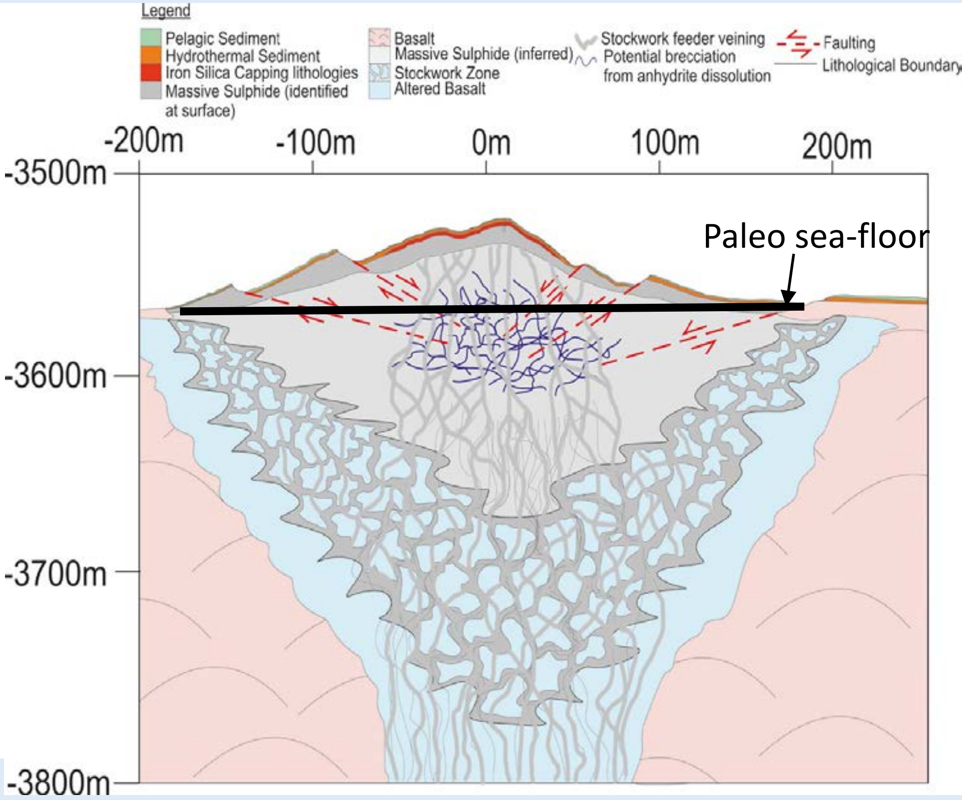
Seismic model



Drilling results



Model of hydrothermal mound



Increasing of resources due to account of SMS below paleo sea-floor

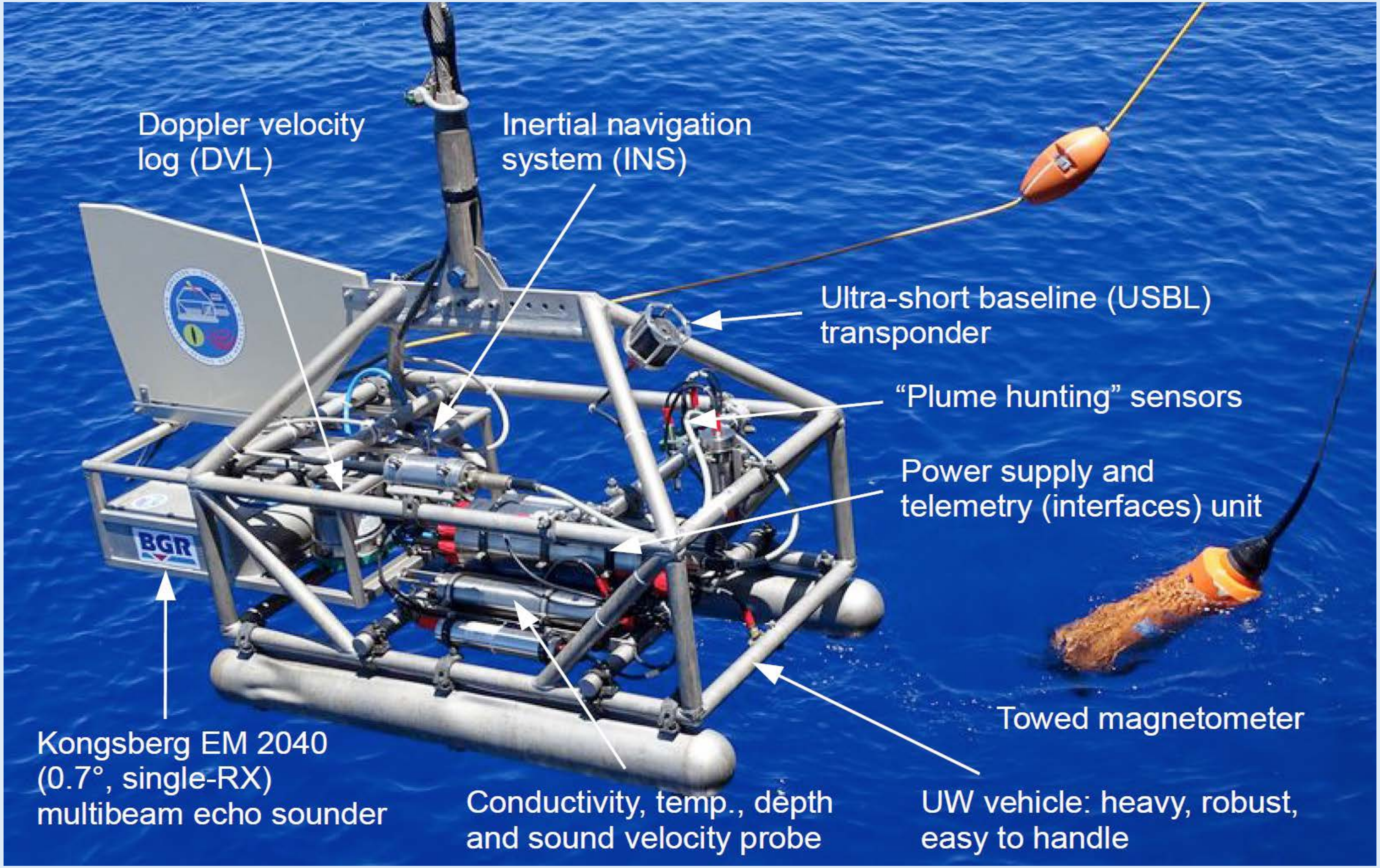
Blue Mining, 2018
Murton et al., 2018

Total resource estimation of TAG area increased up to 33 – 75 млn.t.

New technology: HOMESIDE underwater vehicle

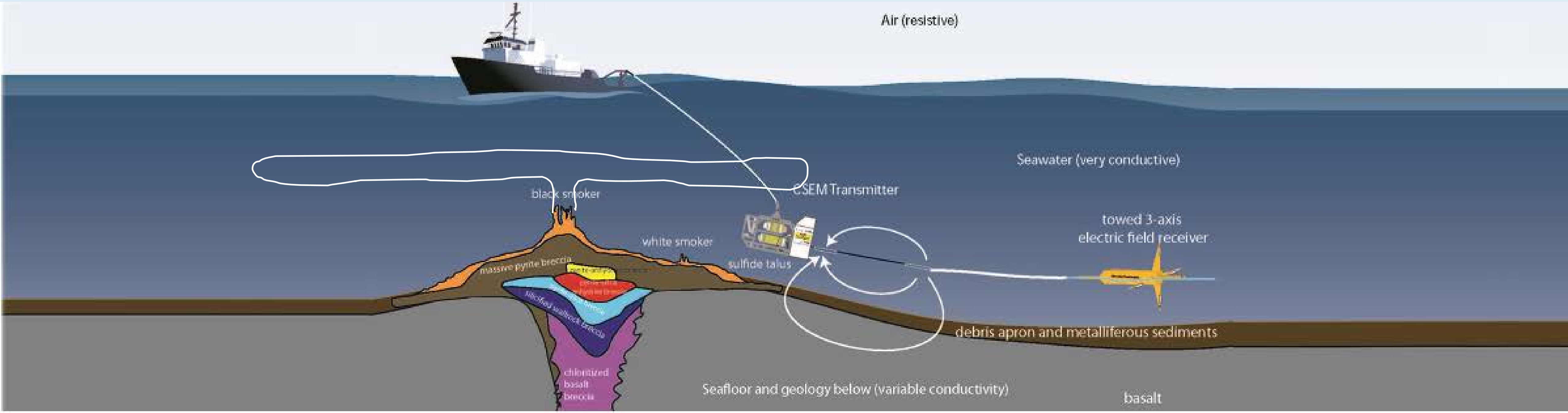
An Advanced Tool for Hydrothermal Plume Hunting and Polymetallic Sulphide Exploration

Combination of censors for detection of anomalies in water column (nephelometry) and at sea-floor (SP, magnetometry)



