UiT The Arctic University of Norway

UNIVERSITETET I BERGEN

CENTRE FOR DEEP SEA RESEARCH

Formation and preservation of seafloor massive sulfide (SMS) mineralization along ultraslow spreading ridges: An insight from the Arctic Ocean

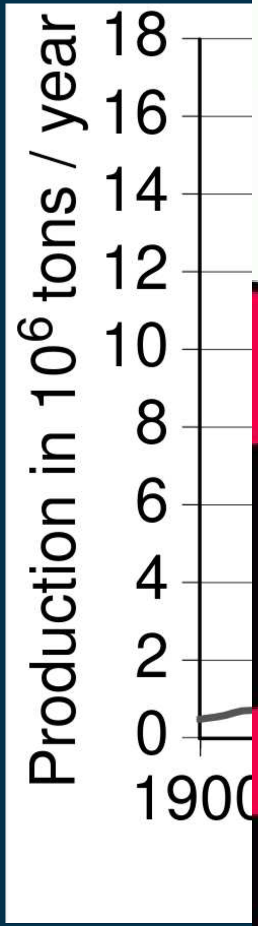
SABINA STRMIC PALINKAS[1,2], ROLF B. PEDERSEN[2], HÅVARD H. STUBSEID[2], MARIE WOLD[2], ERLE BIRKELAND[2], FREDRIK SAHLSTRÖM[1], SIV HJORTH DUNDAS[2], ESZTER SENDULA[1]

[1] UiT The Arctic University of Norway, Department of Geosciences, Tromsø, Norway

[2] University of Bergen, Centre for Deep Sea Research, Bergen, Norway


Cu-rich sample, Aurora Vent Field, 23/07/2023

Growing demand for metals Vs. lack of Social Licence to Operate



World cop

Could deep-sea mineral resources be an alternative?

Climate & Energy | Climate Change | Climate Solutions

Norway moves to open its waters to deep-sea mining

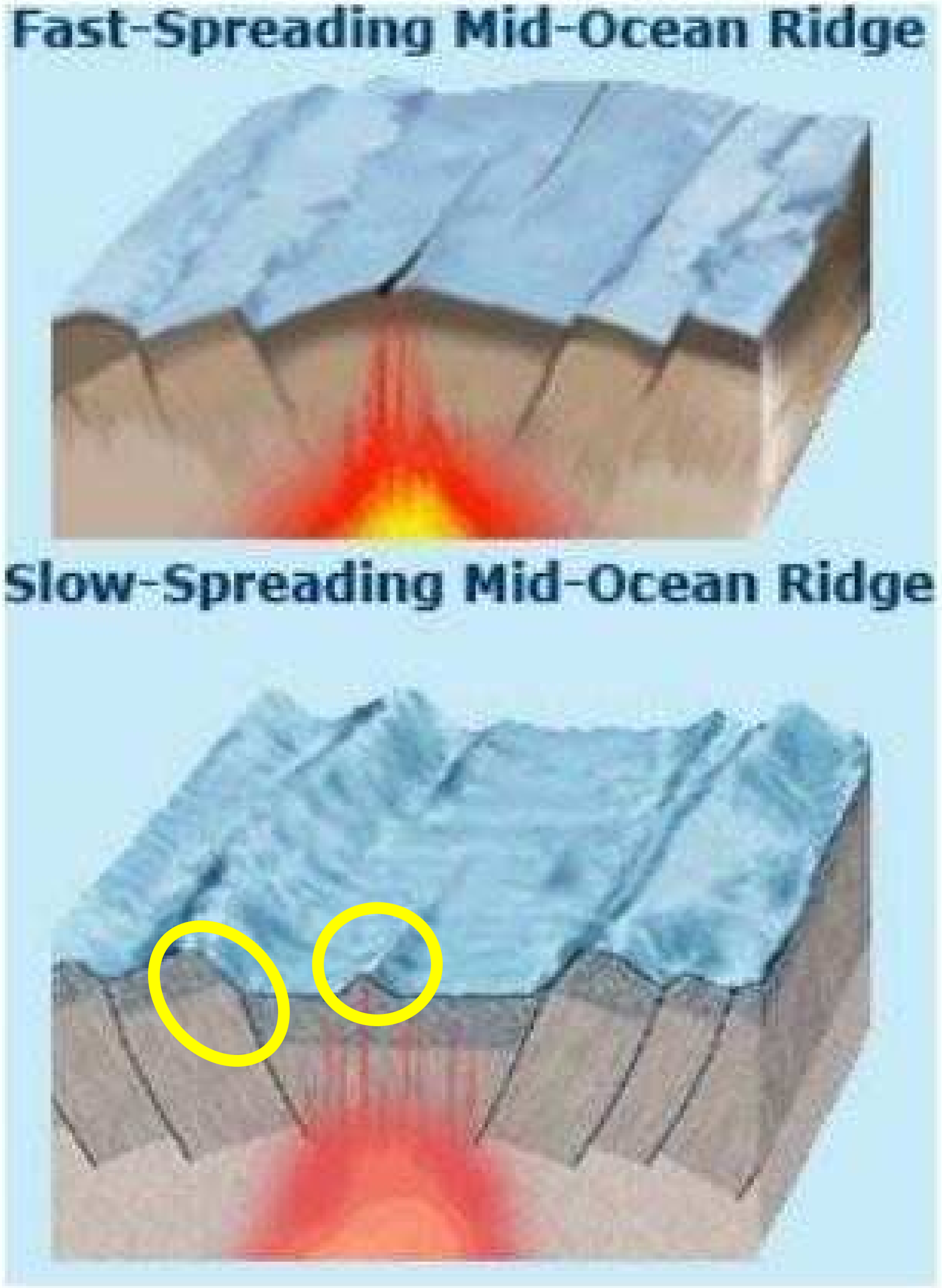
By **Gwladys Fouche** and **Nerijus Adomaitis**

June 20, 2023 3:23 PM GMT+2 · Updated 2 months ago

Aa

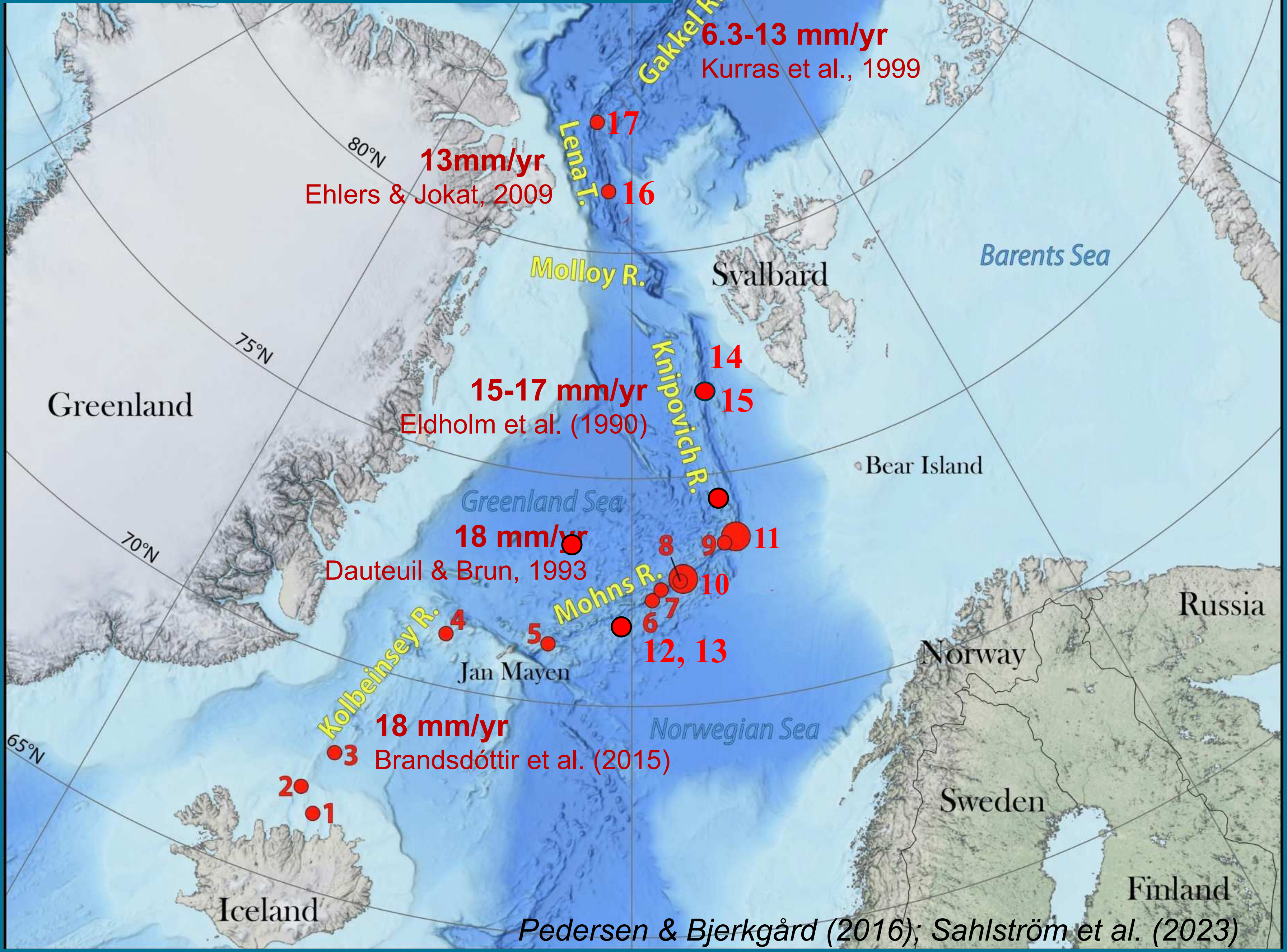
Floating ice is seen during the expedition of the Greenpeace's Arctic Sunrise ship at the Arctic Ocean, September 14, 2020. REUTERS/Natalie Thomas/File Photo *Acquire Licensing Rights*

- Accurate mineral resource estimation
- Deep-sea mining technology
- Environmental impact
- A suite of cost-effective geophysical and geochemical methods suitable for exploration of hydrothermally inactive seafloor deposit (often covered by a thick layer of sediments)



- **Fast-spreading ridges**, like the East Pacific Rise, the spreading rate is 100 to 200 millimeters per year.
- **Slow-spreading ridges,** like the Mid Atlantic Ridge, the spreading rate is 20 to 40 millimeters per year.
- **Ultraslow-spreading ridges**, like the Southwest Indian Ridge, the spreading rate is less than 20 millimeters per year.

Arctic Mid-Ocean Ridges



Pedersen & Bjerkgård (2016); Sahlström et al. (2023)

Kolbeinsey Ridge:
1) Grimsey
2) Kolbeinsey
3) Squid Forest
4) Seven Sisters

Mohns Ridge:
5) Soria Moria/Troll Wall/Perle and Bruse (Jan Mayen Vent Fields)
6) Ægir
7) Copper Hill
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10) Fåvne
11) Loki's Castle
12) Deep Insight
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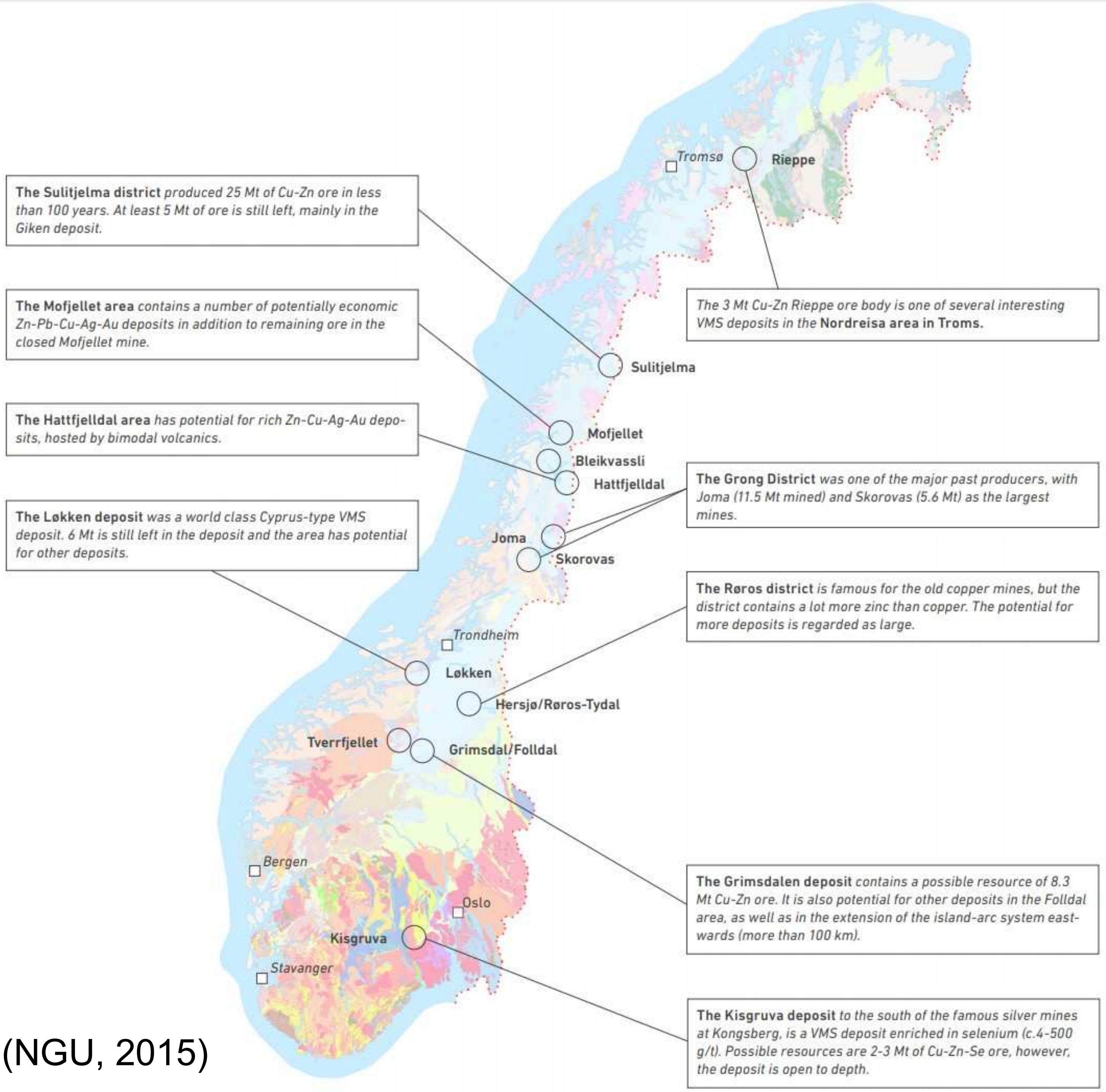
Knipovich Ridge:
14) Jøtul
15) Gygra

Lena Trough/Lucky Ridge:
16) Lucky B/Ultima Thule

Gakkel Ridge:
17) Aurora

VMS deposits in Norway

- Mining of **copper and zinc** from volcanogenic massive sulfide (VMS) deposits has a long tradition in Norway, with more than 450 years of production. Major mining districts included Røros, Løkken, Sulitjelma, Folldal and Grong. More than 100 Mt of ore was extracted from 10 major mines and districts, producing 1.7 Mt Cu and 1.9 Mt Zn.
- These districts still have a large potential for **new discoveries** especially of **strategic commodities** (e.g. Co, V, Sb, Te, Ga, Ge, In,…)



(NGU, 2015)

Mapping, sampling and data collection

- Multiple research cruises since 2017

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NORWEGIAN OFFSHORE DIRECTORATE

EMINENT

(2023-2025)

THE ARCTIC UNIVERSITY OF NORWAY • UIT •

equinor

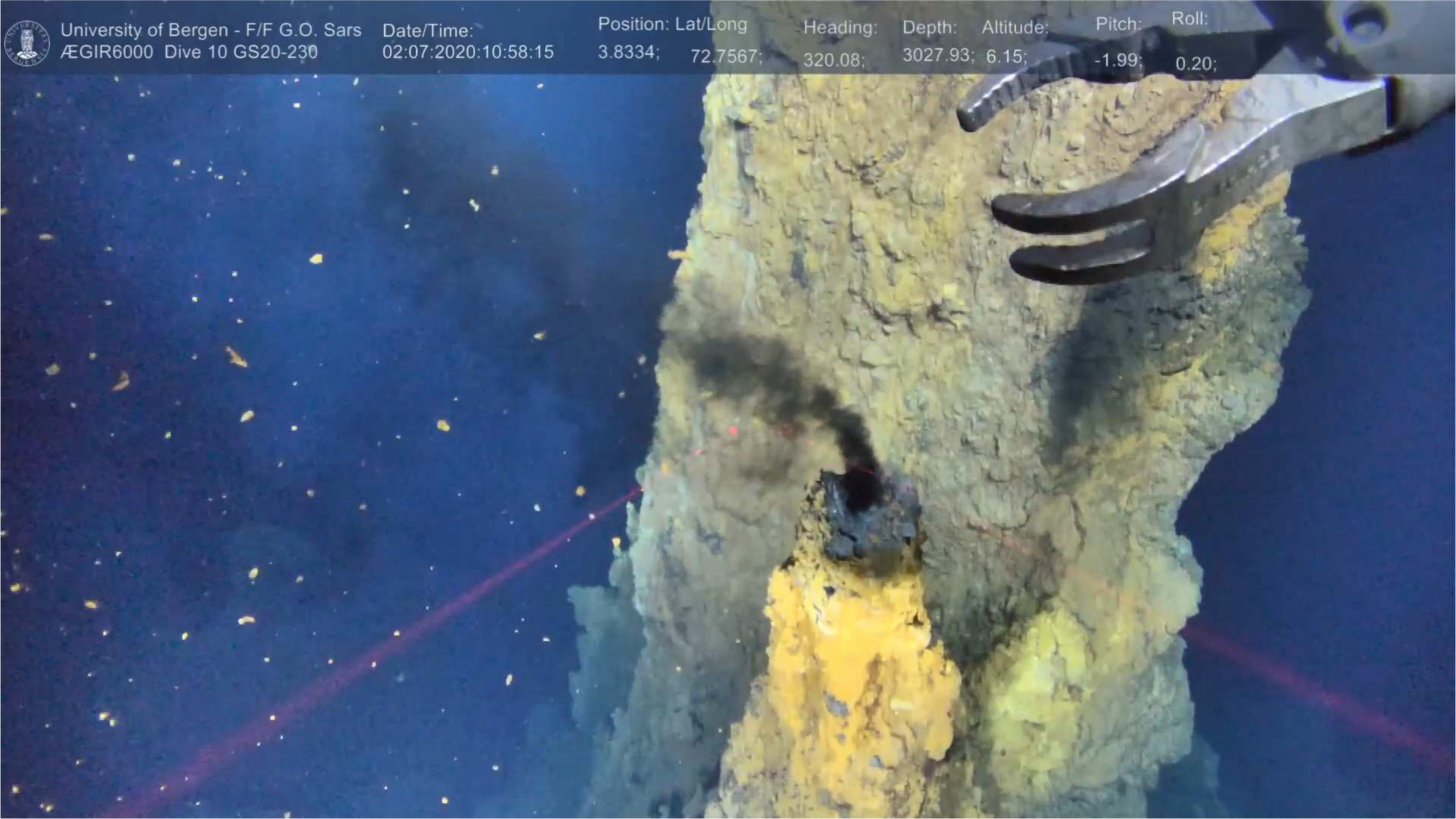
Akademiaavtale (2019-2023)

RV Kronsprins Haakon

Photo: Daniel Albert, GoNorth 2023 Expedition


NORCE

Photo: Daniel Albert, GoNorth 2023 Expedition


University of Bergen - F/F G.O. Sars
ÆGIR6000 Dive 10 GS20-230
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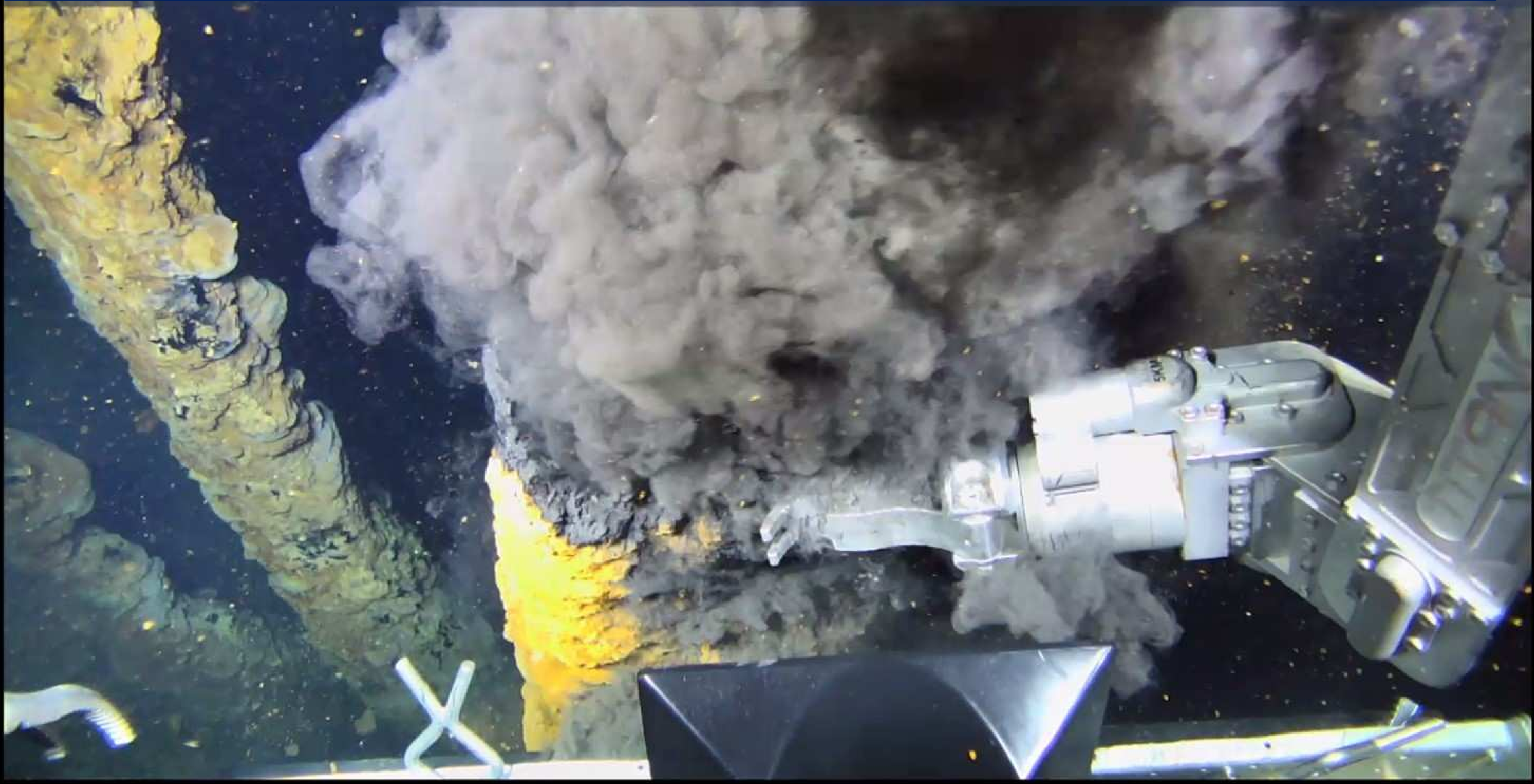
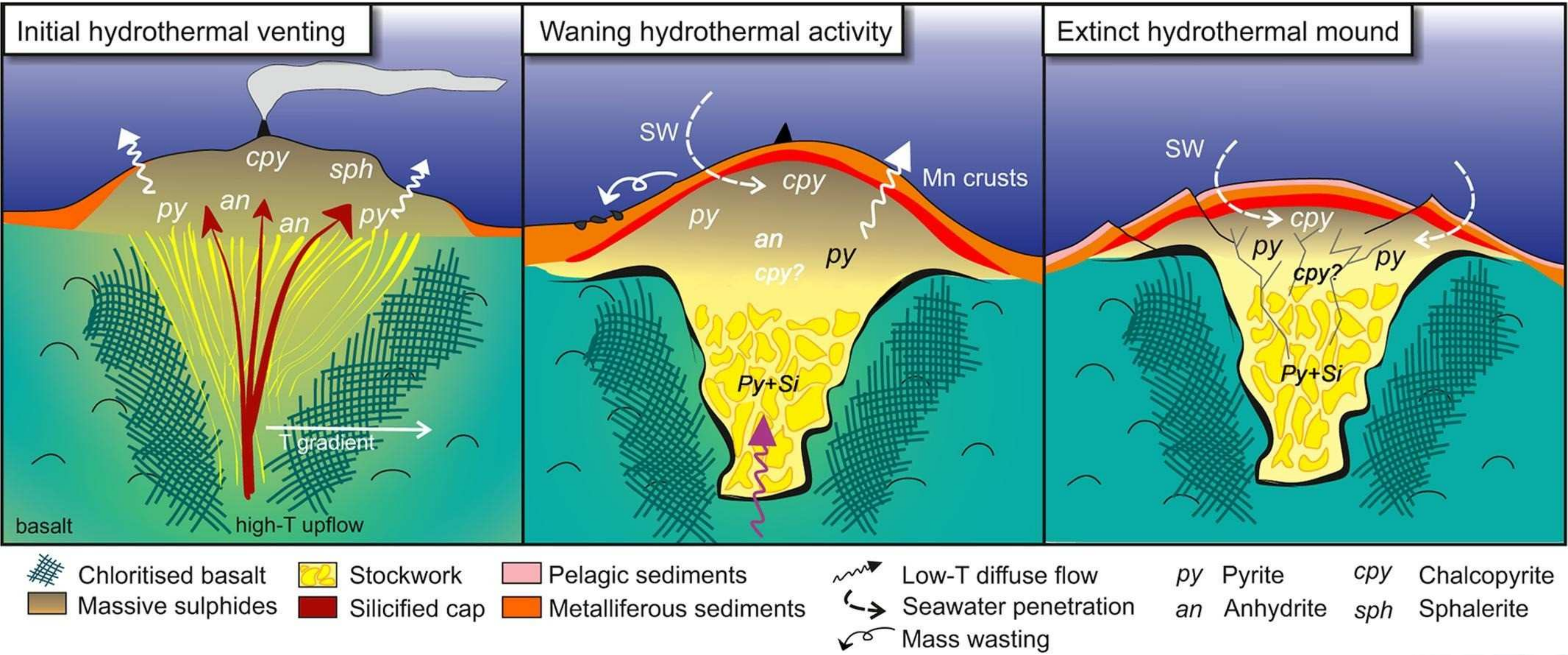
3.8334; 72.7567;
Heading:
320.08;
Depth:
3027.93;
Altitude:
6.15;
Pitch:
-1.99;
Roll:
0.20;

Active vs. Extinct SMS systems

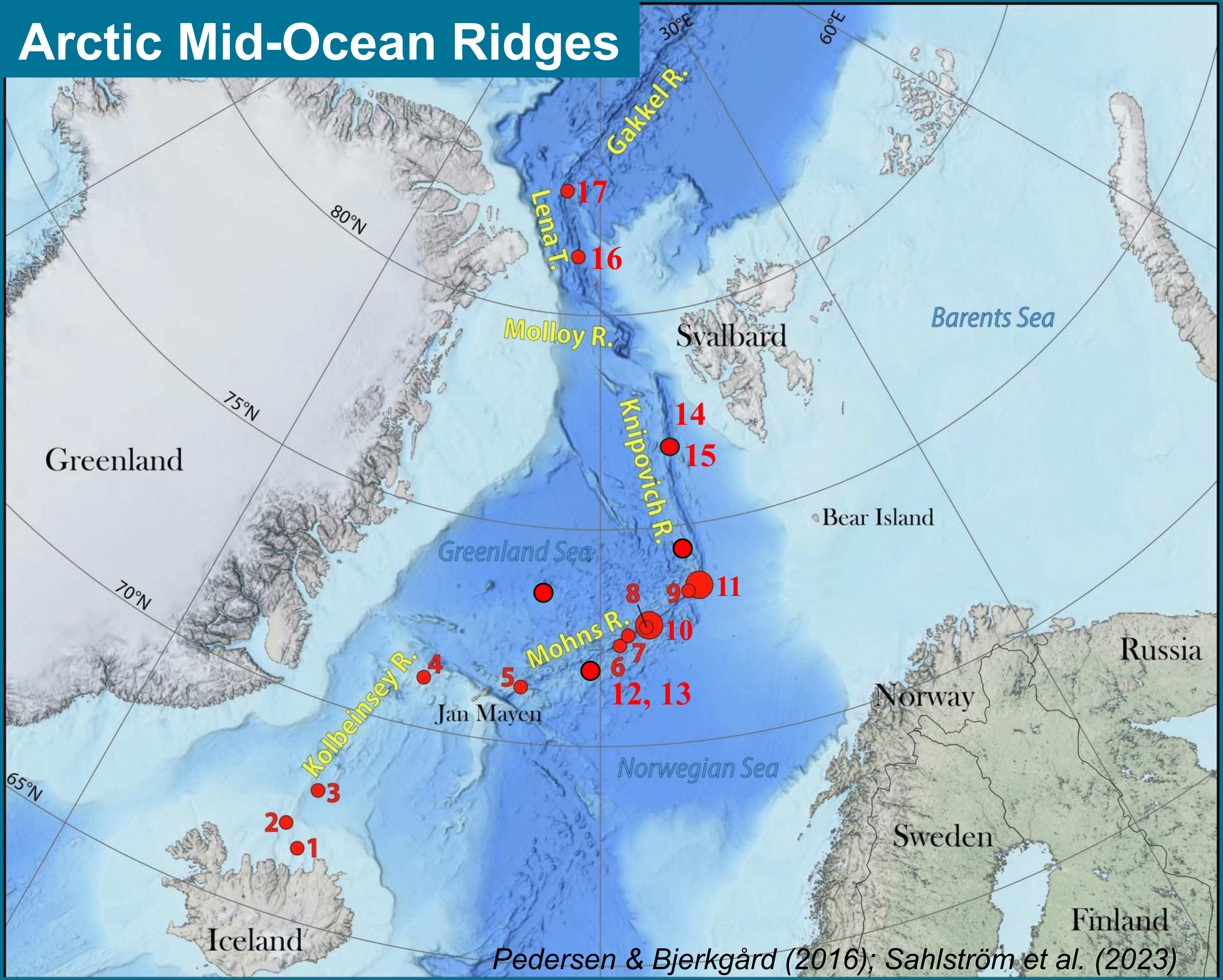


Active vs. extinct submarine hydrothermal systems



Murton et al. 2019

Arctic Mid-Ocean Ridges



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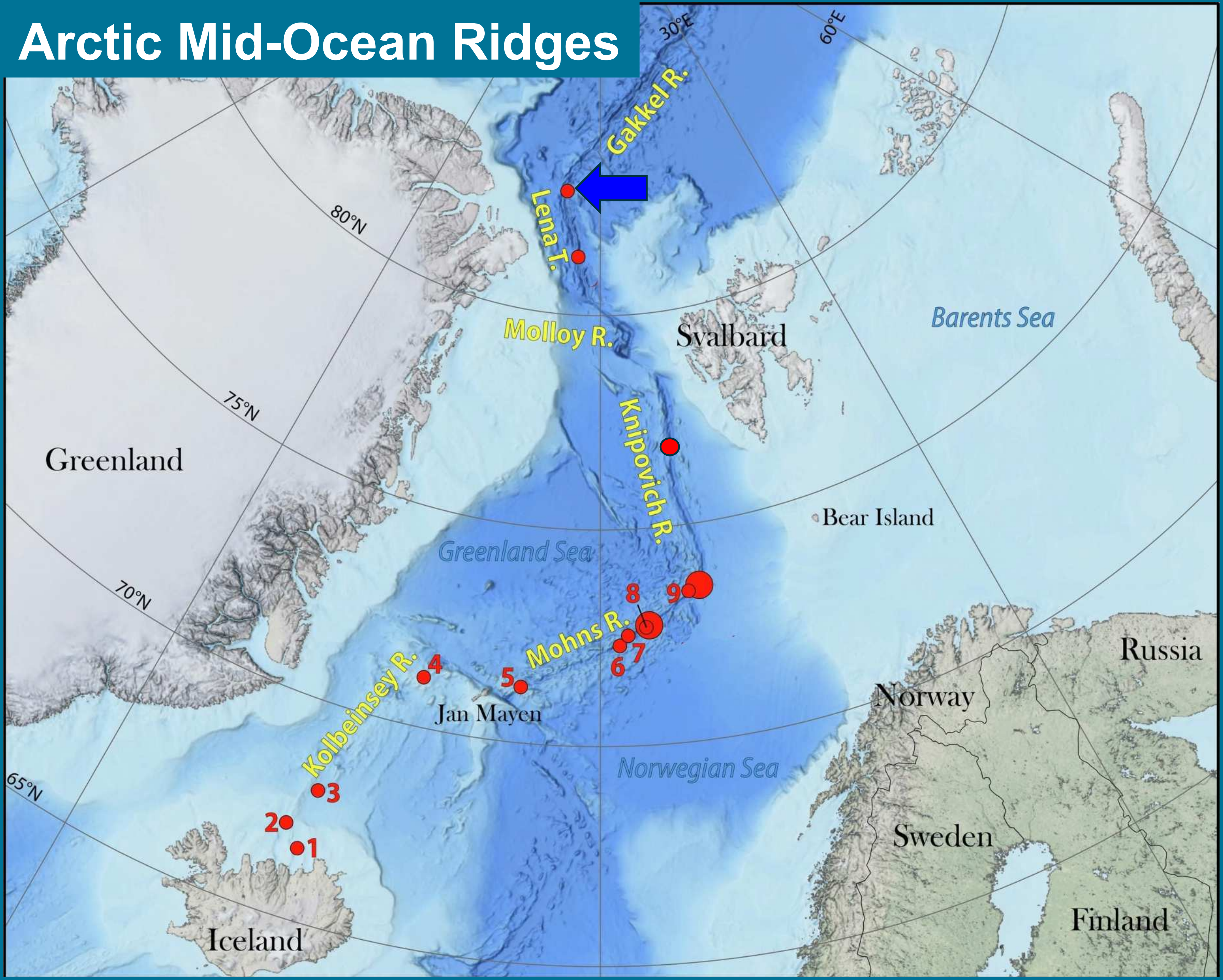
Arctic Mid-Ocean Ridges



Sahlström et al. (2023)