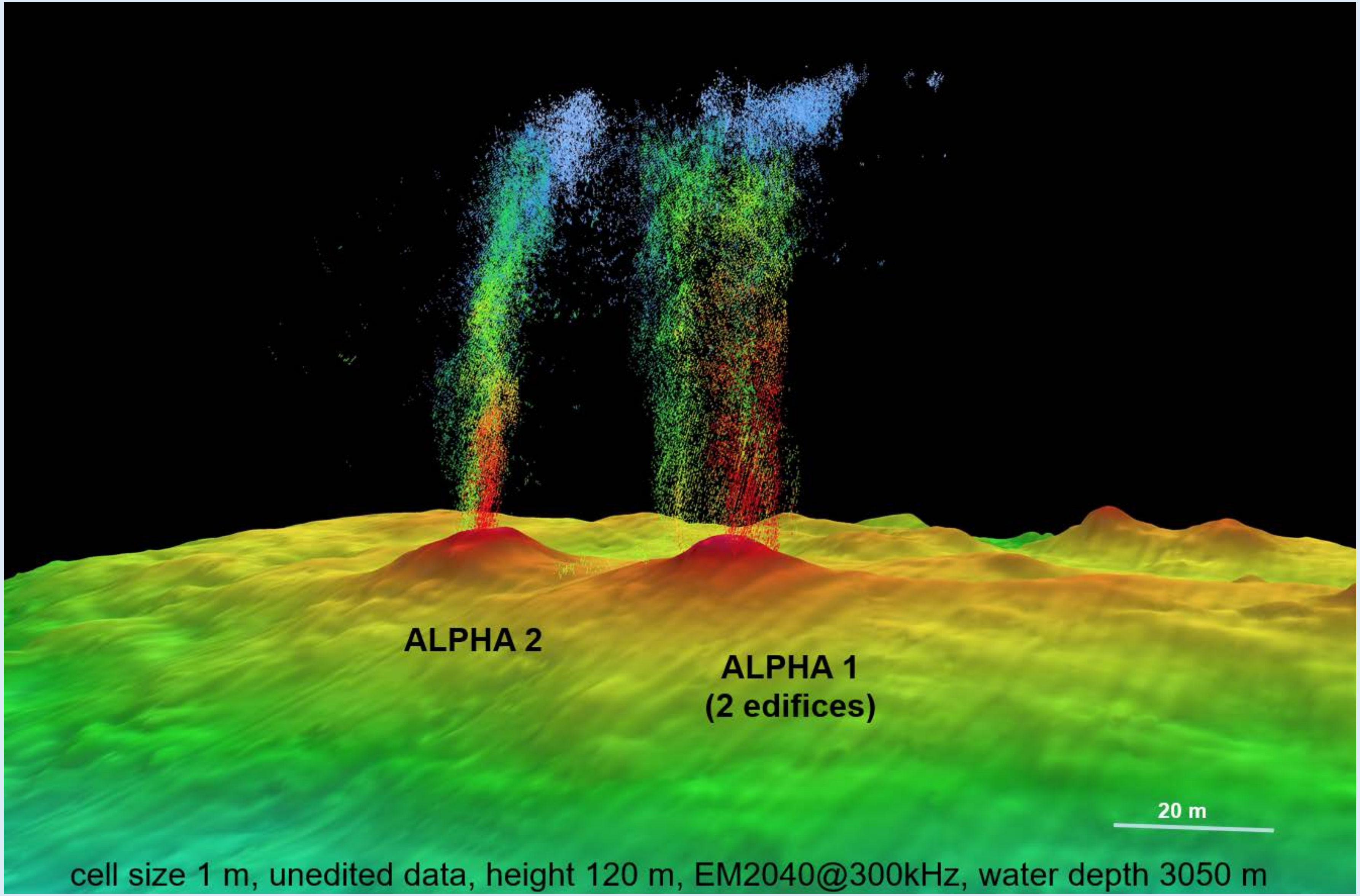
Freitag et al., 2019

Deep-towing system for detection of SMS deposit



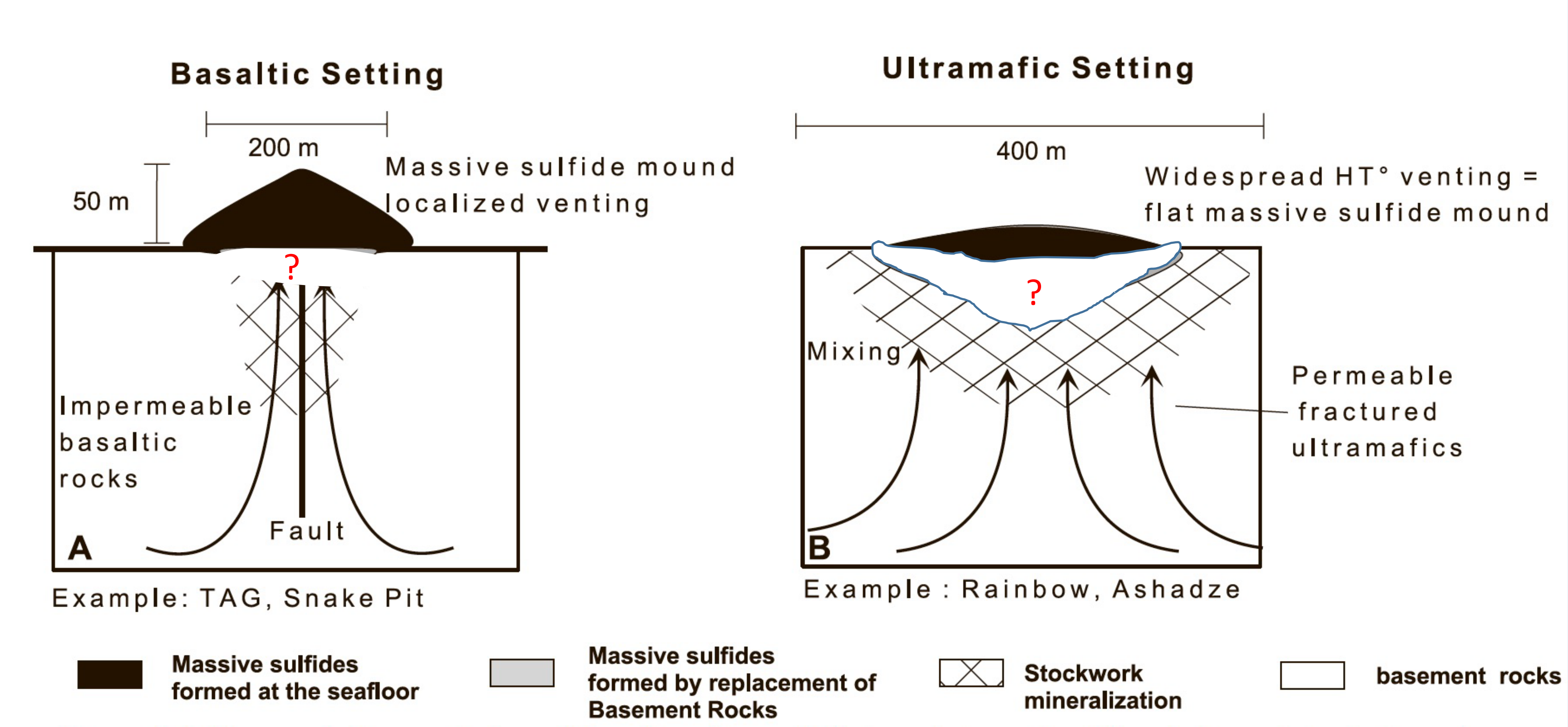
Blue mining project

Extracted water column reflections caused by a hydrothermal plume. The water column reflections are color-coded by attenuation and draped on a high-resolution bathymetry map (ALPHA area 2015 and 2017) (Freitag et al., 2019)



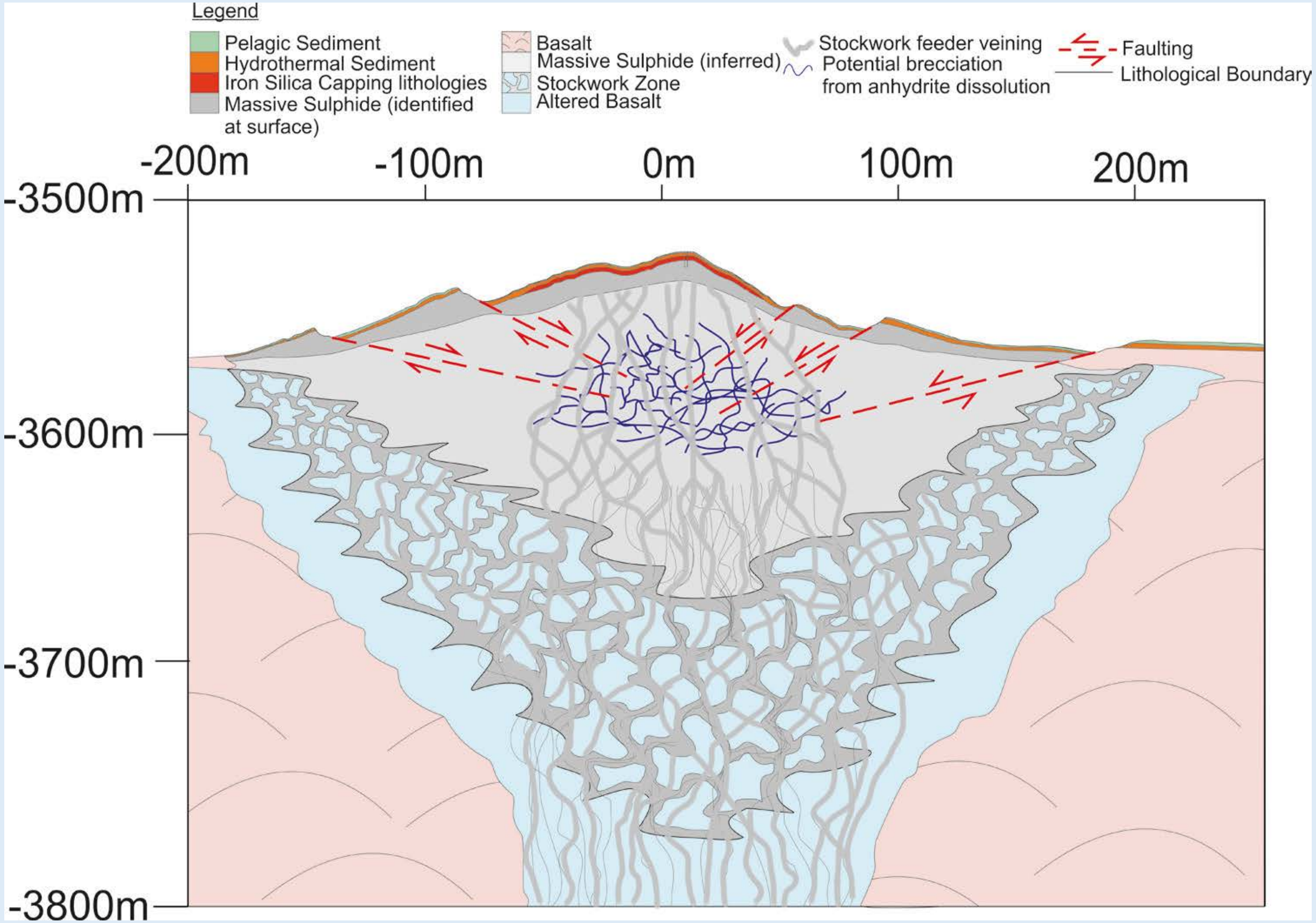
2. Differences in the **morphology of deposits** and type of discharge between basaltic and ultramafic hosted hydrothermal deposits.