Aurora Vent Field, Gakkel Ridge
(82.88°N, 6.25°W, 3900 mbsl)
AMORE 2001 Expedition; USCGC *Healy* and PFS *Polarstern*
High-temperature basalt-hosted ultramafic-influenced vent field
Cu-rich mineralization
German et al. (2022)
Operating copper mines onland currently have an average grade of 0.53%
Cu: 3.9-34.1 wt.%, average: 15.7 wt.%
Co: 0.1-0.8 wt.%, average: 0.5 wt.%
Zn: 1.8-13.7 wt.%, average: 5.3 wt.%
Ag: 7.5-43.1 ppm, average: 21.1 ppm
Ga: 2.7-15.5 ppm, average: 6.7 ppm
Au < 1.8 ppm
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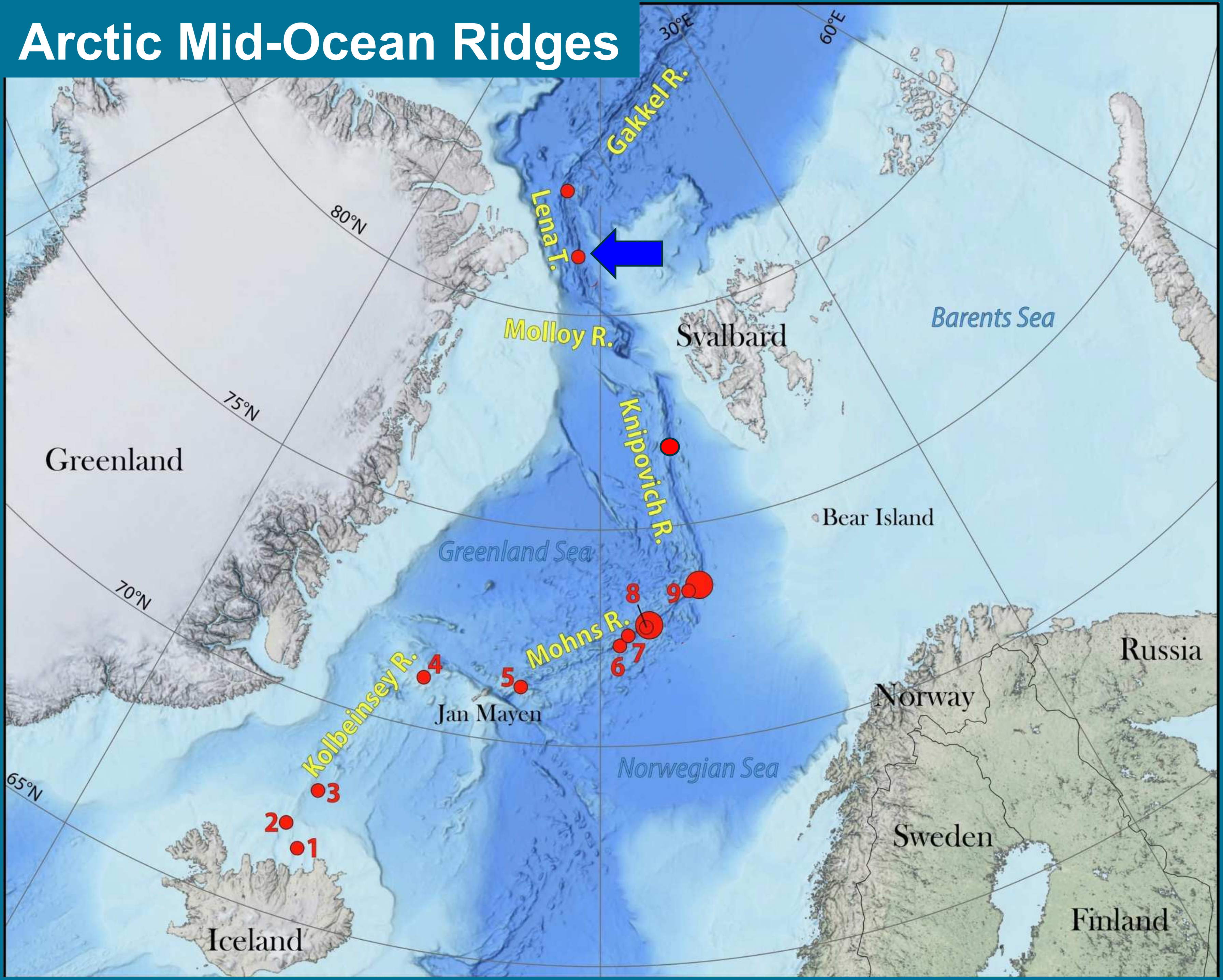
Arctic Mid-Ocean Ridges

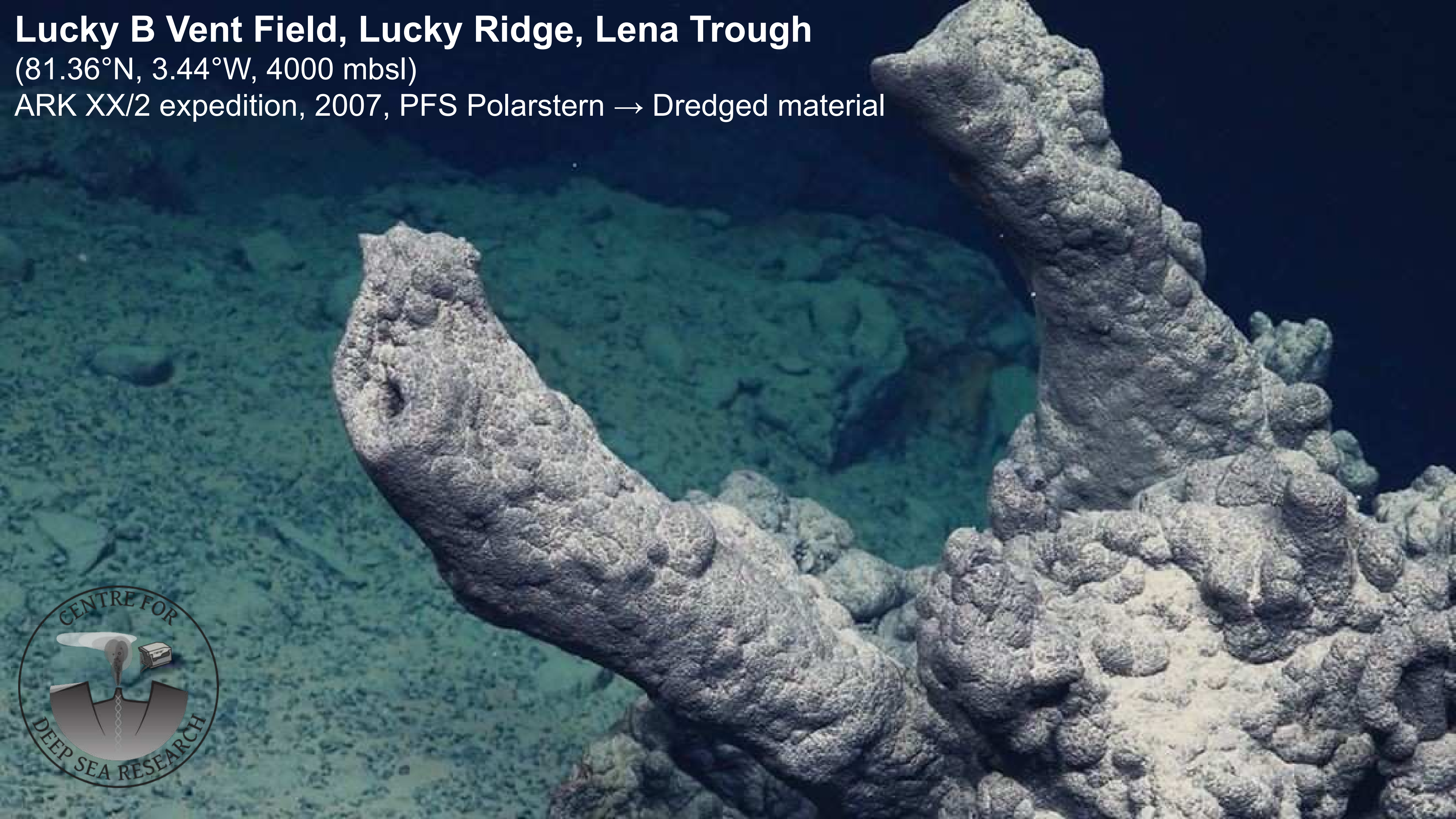


Sahlström et al. (2023)

Lucky B Vent Field, Lucky Ridge, Lena Trough

(81.36°N, 3.44°W, 4000 mbsl)

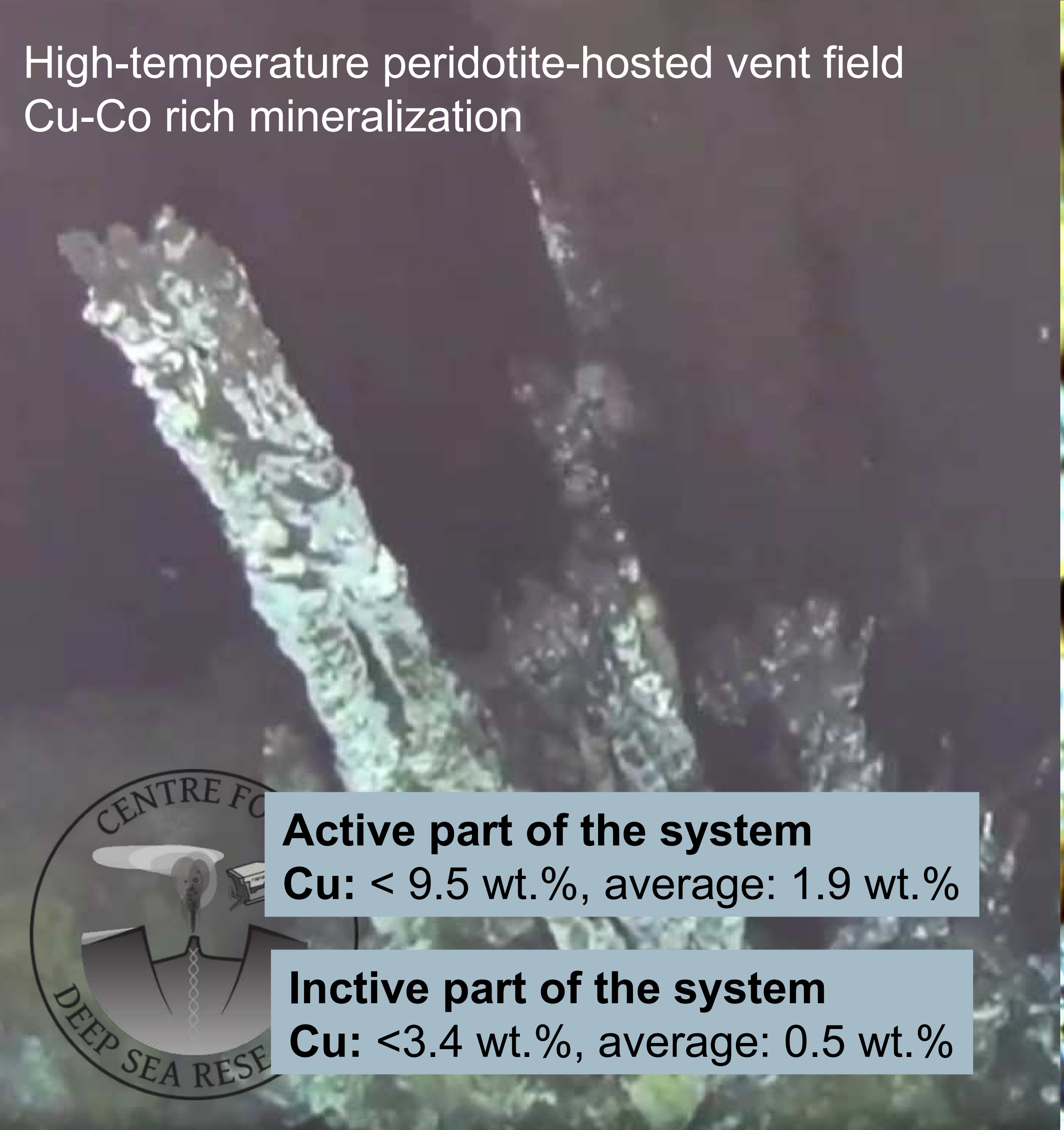
ARK XX/2 expedition, 2007, PFS Polarstern → Dredged material



Lucky B Vent Field, Lucky Ridge, Lena Trough

(81.36°N, 3.44°W, 4000 mbsl)

GoNorth 2023 expedition, RV Kronsprins Haakon → Active vent



High-temperature peridotite-hosted vent field

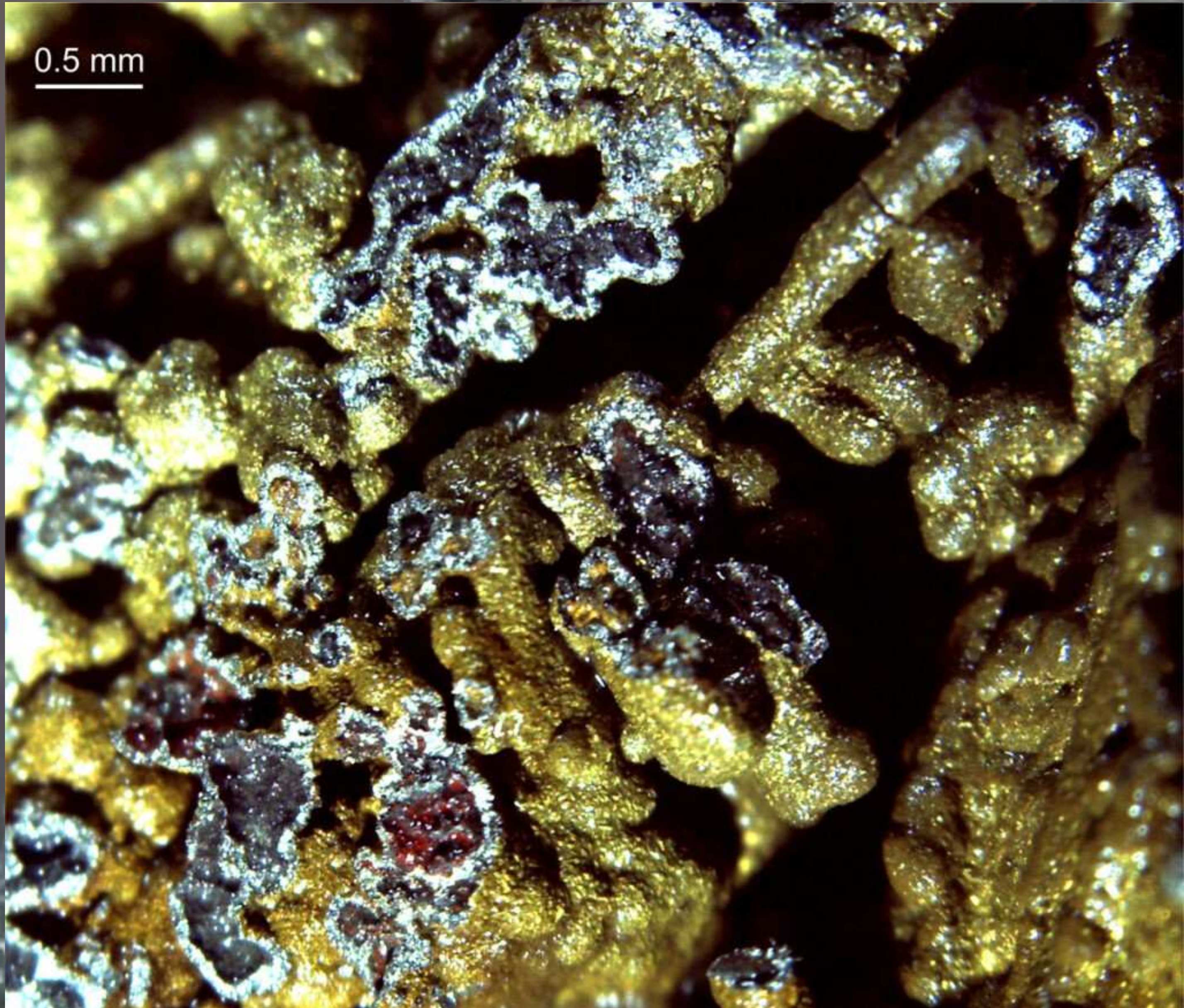
Cu-Co rich mineralization

Active part of the system

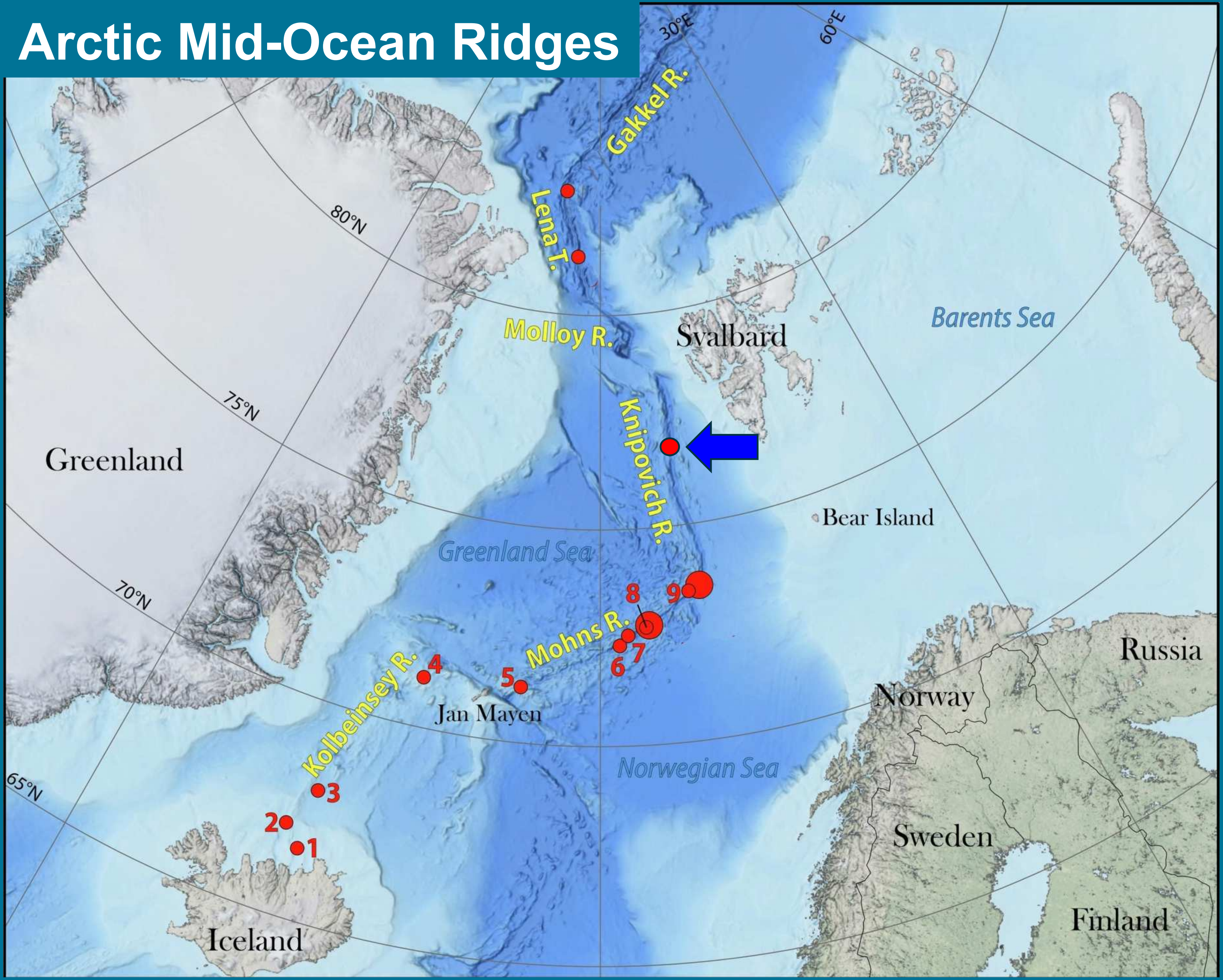
Cu: < 9.5 wt.%, average: 1.9 wt.%

Inctive part of the system

Cu: <3.4 wt.%, average: 0.5 wt.%



Arctic Mid-Ocean Ridges

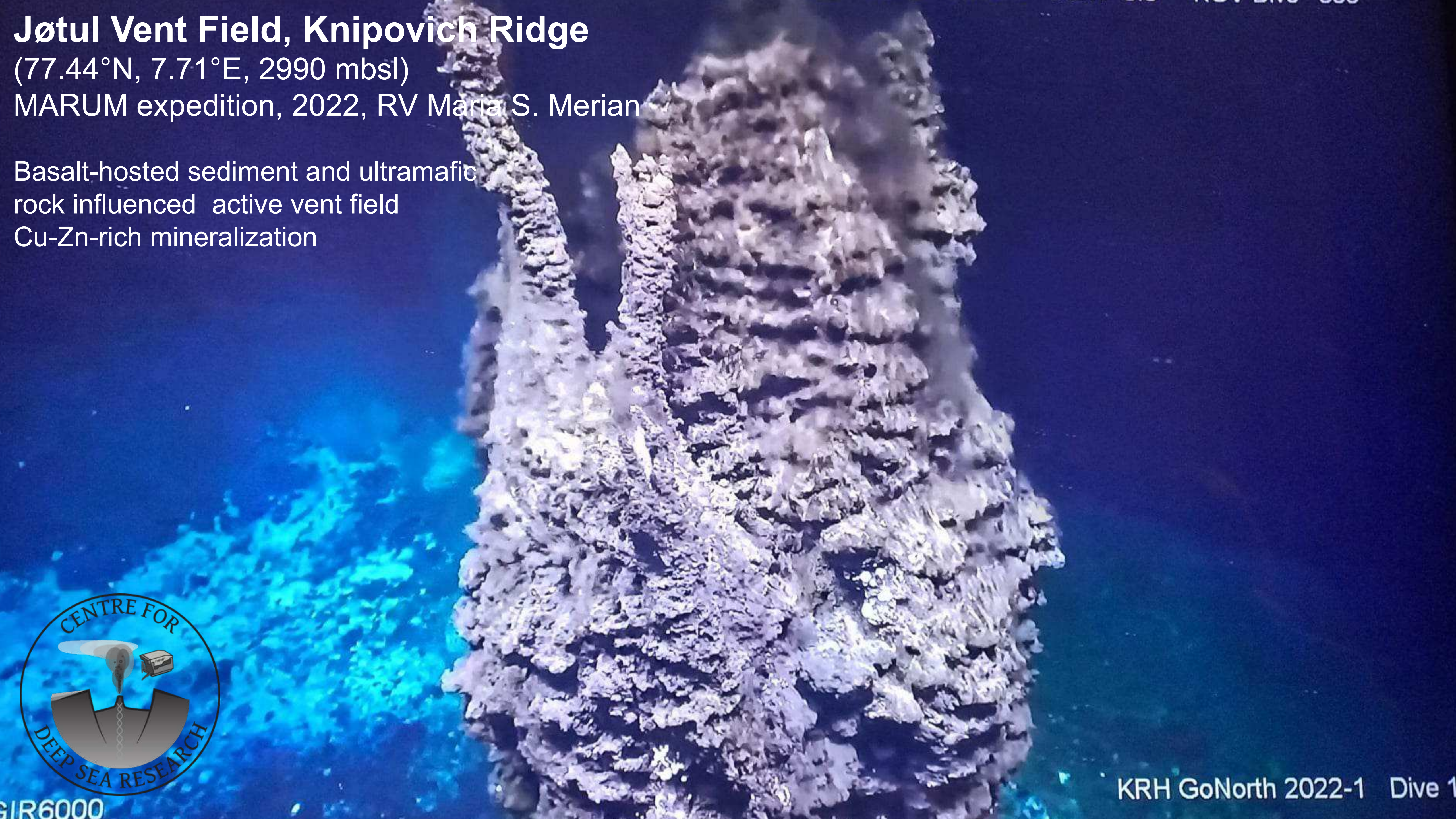


Sahlström et al. (2023)

Jøtul Vent Field, Knipovich Ridge

(77.44°N, 7.71°E, 2990 mbsl)
MARUM expedition, 2022, RV Maria S. Merian

Basalt-hosted sediment and ultramafic rock influenced active vent field
Cu-Zn-rich mineralization



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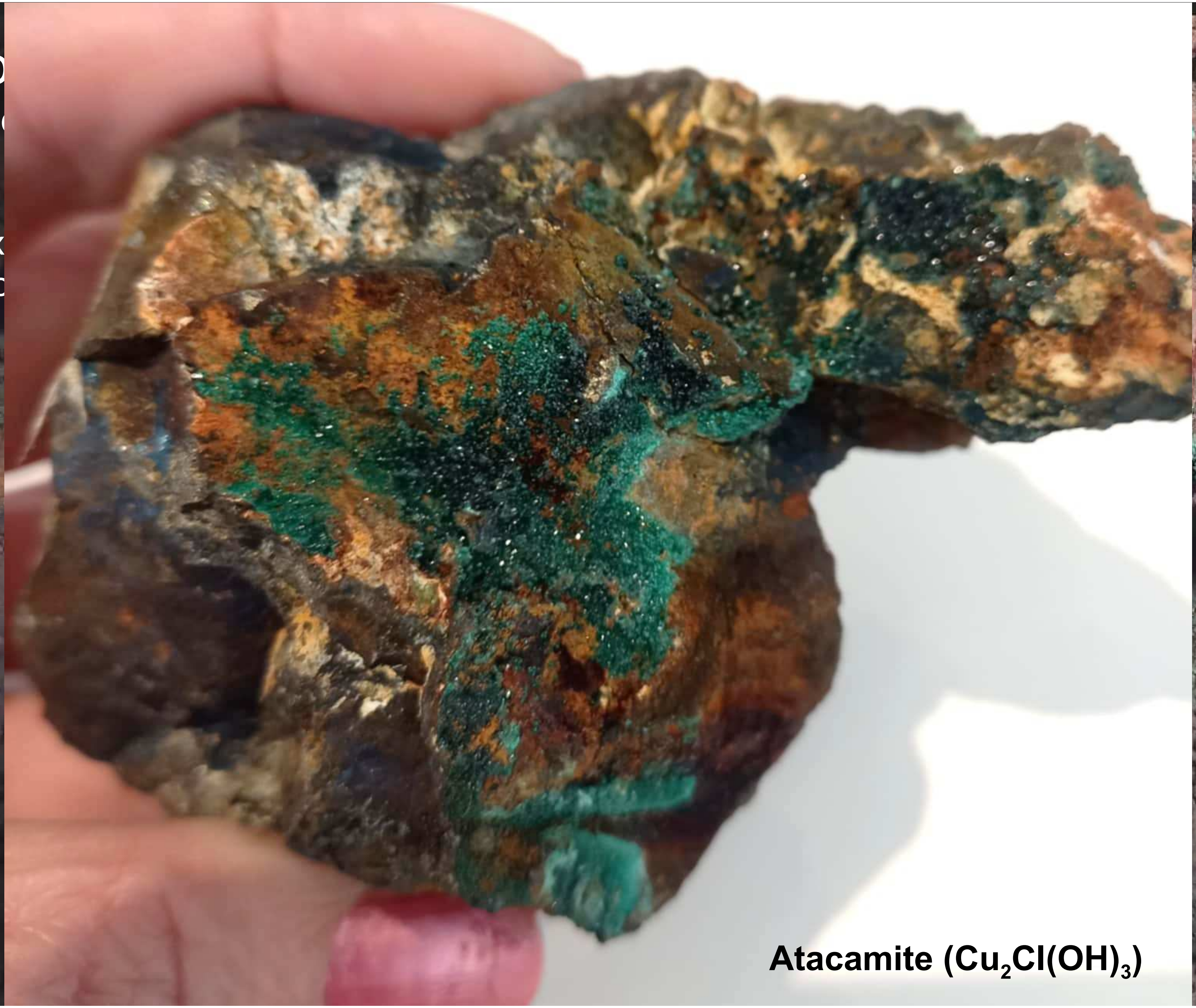
Gygra, Kniep

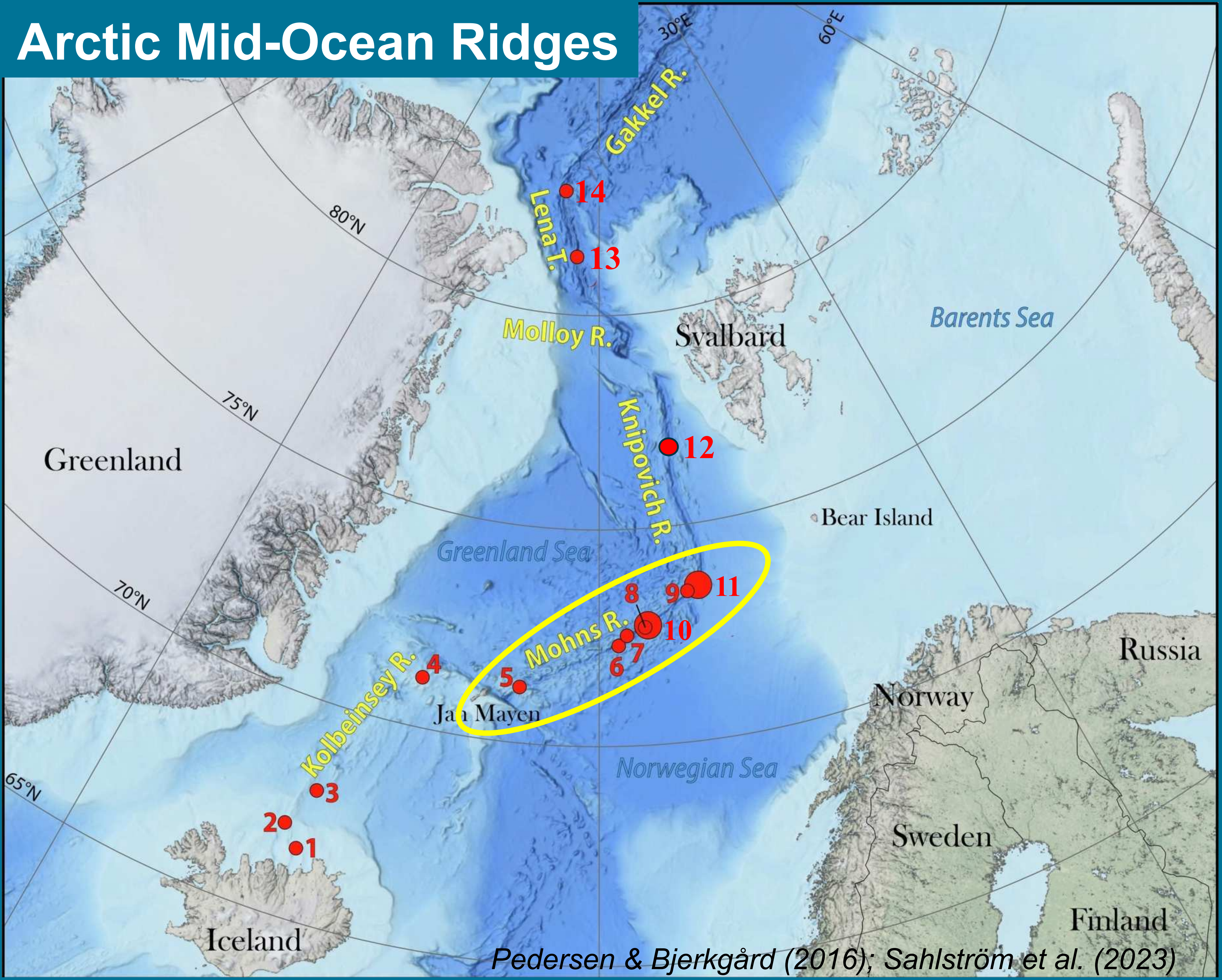
UiB-UiT-NOD expe

Peridotite-hosted ex
Cu rich mineralizatio



Ægir 6000

Arctic Mid-Ocean Ridges



Pedersen & Bjerkgård (2016); Sahlström et al. (2023)

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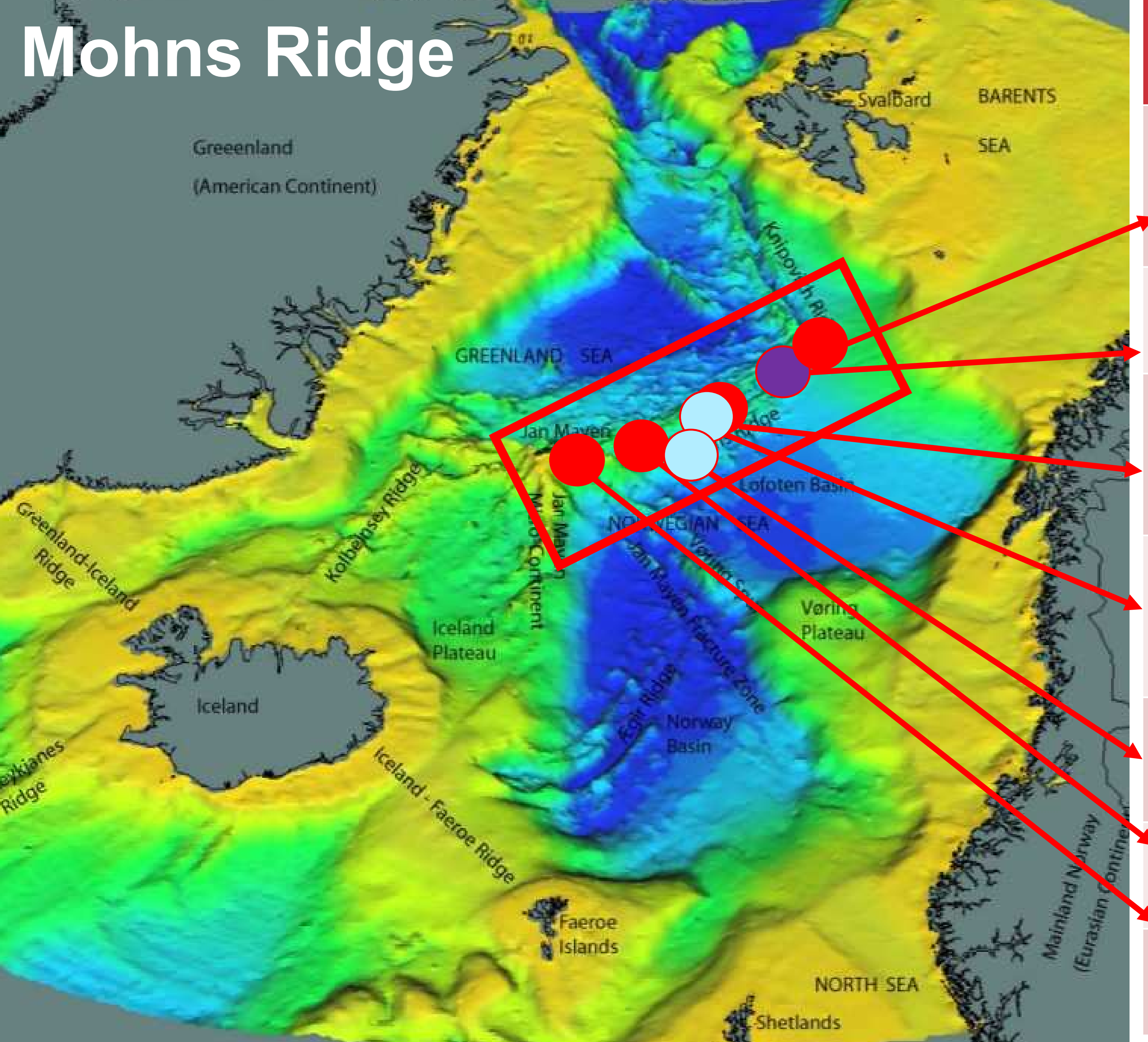
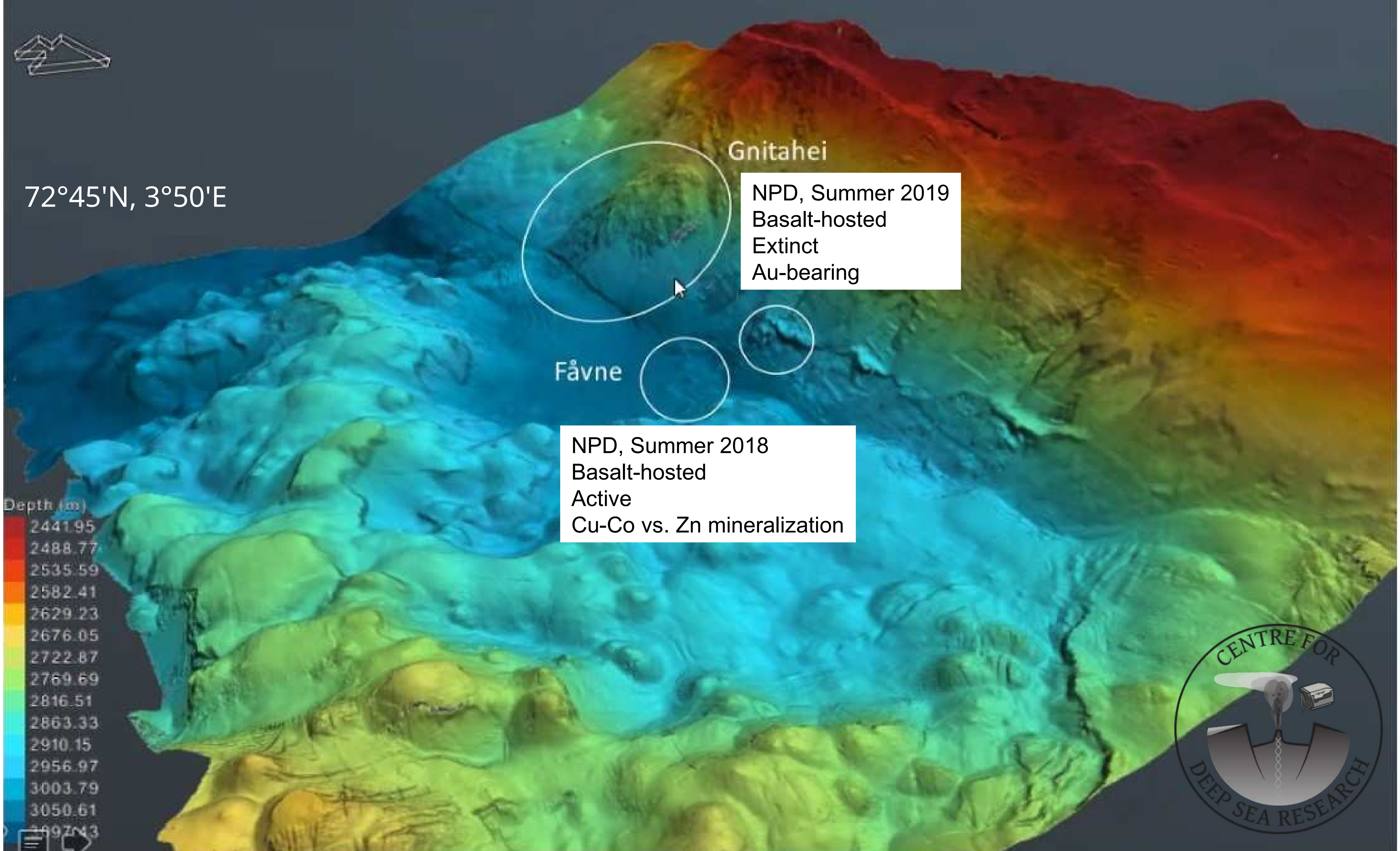
Mohns Ridge