Compared to (a) basaltic hosted fields, discharge is less focused in (b) ultramafic environments, where no real mound is formed



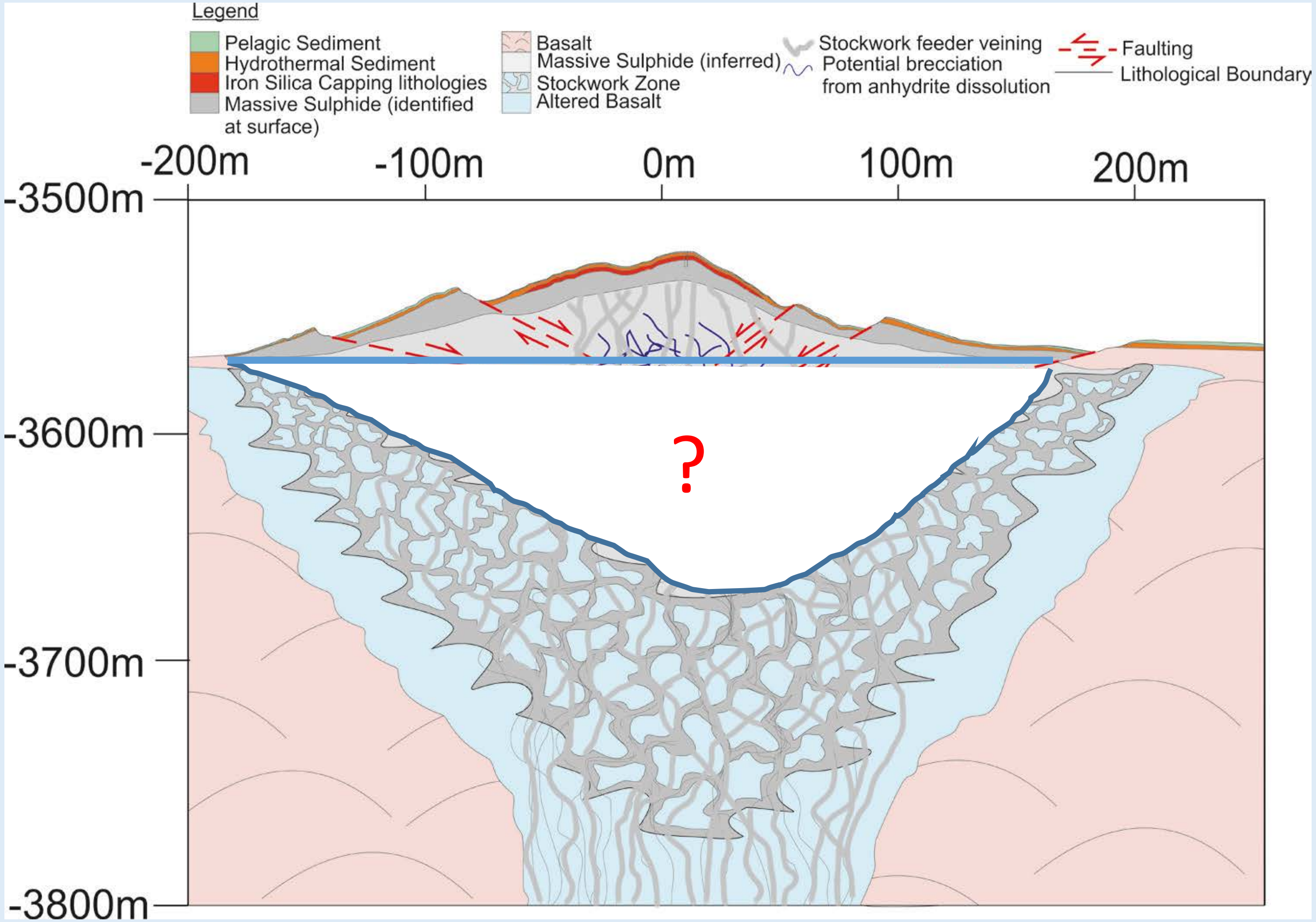
Fouquet et al., 2010

Model of increasing of resources due to account of SMS below sea floor (TAG)



Blue Mining, 2018
Murton et al., 2018

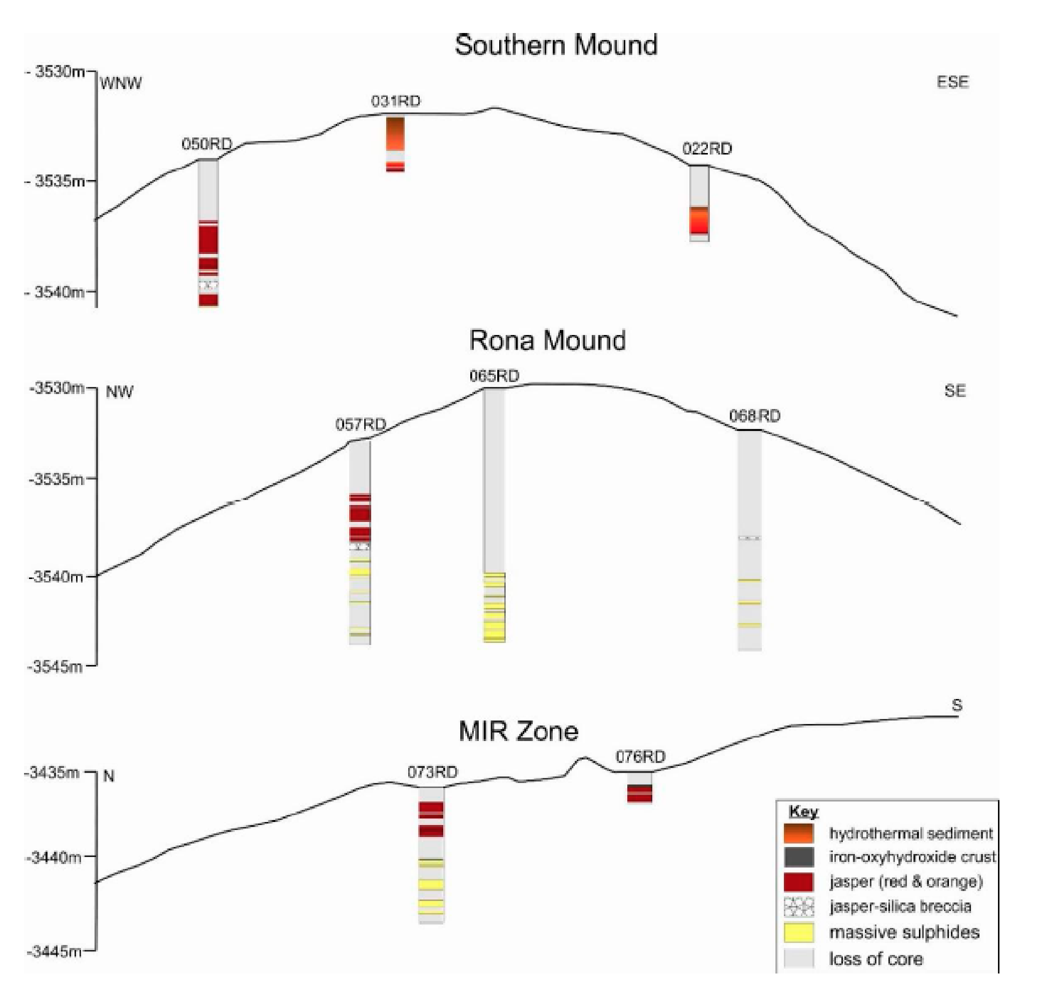
Model of SMS hydrothermal mound based on geophysical data (seismic and conductivity)