Vent field	Characteristics
Loki's Castle (~2300 m)	Basalt-hosted, sediment influenced (Pb, Zn, Cu, Au, Brt + Hg, Tl, Cd,…)
Mohns Treasure (~2600 m)	Basalt-hosted (Cu, Zn, Au)
Fåvne (~3000 m)	Basalt-hosted, ultramafic rock influenced (Cu, Co vs. Zn)
Gnitahei (~2700 m)	Extinct, Basalt-hosted, sub-seafloor mineralization (Au)
Deep Insight (~1300 m)	Extinct, Basalt-hosted (Cu)
Æegir (~2400 m)	Basalt-hosted (Cu, Zn)
Soria Moria (~700 m)	Basalt-hosted (Zn, Brt)


72°45'N, 3°50'E
Gnitahei
NPD, Summer 2019
Basalt-hosted
Extinct
Au-bearing
Fåvne
NPD, Summer 2018
Basalt-hosted
Active
Cu-Co vs. Zn mineralization
Depth (m)
2441.95
2488.77
2535.59
2582.41
2629.23
2676.05
2722.87
2769.69
2816.51
2863.33
2910.15
2956.97
3003.79
3050.61
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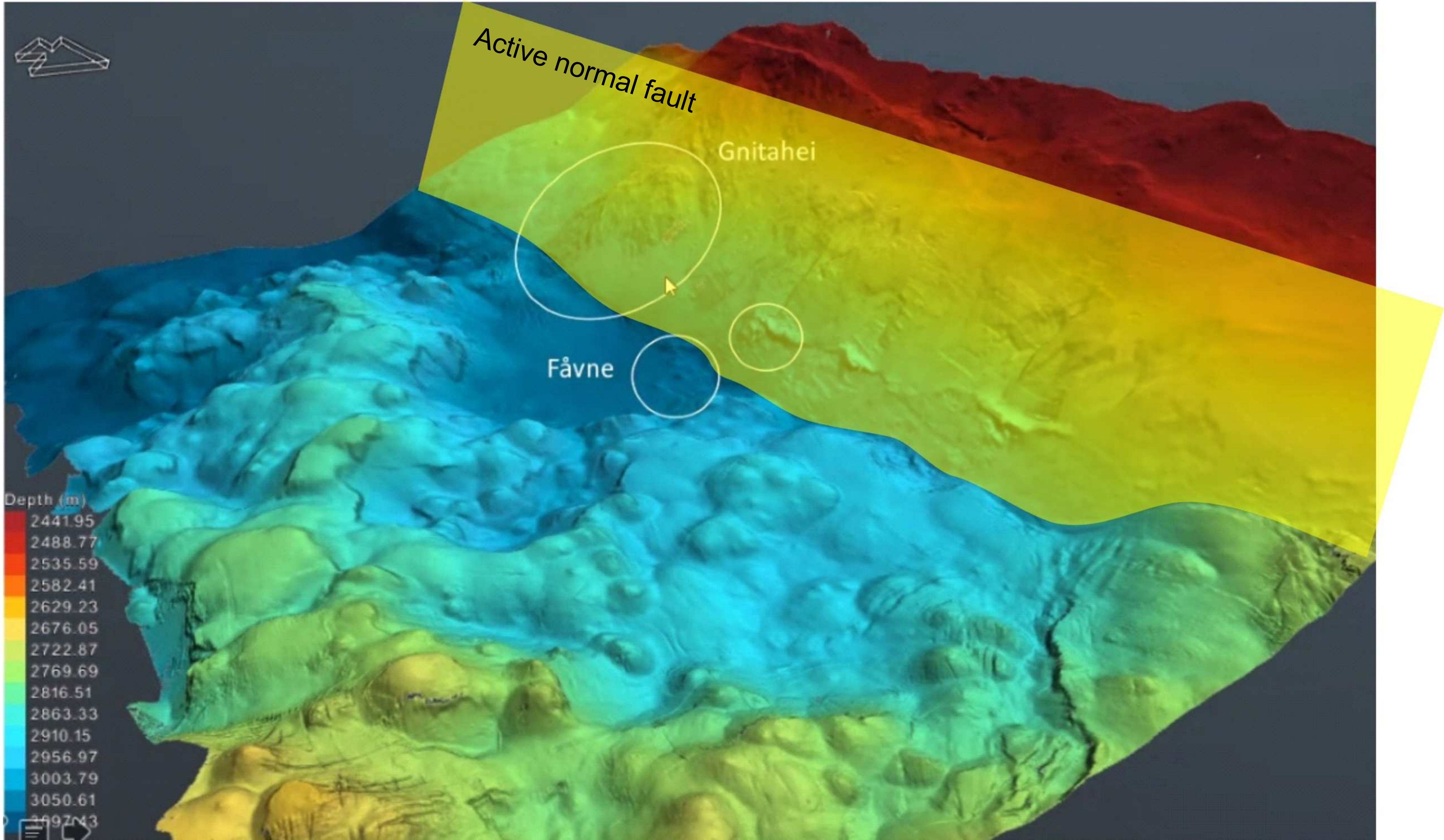
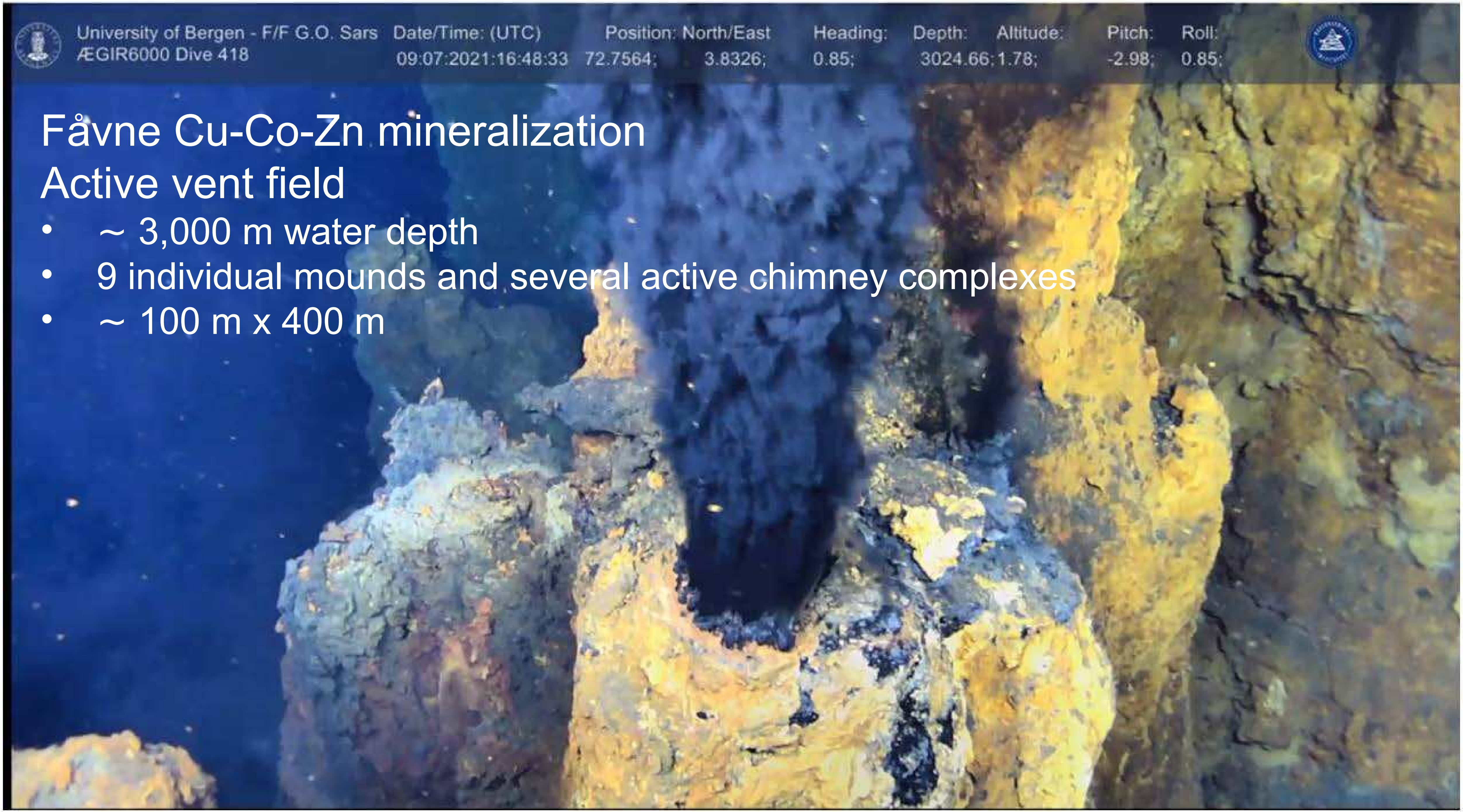
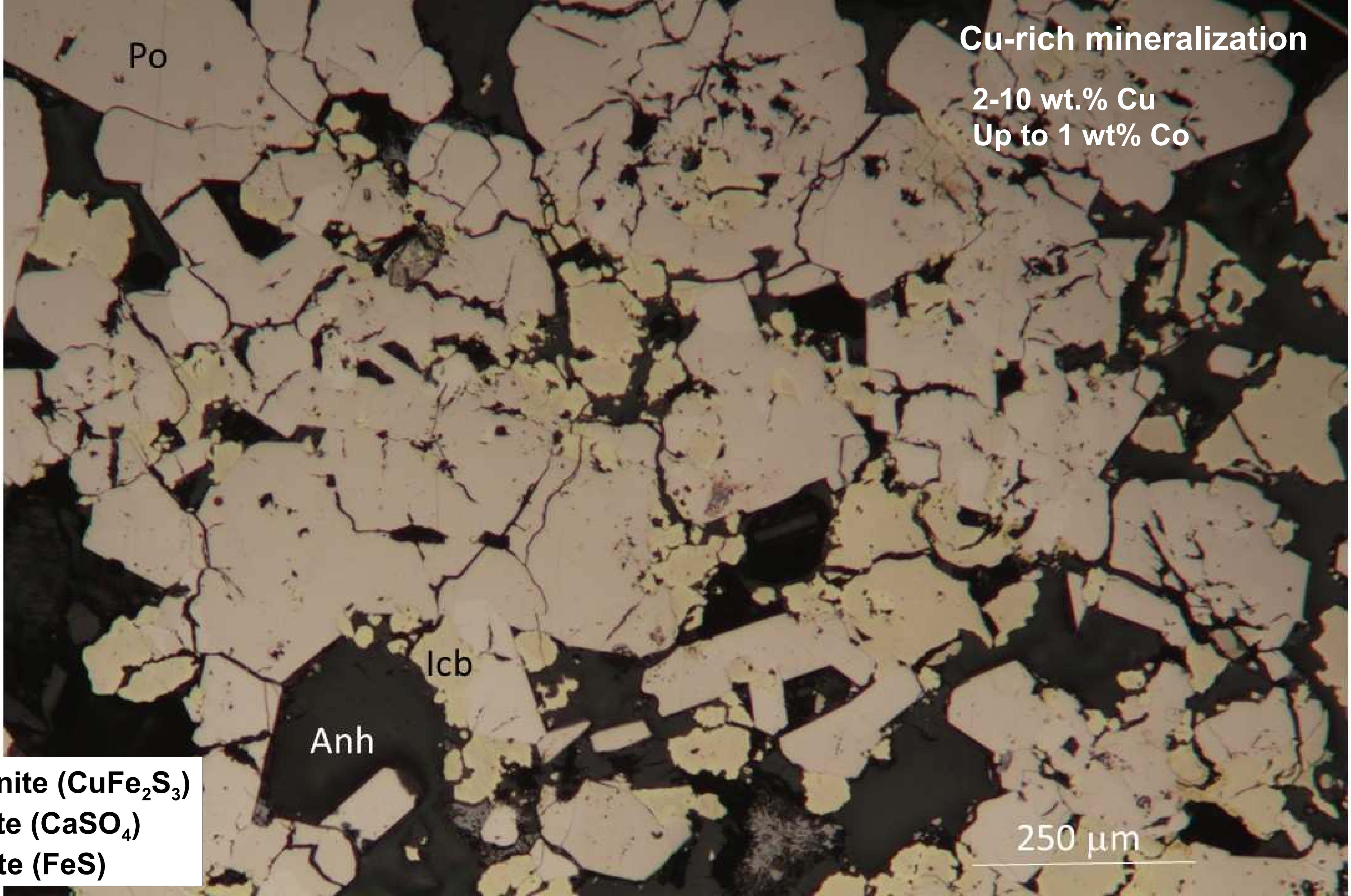

Active normal fault
Gnitahei
Fåvne
Depth (m)
2441.95
2488.77
2535.59
2582.41
2629.23
2676.05
2722.87
2769.69
2816.51
2863.33
2910.15
2956.97
3003.79
3050.61