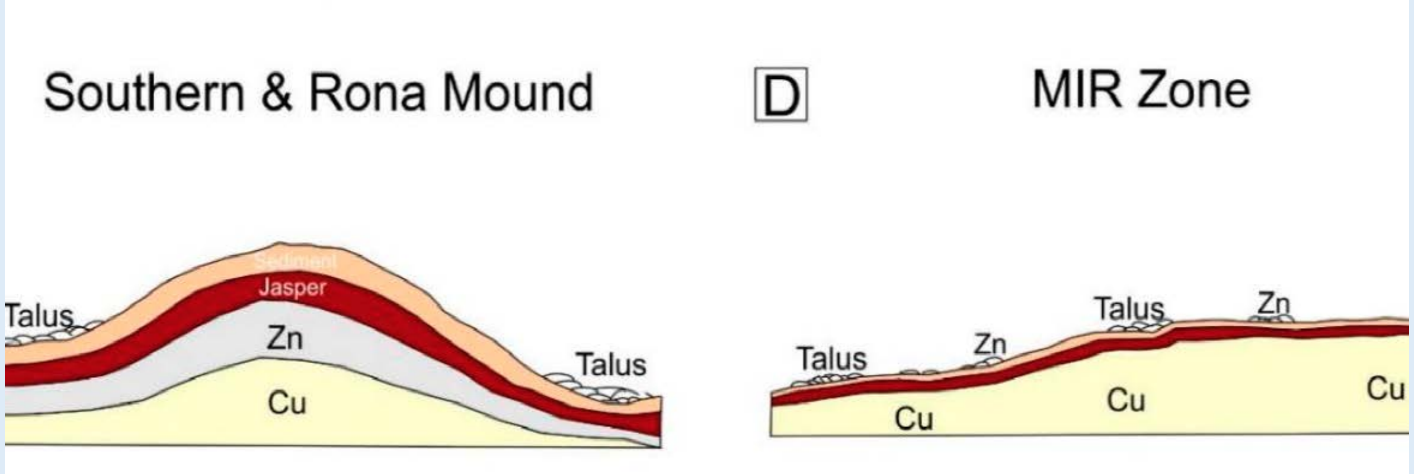


Sub sea-floor
Massive sulfides
Not confirmed
by drilling!

Blue mining, 2018
Murton et al., 2018

3. Silica and iron-oxyhydroxide (jasper) layer
within hydrothermal mounds at the TAG field
(drilling data)



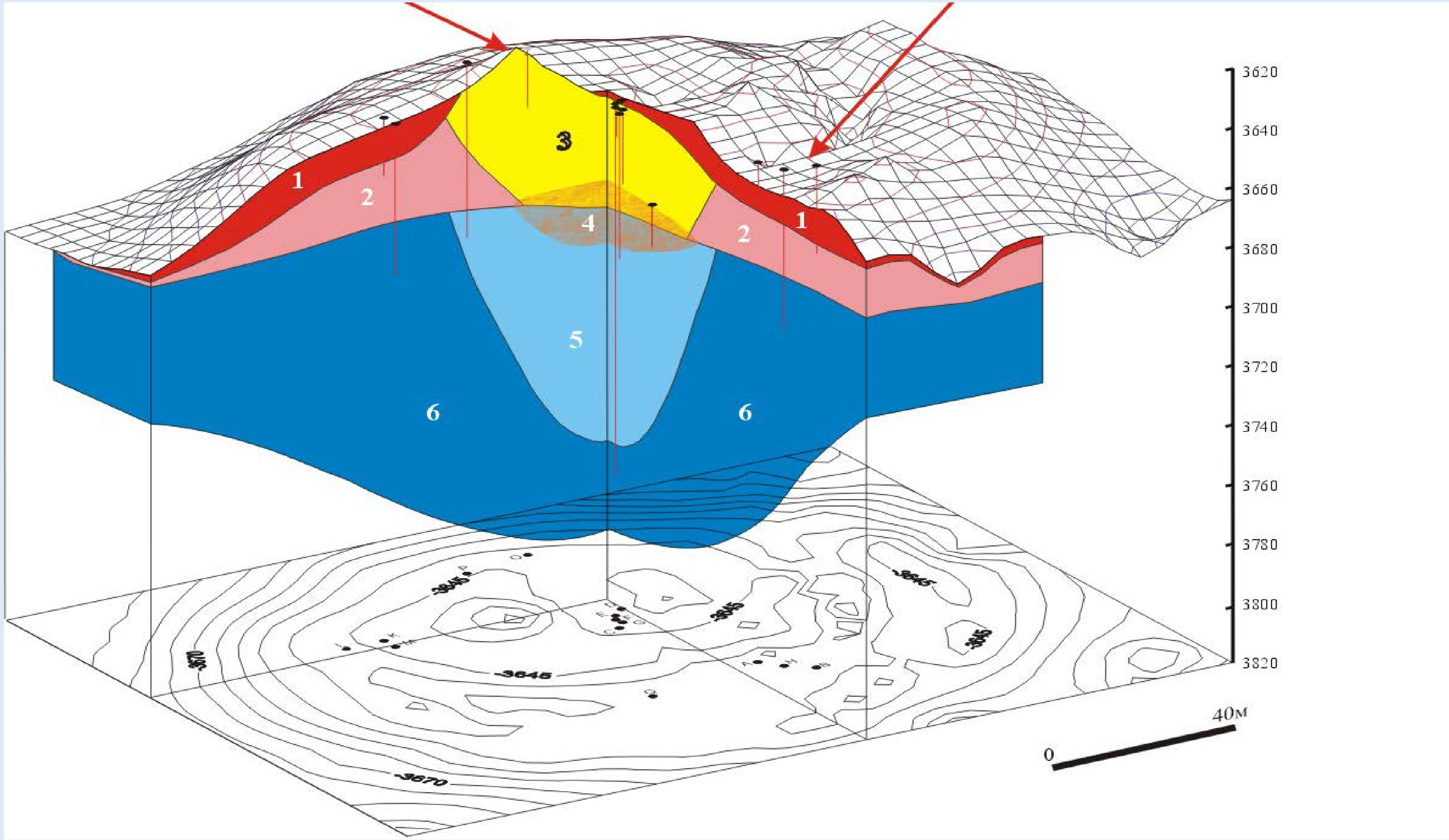


Lehrmann et al., 2018

4. Zone refining

High-temperature venting Area
Black smokers

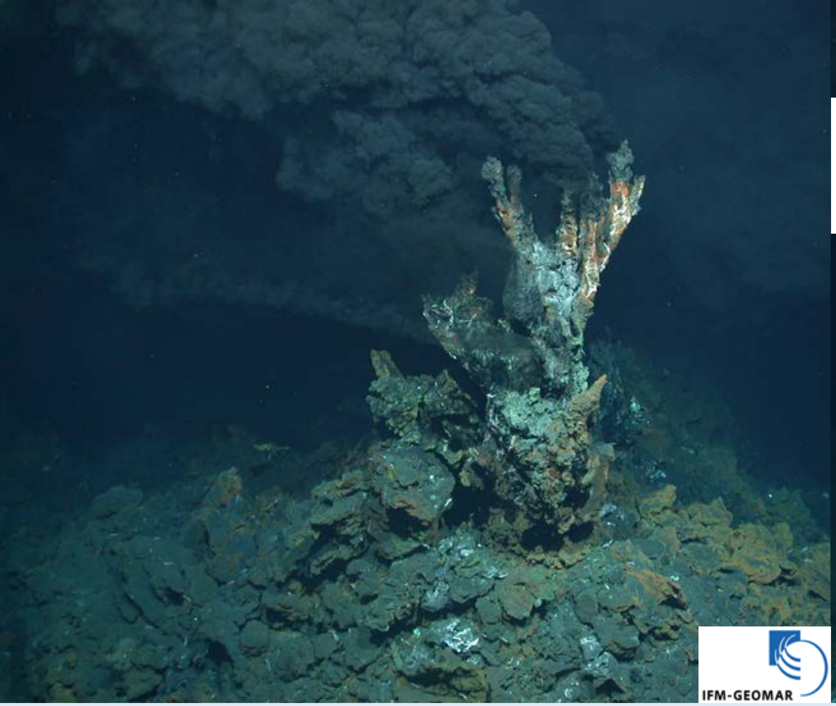
Low-temperature venting Area
Kremlins

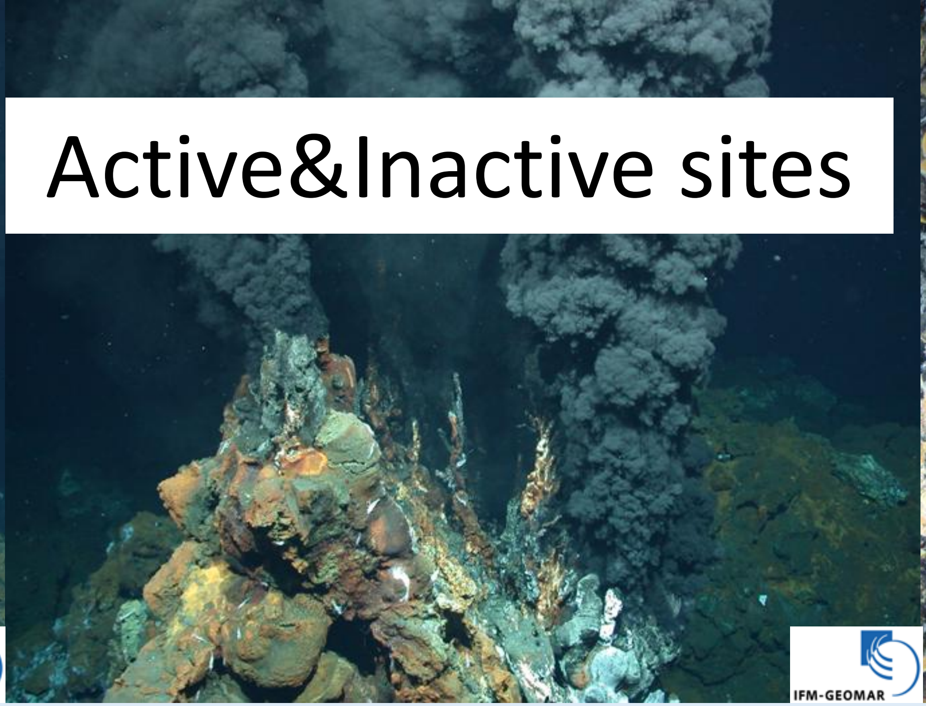


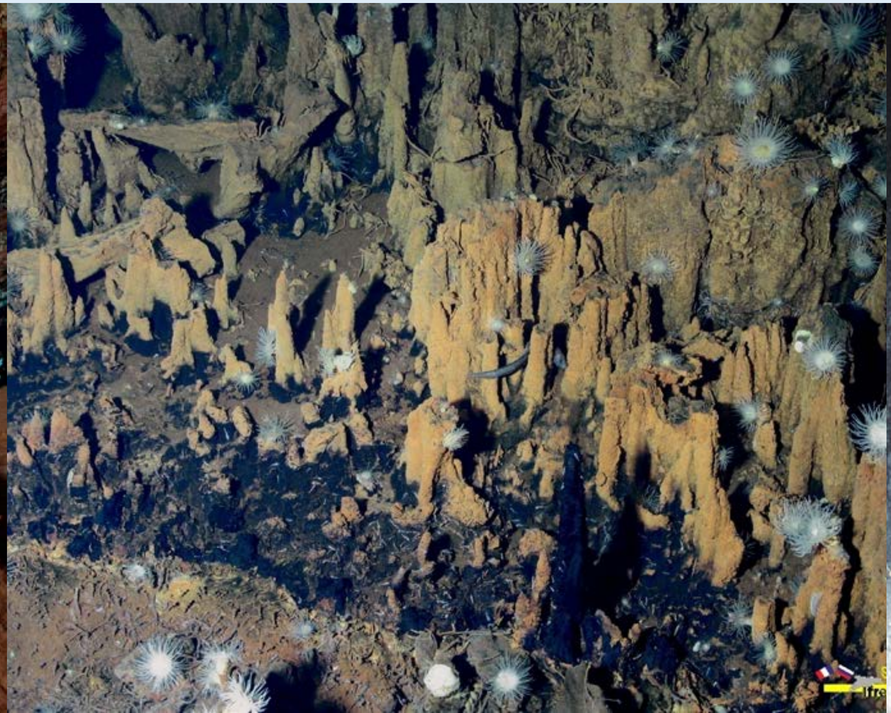
Inner structure of Active mound, TAG area

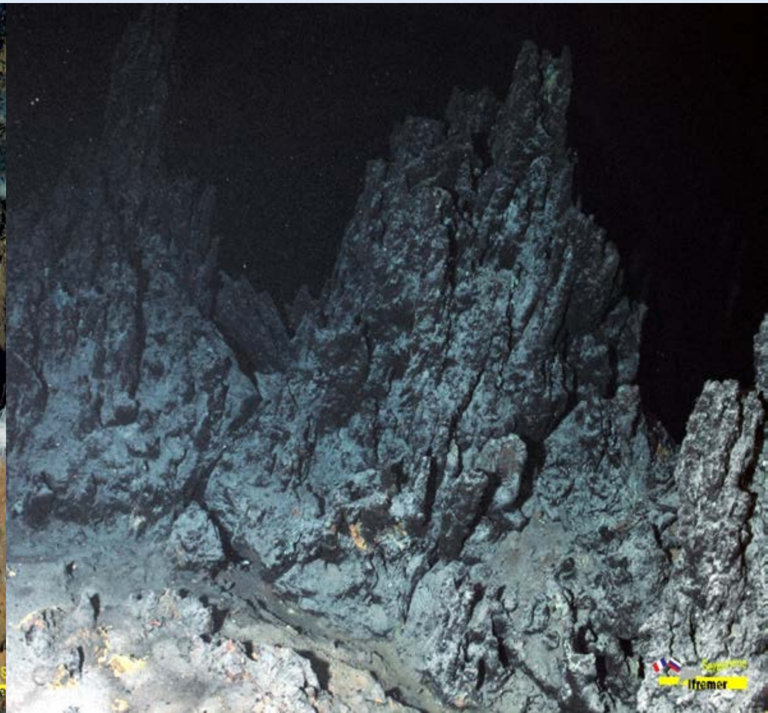
1- Cu-Zn sulfides 2 – Si-Cu-Zn zone 3 – Ca-Cu-Zn zone 4 – Ca zone 5 - Si-Ca zone Red lines – drill holes

Active&Inactive sites

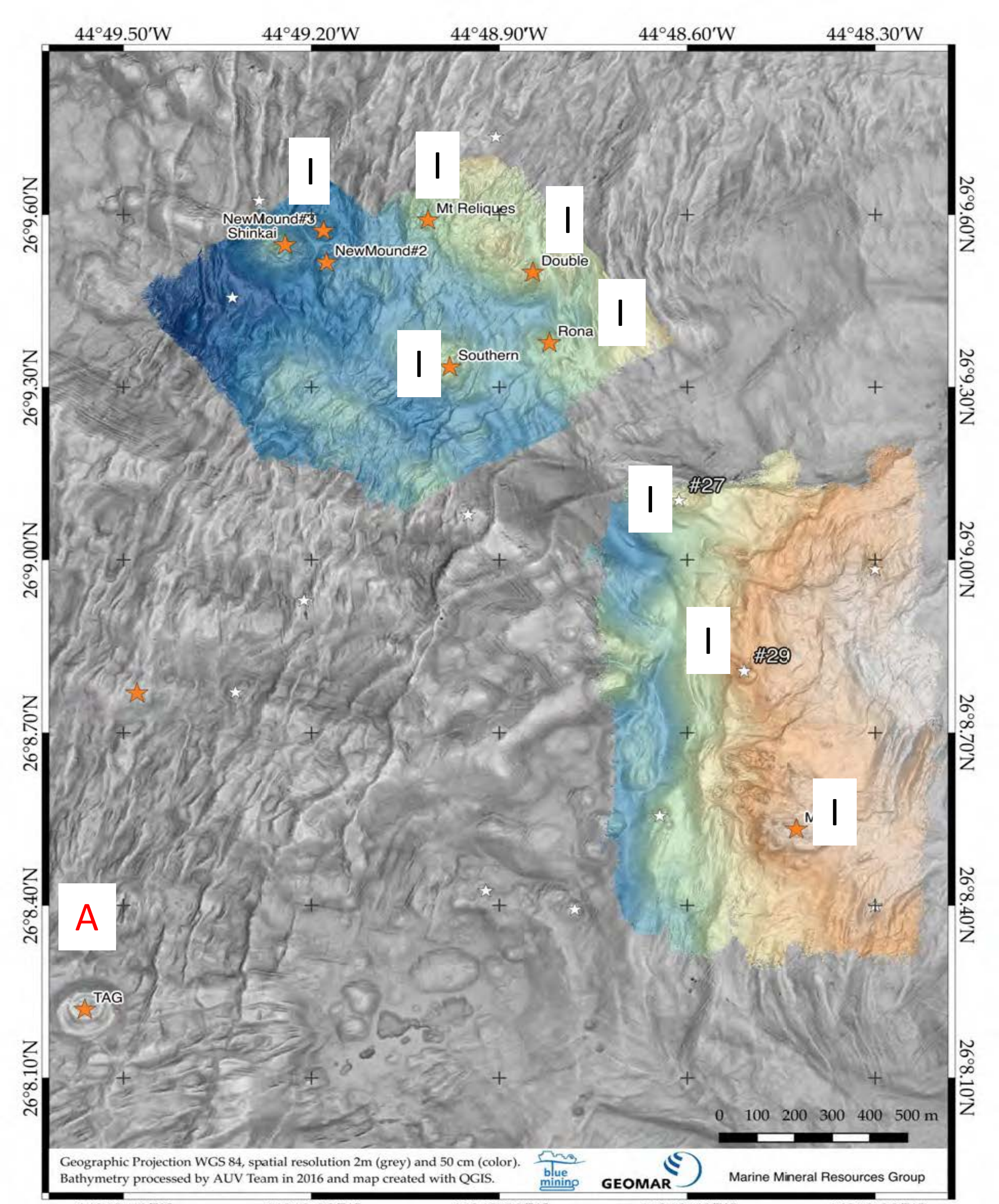








Active (A) and Inactive (I) hydrothermal mounds at the TAG area



Distance between
Active and Inactive sites – 8 km

Resources (mln t):
Active 4.0
Inactive 30 - 70

Cruise Report…, 2016
Murton et al., 2018

Resources of the SMS deposits (REA, northern equatorial MAR)

Deposit	Activity	Latitude (N)	Water depth (meters)	Est.resources (mln. tonnes)
Ashadze-1	**Active**	12° 58.5'	4200	**1.74**
Ashadze-2	**Active**	12° 59.5'	3250	**5.70**
Irinovskoye (I/A)	**Active**	13° 20'	2600	**0.45**
Semyenov-1	**Inactive**	13° 31'	2400-2600	**8.0**
Semyenov-2	**Active**	13° 31'	2400-2600	**3.7**
Semyenov-3	**Ir**	[illegible]	2400-2600	**8.6**
Semyenov-4	**Ir**	[illegible]	2400-2600	**42.00**
Semyenov-5	**Ir**	[illegible]	2400-2600	**5.0**
Logatchev-1	**A**	[illegible]	3100	**1.75**
Logatchev-2	**A**	[illegible]	2720	**0.25**
Krasnov	**Inactive**	16° 38'	3700-3750	**13.95**
Победа 1	**Active**	17° 08'	2100-2450	**1.8**
Zenith-Victoria	**Inactive**	20° 08'	2370-2390	**11.00**
Puy des Folles	**Inactive**	20°30.5'	1940 - 2000	**10.00**