Fåvne Cu-Co-Zn mineralization
Active vent field

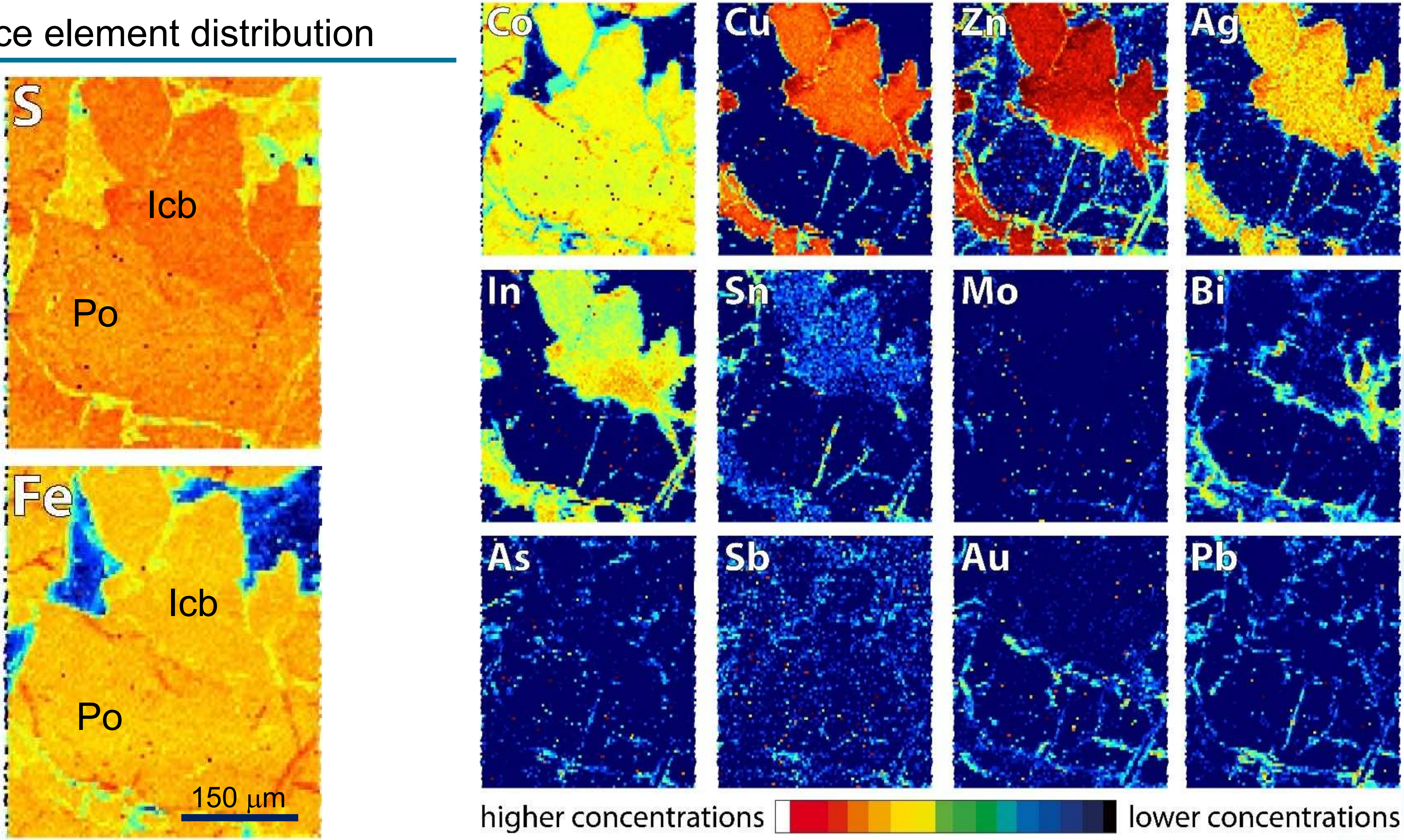
- ~ 3,000 m water depth
- 9 individual mounds and several active chimney complexes
- ~ 100 m x 400 m

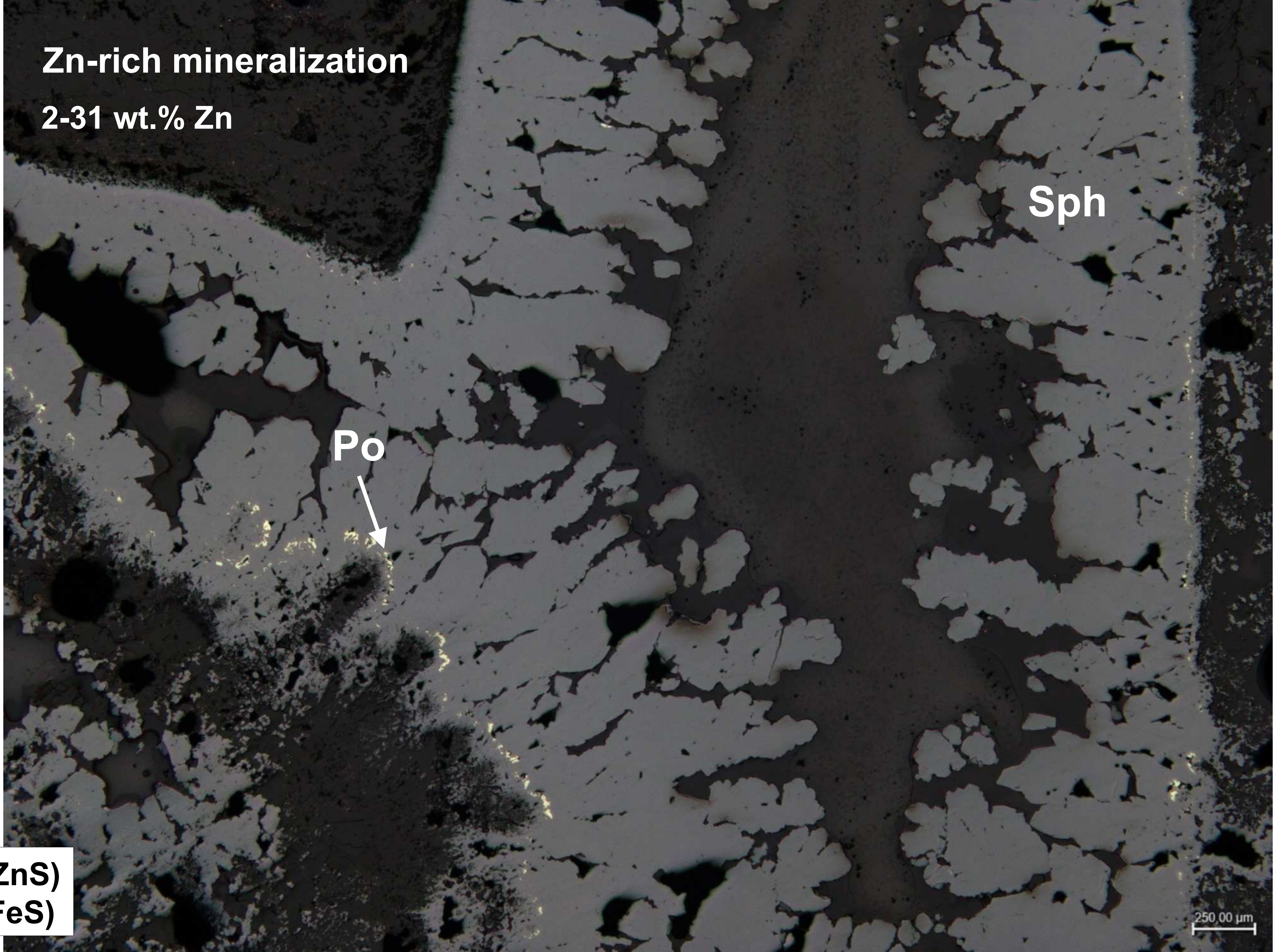




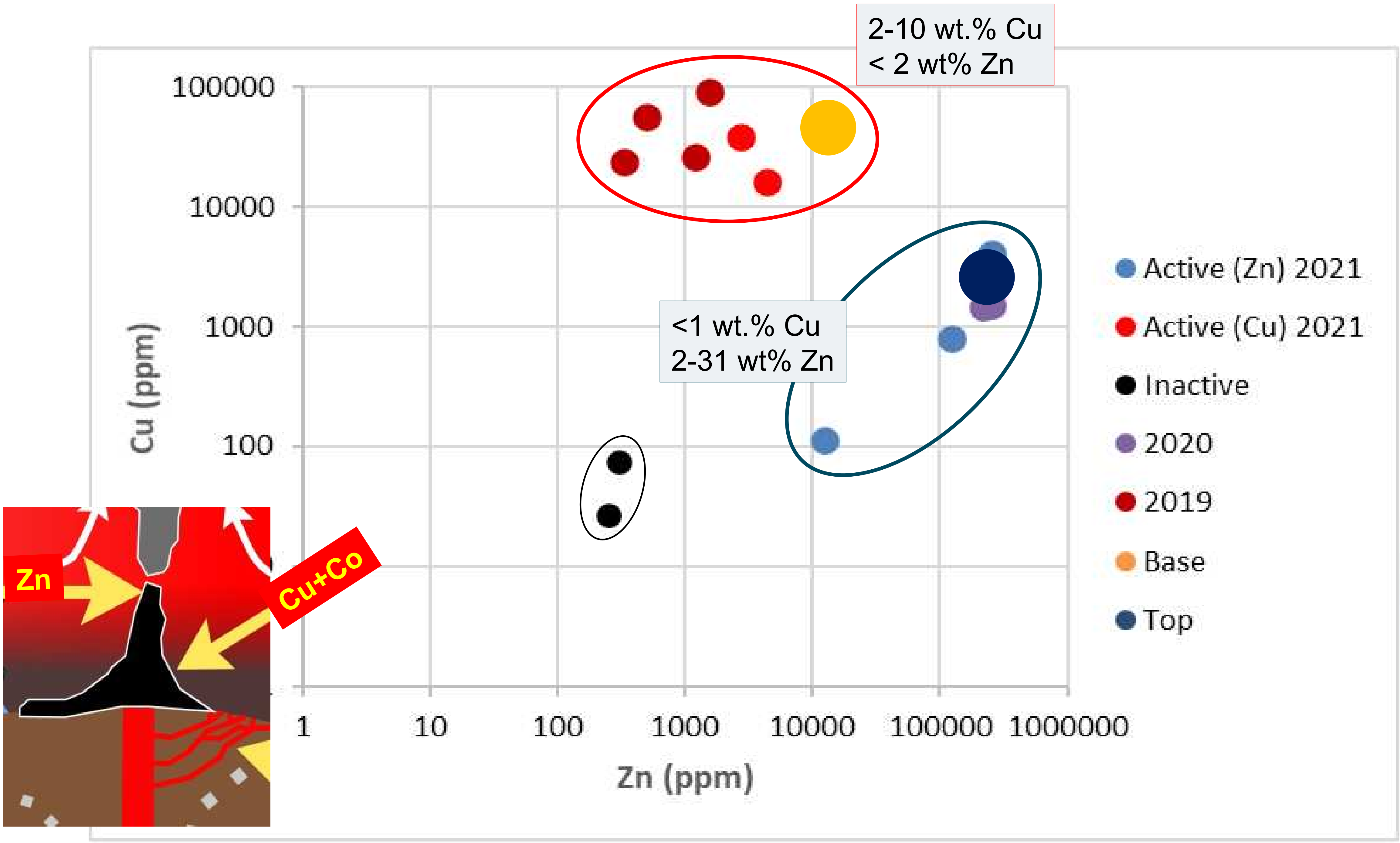
Isocubanite ($CuFe_2S_3$)
Andydrite ($CaSO_4$)
Pyrrhotite (FeS)

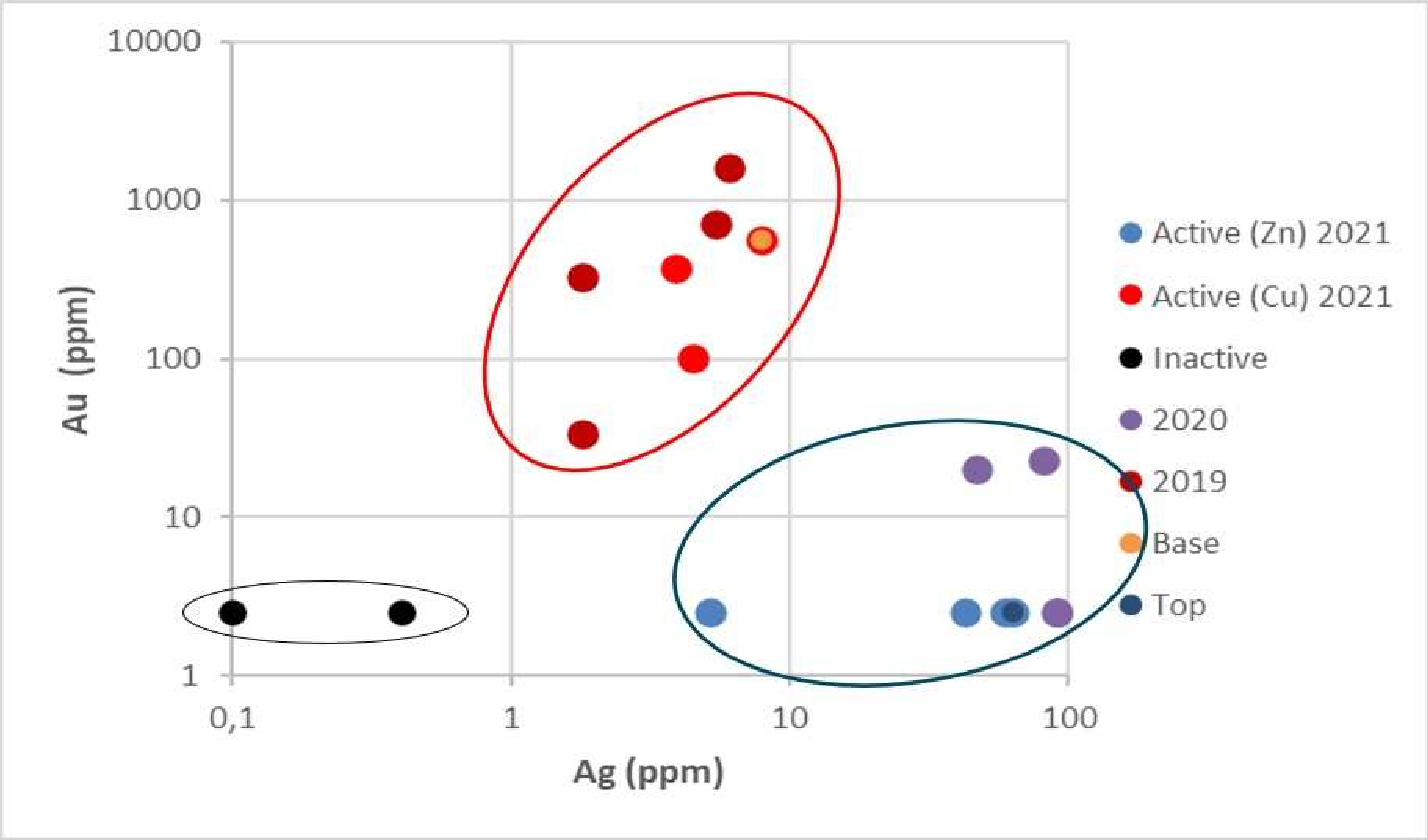
Trace element distribution





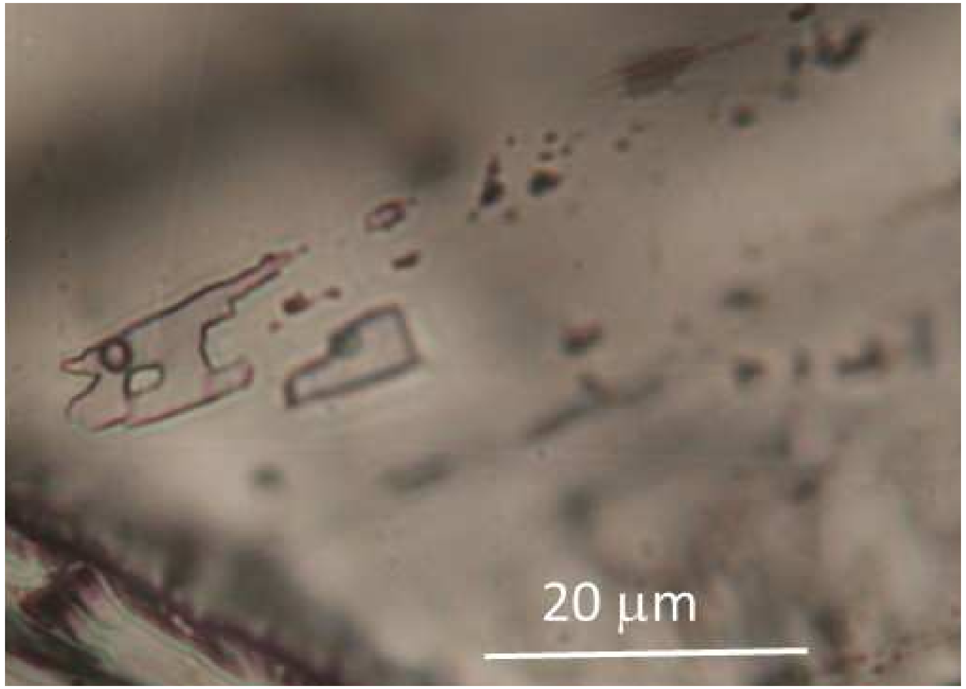
Sphalerite (ZnS)
Pyrrhotite (FeS)

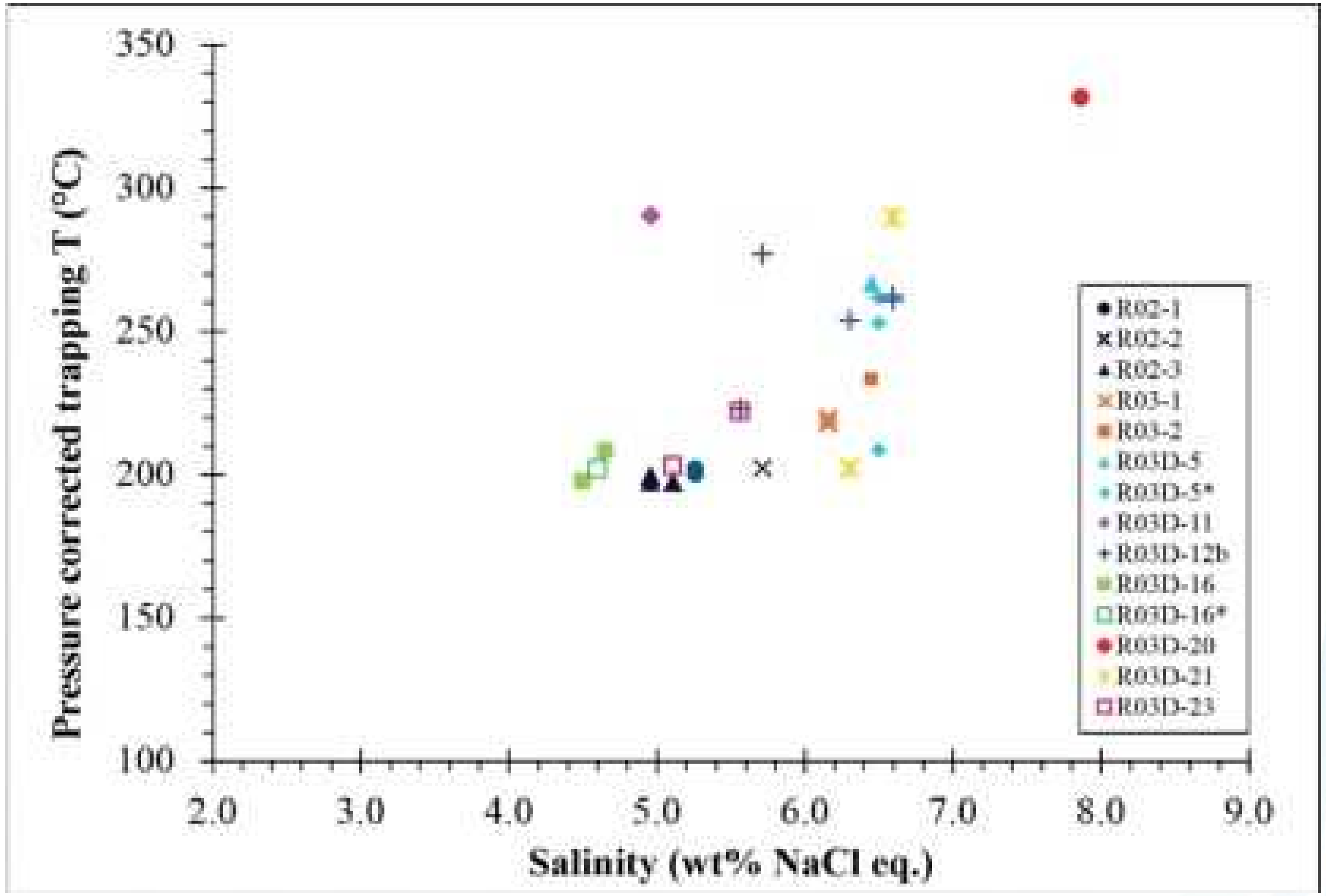

2-10 wt.% Cu
< 2 wt% Zn
<1 wt.% Cu
2-31 wt% Zn
100000
10000
1000
100
Cu (ppm)
1
10
100
1000
10000
100000
1000000
Zn (ppm)
Active (Zn) 2021
Active (Cu) 2021
Inactive
2020
2019
Base
Top
Zn
Cu+Co



10000
1000
100
10
1
0,1
1
10
100
Au (ppm)
Ag (ppm)
Active (Zn) 2021
Active (Cu) 2021
Inactive
2020
2019
Base
Top

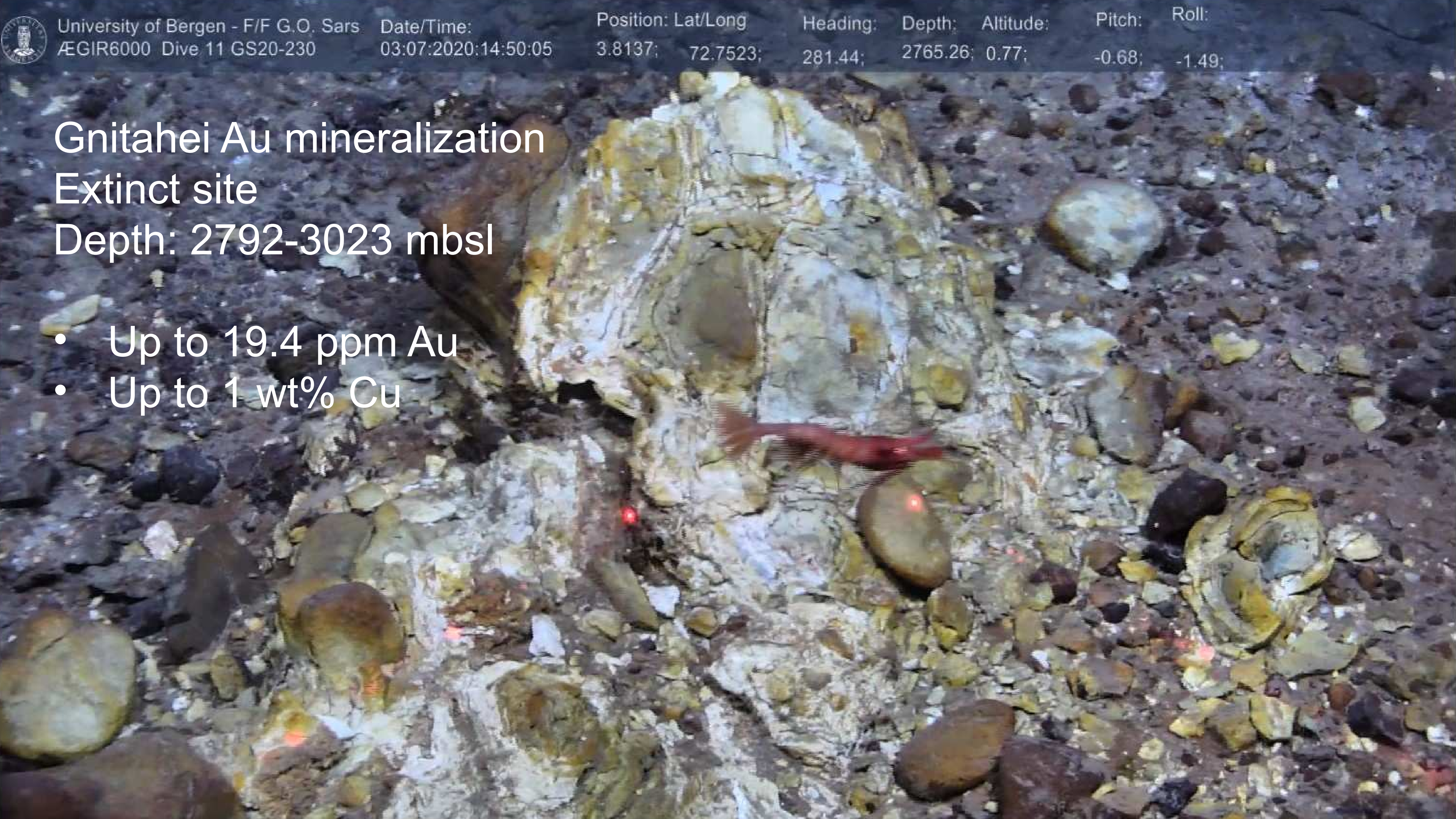
Fluid inclusion study



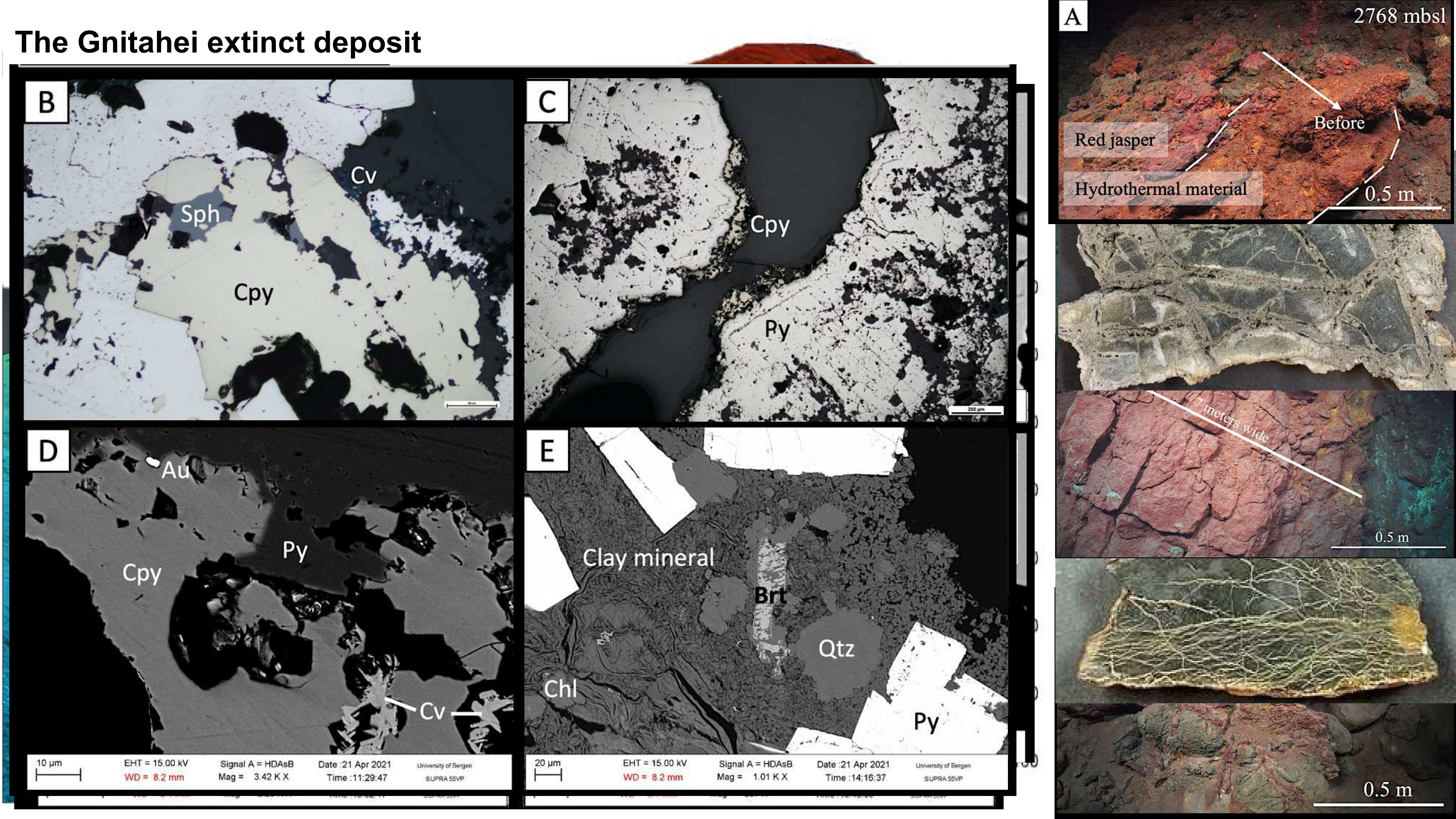


- Anhydrite, Cu-rich mineralization
- NaCl-$CaCl_2$-H_2O system
- L+V and L-only FIAs
- Uniform F within individual FIAs
- 4 – 8 wt.% NaCl equ.
- Th= 160 – 332°C

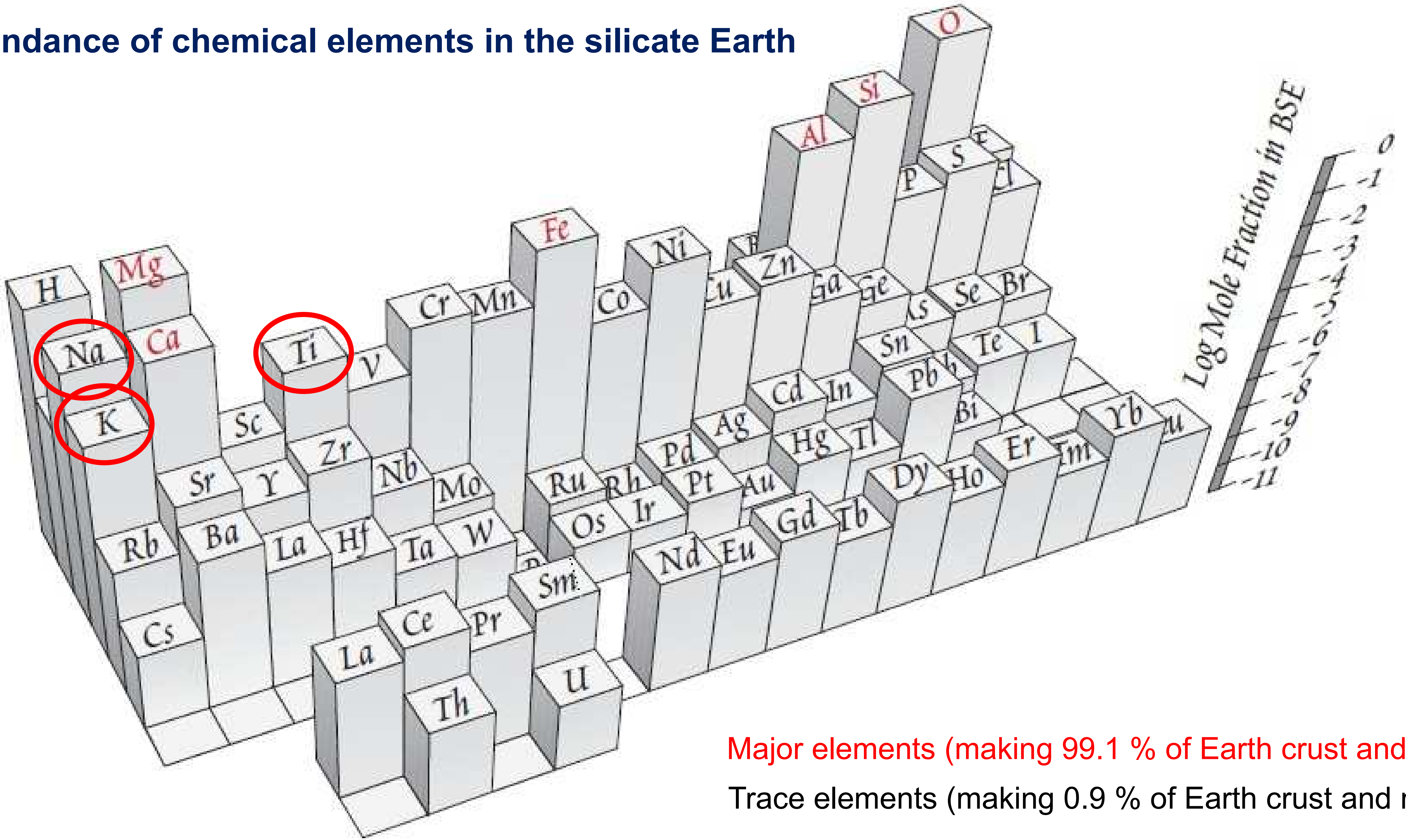
- Abundant anhydrite → prevents infiltration of seawater → supports conductive cooling


University of Bergen - F/F G.O. Sars
ÆGIR6000 Dive 11 GS20-230
Date/Time:
03:07:2020:14:50:05
Position: Lat/Long
3.8137; 72.7523;
Heading:
281.44;
Depth:
2765.26;
Altitude:
0.77;
Pitch:
-0.68;
Roll:
-1.49;
Gnitahei Au mineralization
Extinct site
Depth: 2792-3023 mbsl
• Up to 19.4 ppm Au
• Up to 1 wt% Cu

The Gnitahei extinct deposit



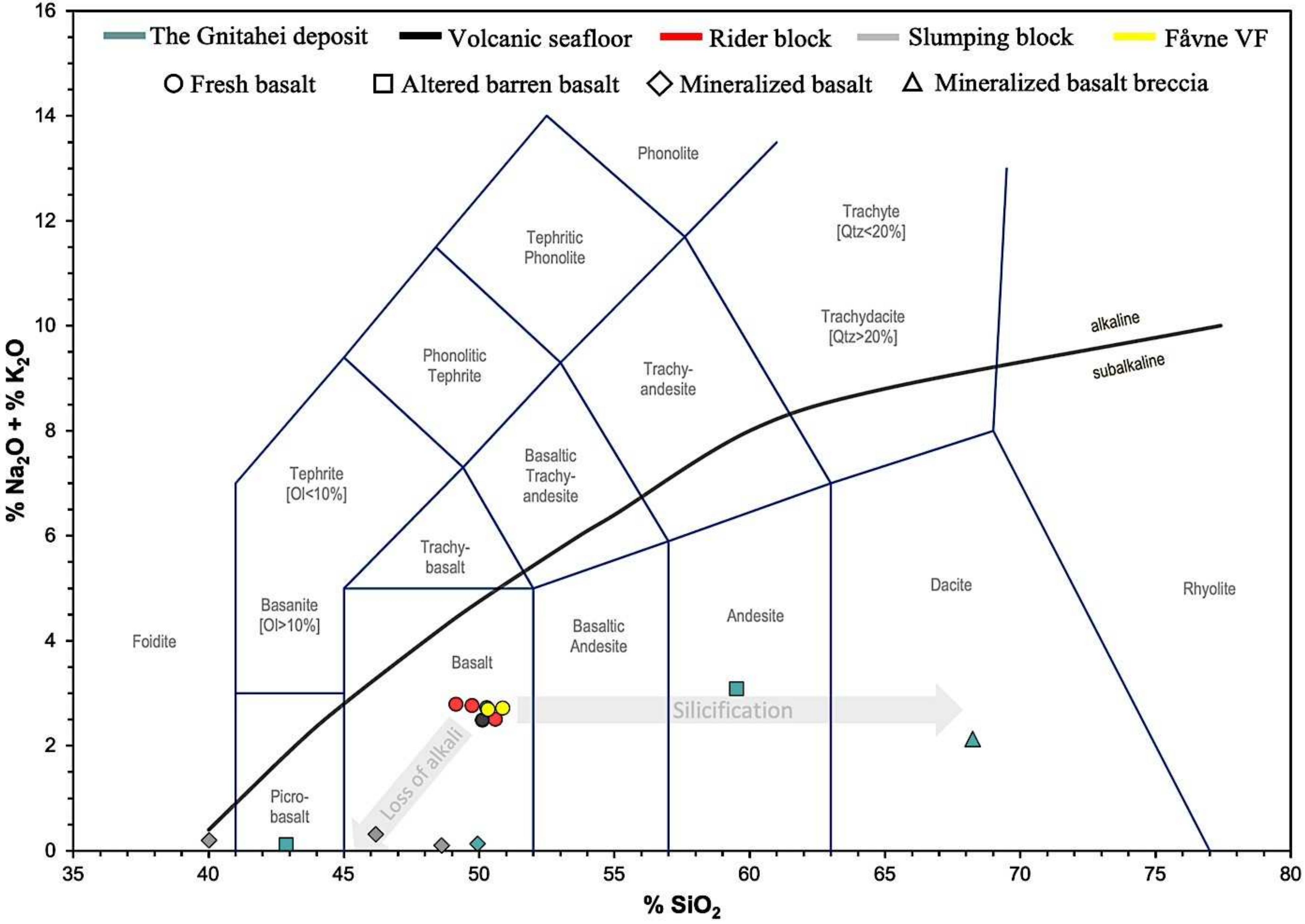
Abundance of chemical elements in the silicate Earth