Resources (mln t):
Active 16.0
Inactive 90.0

Characteristics of deep-sea minerals

Parameters	Nodules	Crusts	Massive sulfides
Morphology	2-D deposits on the bottom sediments	2-D deposits on the rocks	**3-D deposits on the rocks and sediments**
Mineralogy	Oxides & Hydroxides	Oxides & Hydroxides	**Sulfides**
Chemistry/Major elements	Mn, Ni, Co, Cu	Co, Mn, Cu (REE?)	**Cu, Zn, Pb, Au, Ag**
Grade distribution*	Homogeneous on regional scale	Homogeneous on regional scale	**Very heterogeneous on regional and local scale**
Formation	Hydrogenetic & Diagenetic From cold ambient sea/pore waters	Hydrogenetic From cold ambient seawaters	**Hydrothermal** **From hot fluids**
Age (max), years **Growth rates**	n x 10^7 mm/10^6	n x 10^7 mm/10^6	**n x 10^5** **Fast**
Ancient analogues	No	No	**Volcanogenic Massive Sulfides (VMS)**
Footprint of 2 mln mining activity on the seafloor*	150 km^2	25 km^2	**0.2 km^2**
Processing technology	New	New	**Exist/traditional for VMS**

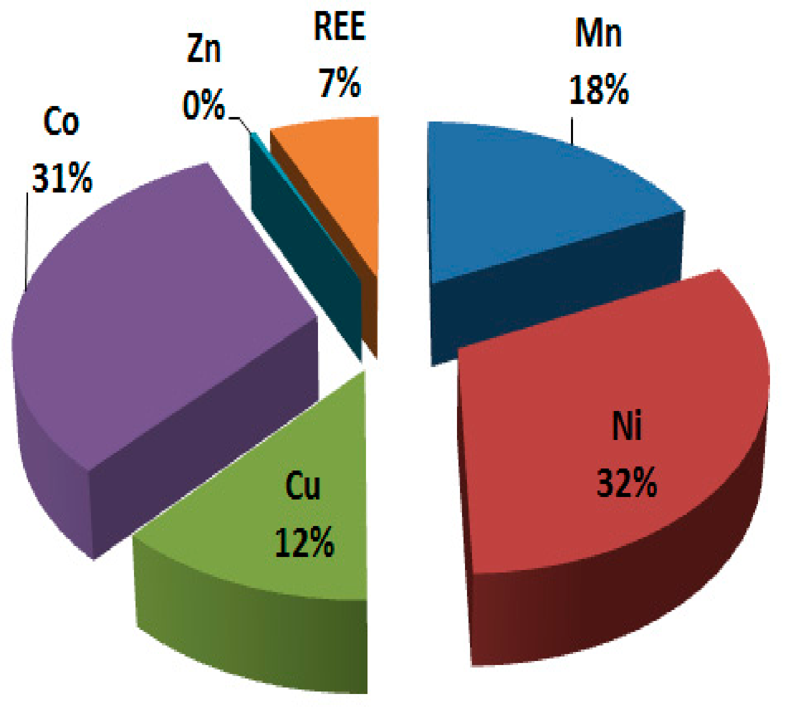
* Petersen et al., 2016

Components and global resources of deep-sea mineral deposits

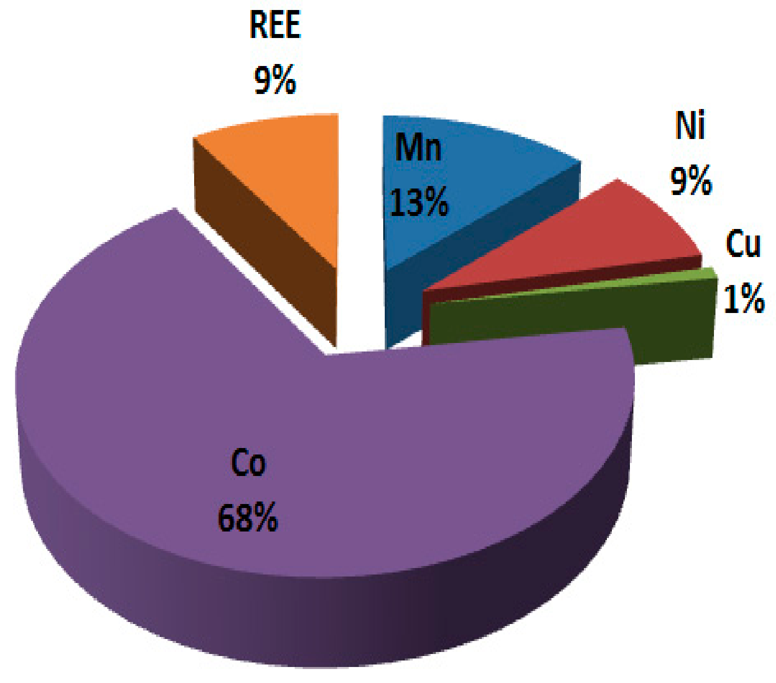
	Nodules	Crusts	SMS
Major components	Mn, Ni, Co, Cu	Co, Mn, Cu, REE	**Cu, Zn, Pb, Au, Ag**
Minor components/ Byproducts	Mo, Li, REE, Tl, Zr, Ti, Ge	Te, Mo, Bi, W, Ti, Pt, V, Nb, Y	**Se, Te, Ge, Bi, As, Cd, Ga, Tl, In**
Global resources, mln t	38 900 (Sergeev et al., 2017)	35 100 (Halbach et al., 2017)	**4 000**
Resources in “Prime zones”, mln t	21 100 (CCZ) (Hein et al., 2013)	7 533 (NPPCZ) (Hein et al., 2013)	**300 (NAEZ)**

CCZ – Clarion-Clipperton Zone
NPPCZ – North Pacific Prime Crust Zone
NAEZ – North Atlantic Equatorial Zone

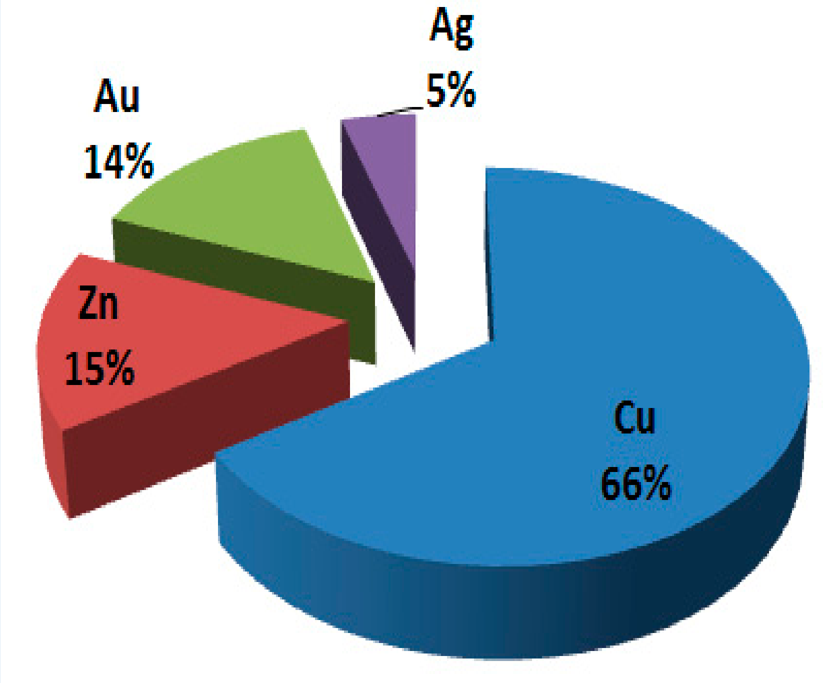
Potential value of metals in different types of deep-sea deposits



Nodules

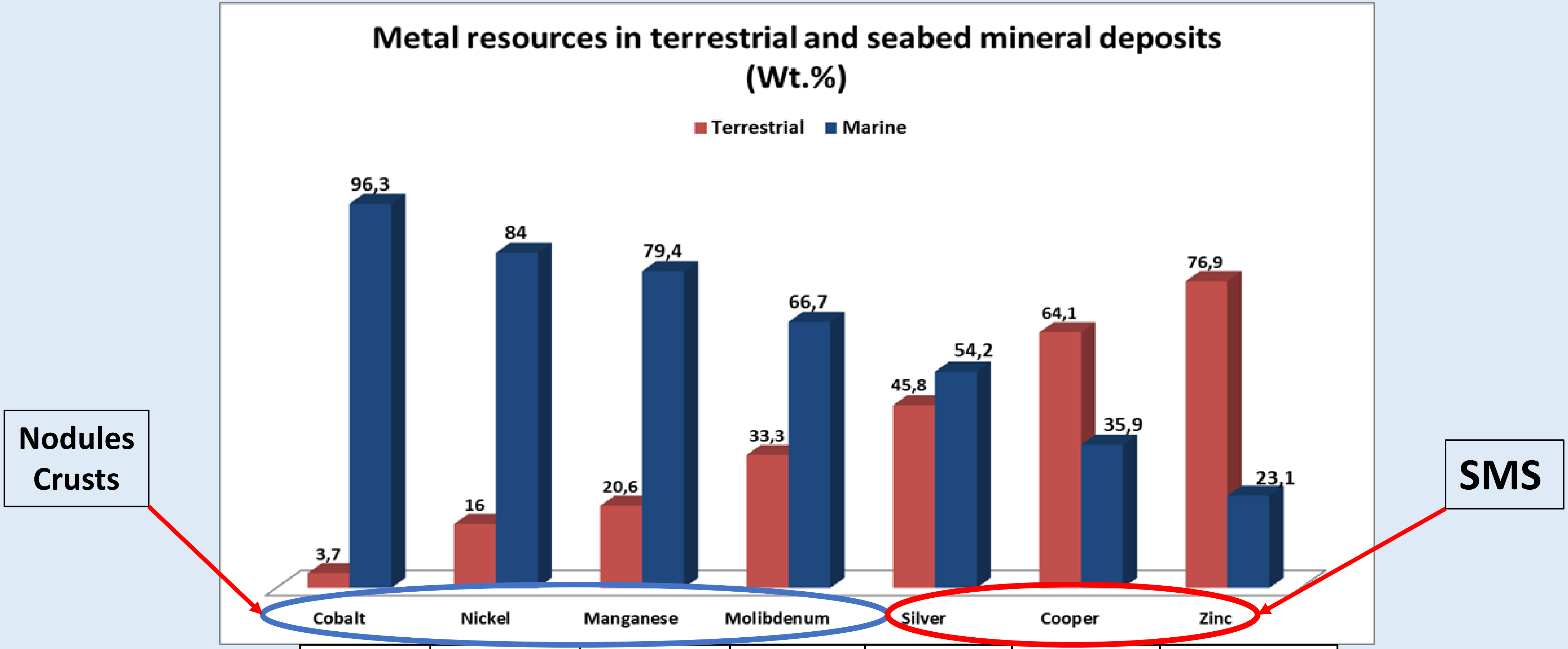


Crusts



SMS

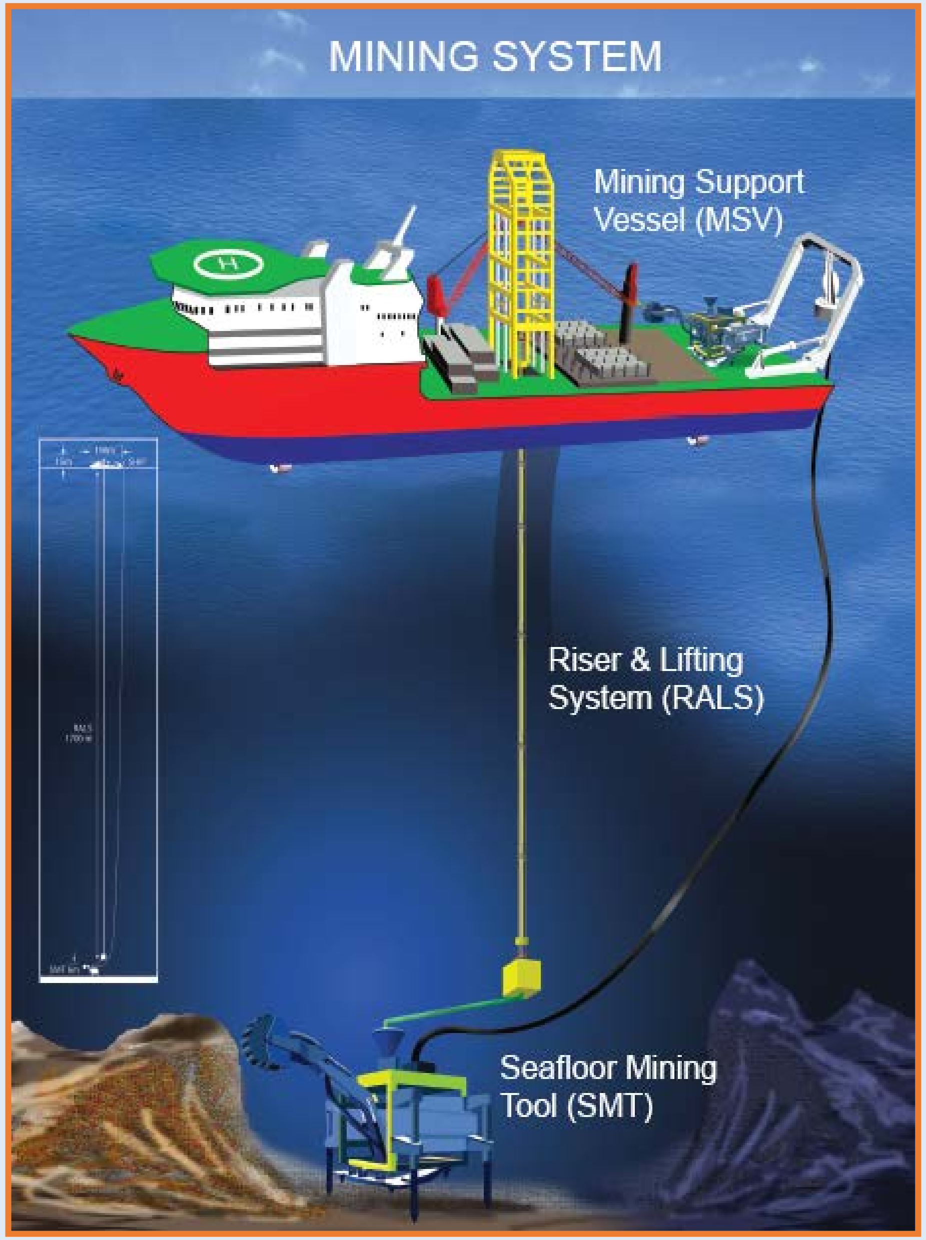
Graphical of estimated metals percentage of resources and millions of tons reserves in terrestrial versus submarine mineral deposits.



446	684	22,586	40	1.3	761	540
17	130	5,846	20	1.1	1,360	1,800

Source: USGS

Mining technology and perspectives



Leading companies/countries in SMS mining systems development

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

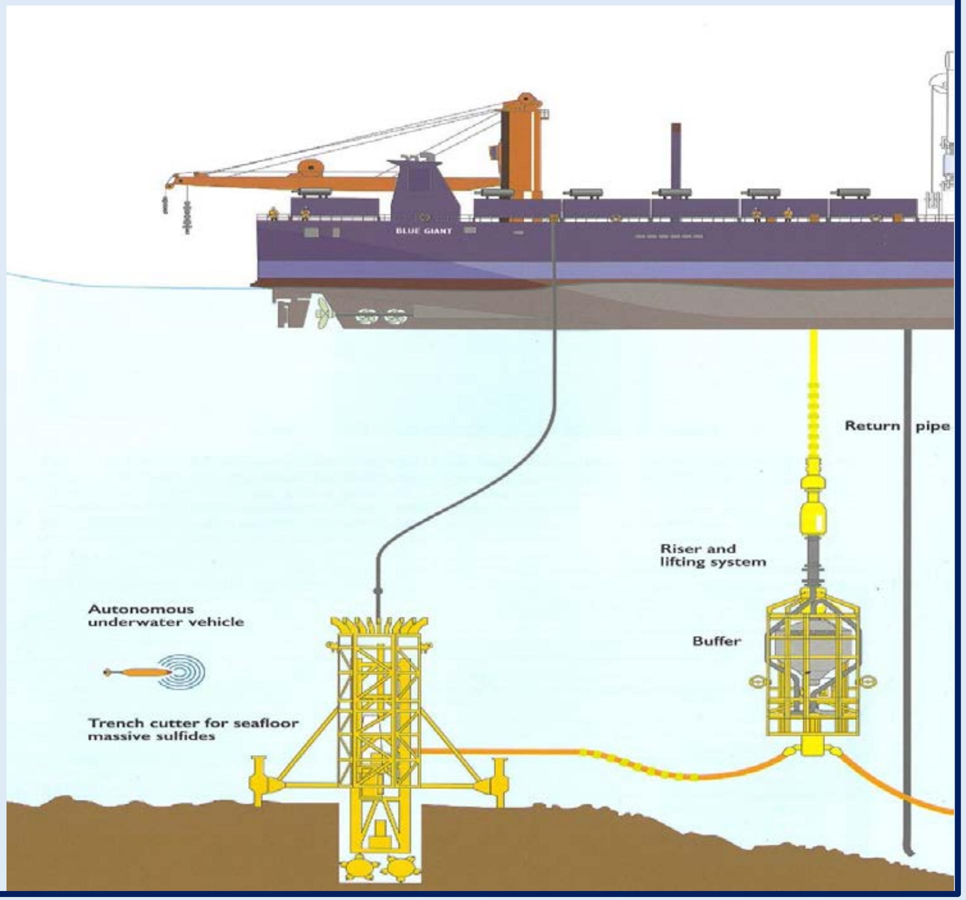
www.nautilusminerals.com

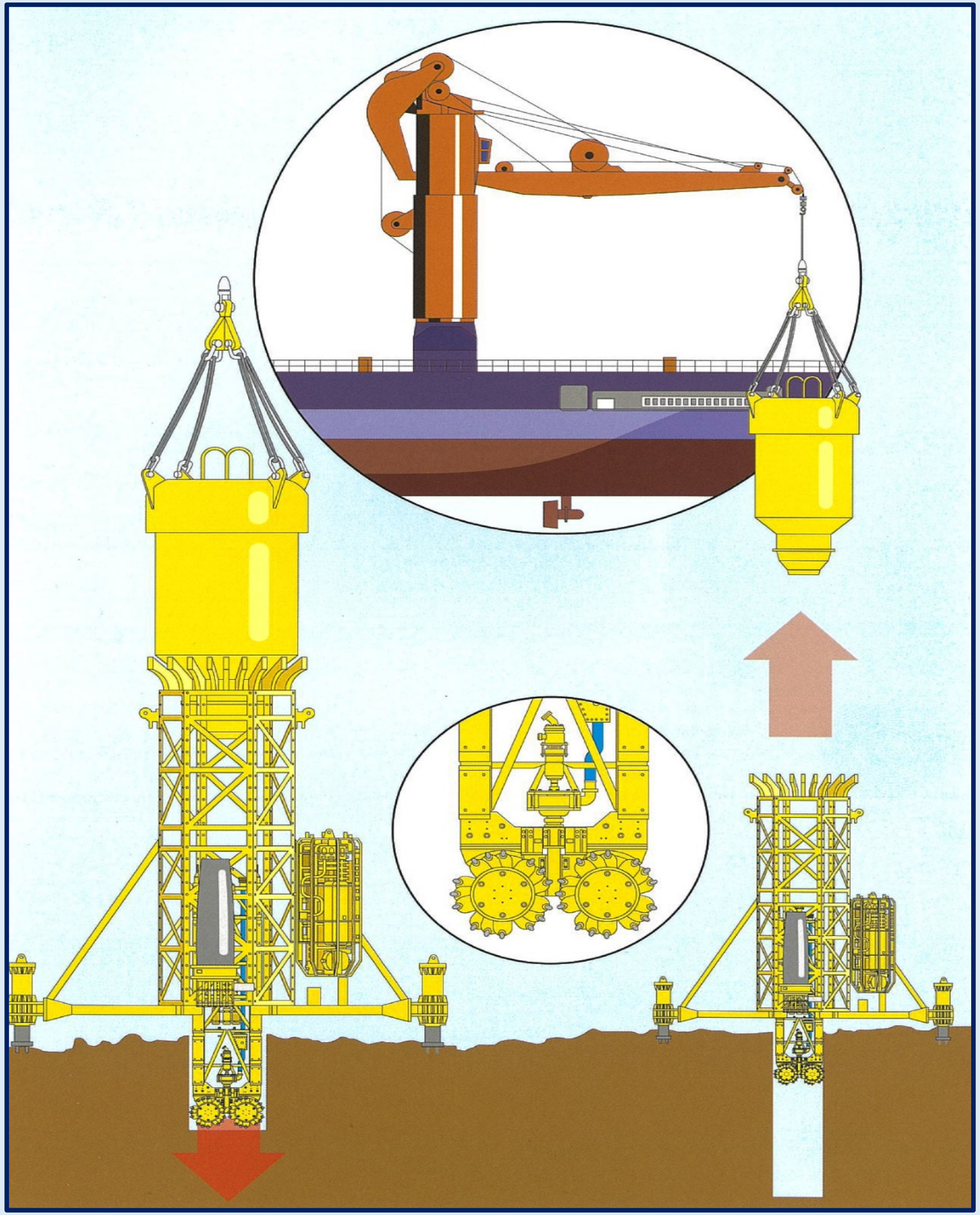
Nautilus Minerals Update

June, 2016

Seafloor Mining Tools

Building Momentum

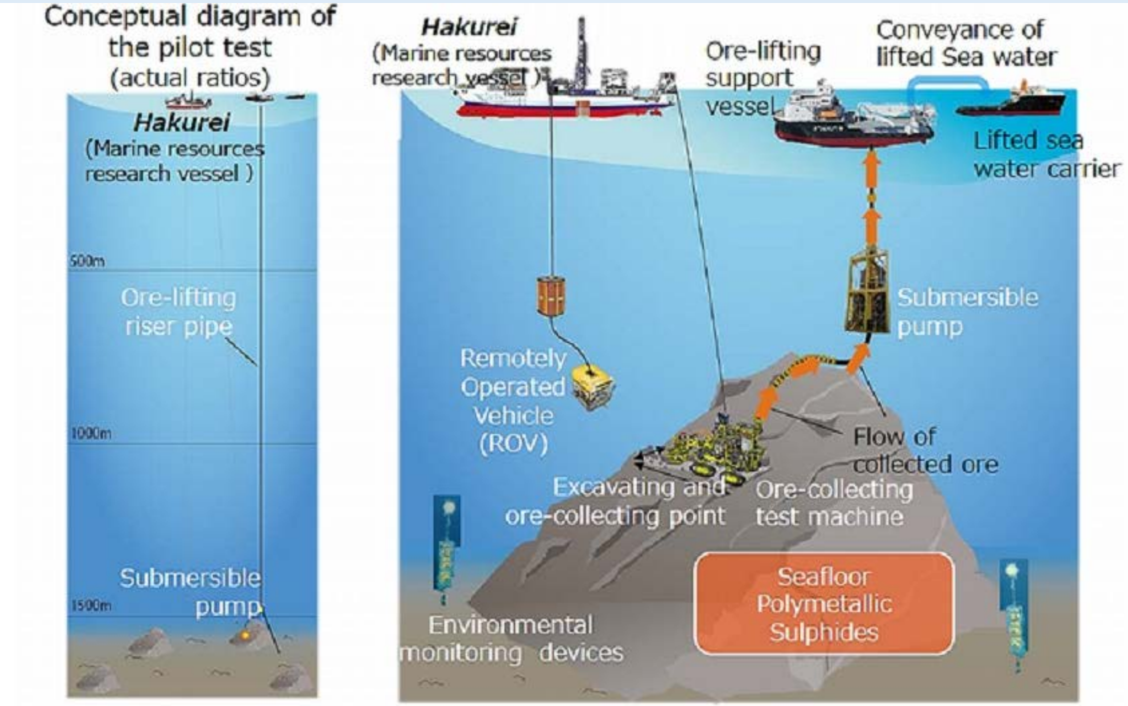




BAUER MASCHINEN

BAUER Maschinen GmbH
Drilling equipment for offshore foundations and subsea exploration, sea-bed drill rigs

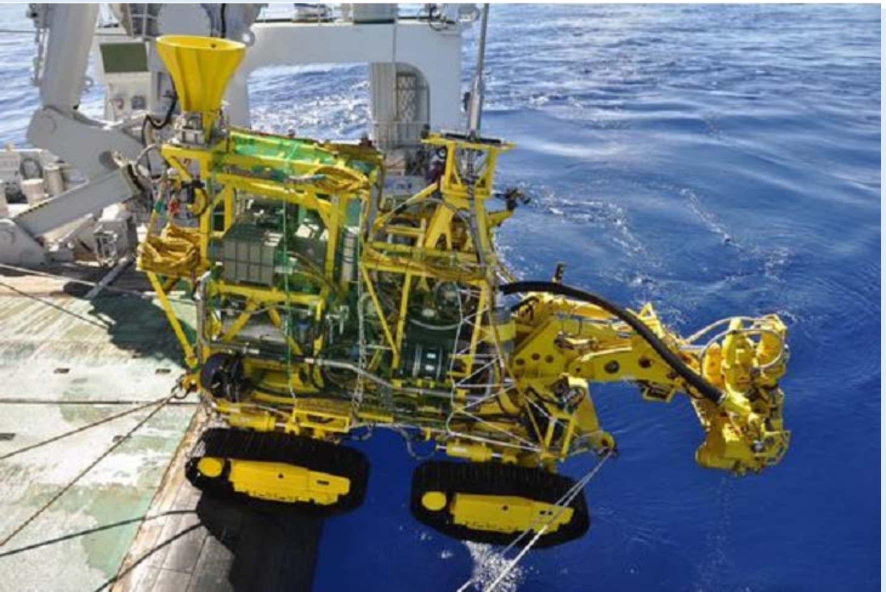
26.09.2017



METI
Ministry of Economy, Trade and Industry

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



Conclusions

- Distribution of SMS deposits along the MAR demonstrates high variability in distance between separate sites (from ten to hundred km and more)
- Current resource estimation of SMS deposits in the North Atlantic (first hundreds mln t) is not reliable. Potential resources could be increased dramatically (2-3 times higher) as a result of extension of the exploration area (up to 20 km) or could be decreased as a result of drilling SMS deposits outcropping on the sea floor
- Due to the absence of economic model for SMS mining it is not possible to determine the level of resources which could be commercially interesting for future exploitation. Suggested profitable level of annual nodules production (3 mln t/year) is not applicable for SMS and should be a subject for the special study

Resources Uncertainties:

- Tonnage (before drilling all estimation has preliminary character)
- Heterogeneity/zonality of SMS deposits does not allow to evaluate reliable metal resources
- Without feasibility study any financial model has preliminary character
- Feasibility study could not be executed before test mining which is not conducted yet
- All prospects for exploitation have preliminary character

Conclusions

The following parameters of active and inactive SMS deposits should be take into account for the estimation of environmental impact, regulations and scenario of the exploitation:

- Distances between active and inactive sites vary from tens of meters to tens of kilometers
- Resources of inactive active SMS deposits are larger than inactive one, but this issue is still under discussion

P.S.
Evaluation of environmental impact and limitation of mining operations

Distance between Active and Inactive sites	**Sites**	**Environmental impact of mining**	**Mining operations**
n x 10 meters	Chimneys within hydrothermal field	Yes, Serious	✖
n x 100 meters	Hydrothermal fields within cluster	?	?
n x 1 km	Hydrothermal fields within cluster	Not serious	✚
n x 10 km	SMS deposits within Exploration Area	Not serious	✚