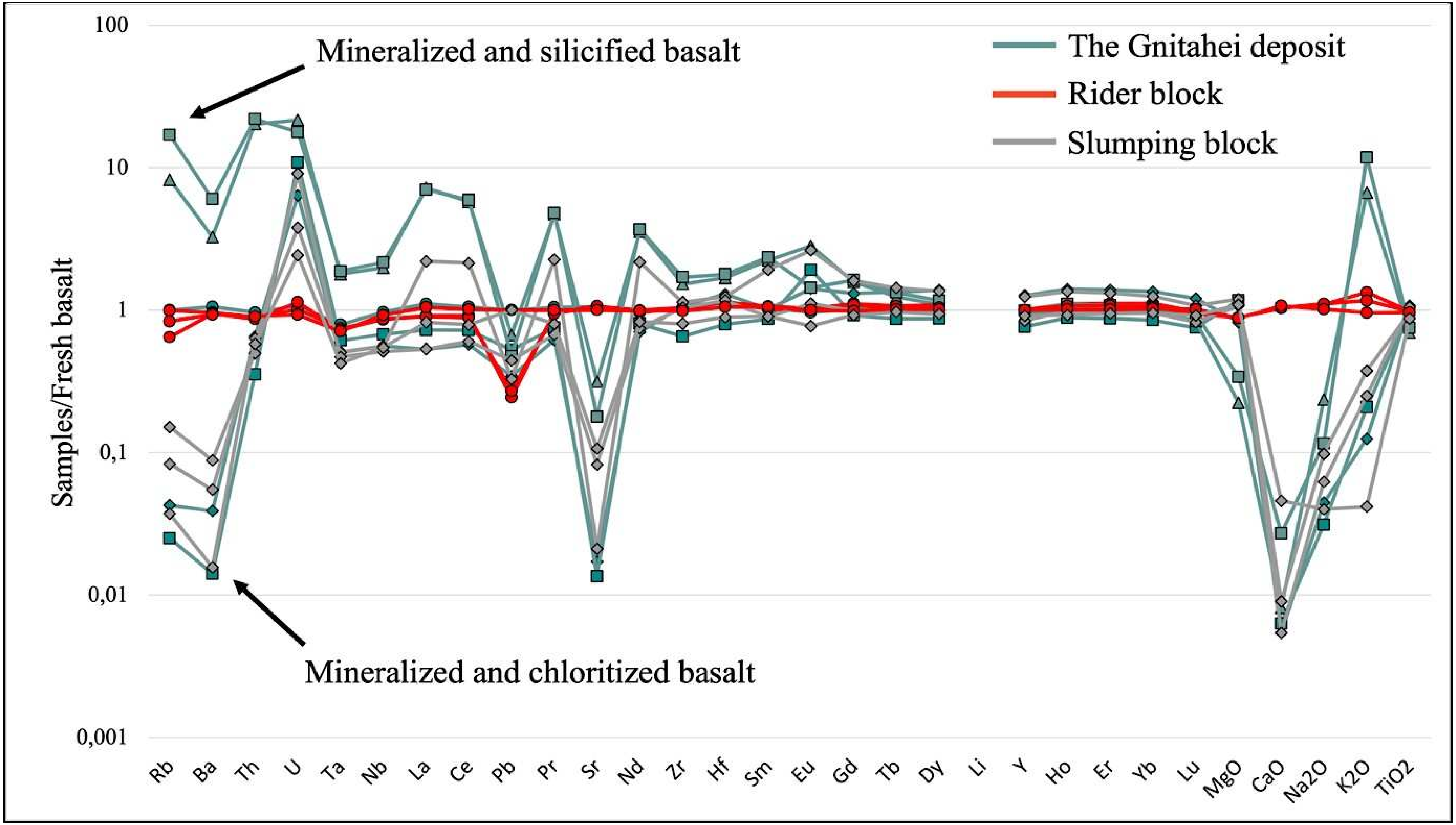
Major elements (making 99.1 % of Earth crust and mantle)

Trace elements (making 0.9 % of Earth crust and mantle)

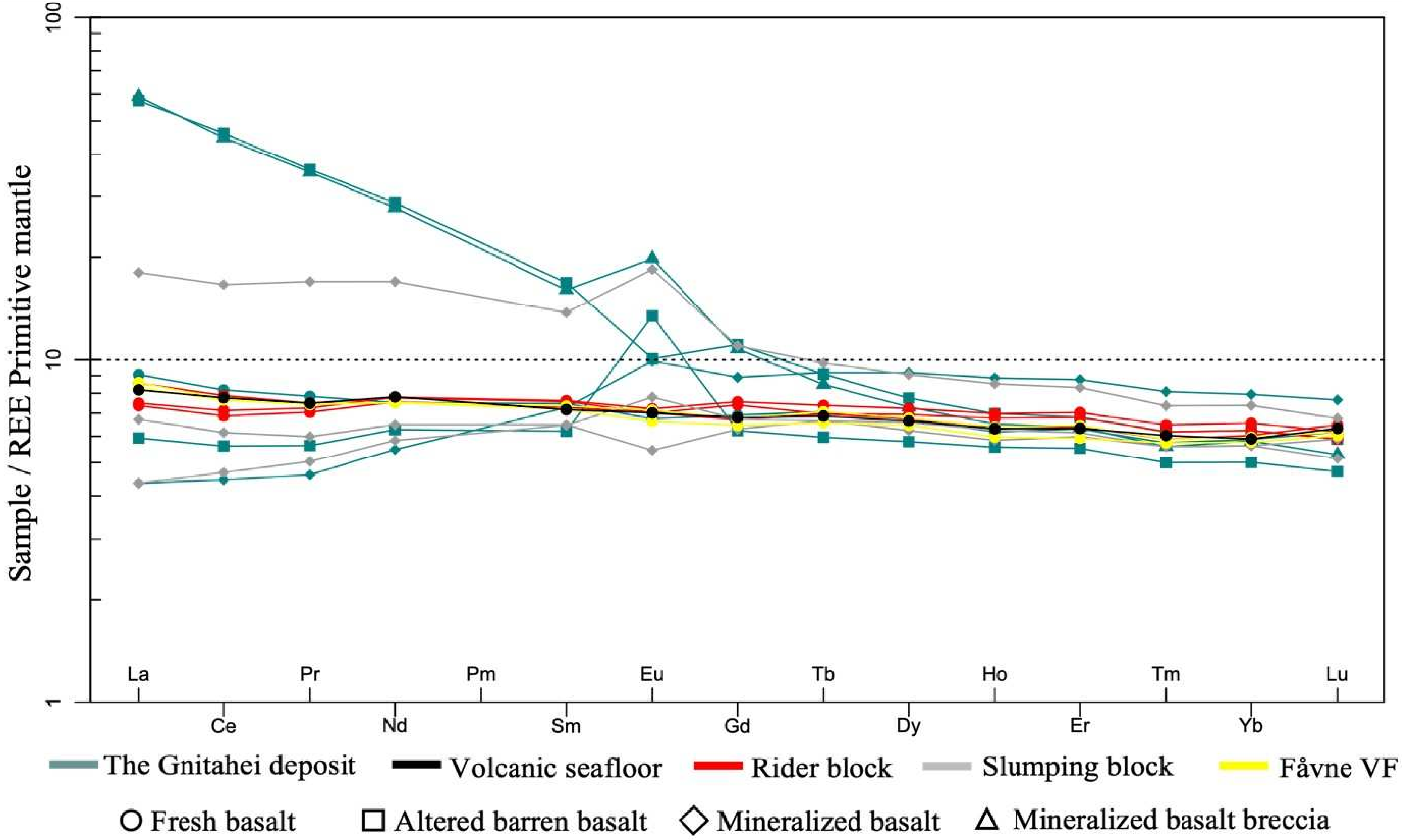
White (2013)



The Gnitahei deposit
Volcanic seafloor
Rider block
Slumping block
Fåvne VF
Fresh basalt
Altered barren basalt
Mineralized basalt
Mineralized basalt breccia
Phonolite
Tephritic Phonolite
Phonolitic Tephrite
Tephrite [Ol<10%]
Basanite [Ol>10%]
Foidite
Picro-basalt
Trachy-basalt
Basaltic Trachy-andesite
Trachy-andesite
Trachyte [Qtz<20%]
Trachydacite [Qtz>20%]
Basalt
Basaltic Andesite
Andesite
Dacite
Rhyolite
alkaline
subalkaline
Silicification
Loss of alkali
% Na2O + % K2O
% SiO2



Mineralized and silicified basalt
Mineralized and chloritized basalt
The Gnitahei deposit
Rider block
Slumping block
Samples/Fresh basalt
100
10
1
0,1
0,01
0,001
Rb
Ba
Th
U
Ta
Nb
La
Ce
Pb
Pr
Sr
Nd
Zr
Hf
Sm
Eu
Gd
Tb
Dy
Li
Y
Ho
Er
Yb
Lu
MgO
CaO
Na2O
K2O
TiO2



100
10
1
Sample / REE Primitive mantle
La
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
The Gnitahei deposit
Volcanic seafloor
Rider block
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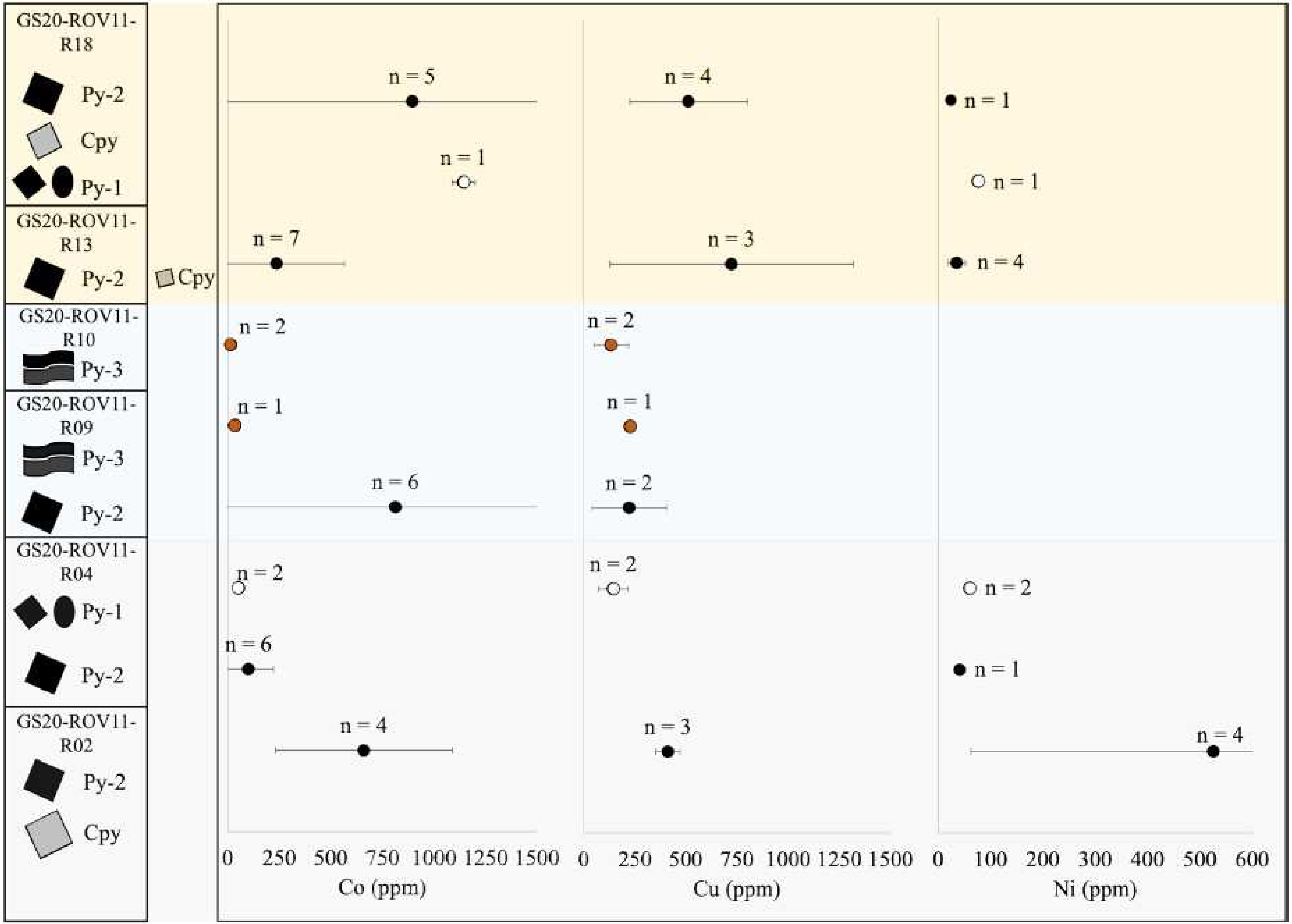
Fåvne VF
Fresh basalt
Altered barren basalt
Mineralized basalt
Mineralized basalt breccia

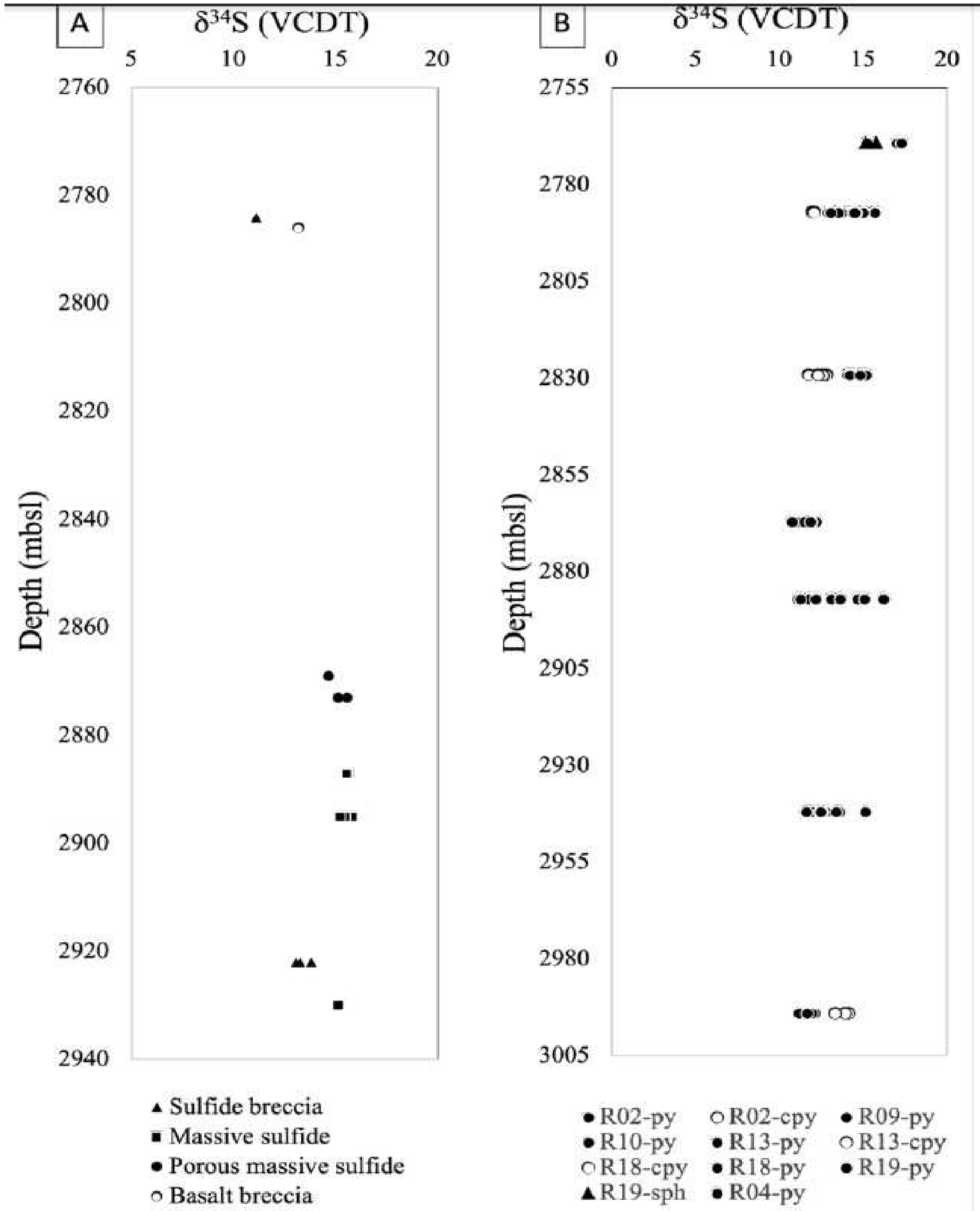


GS20-ROV11-R18
Py-2
Cpy
Py-1
GS20-ROV11-R13
Py-2
Cpy
GS20-ROV11-R10
Py-3
GS20-ROV11-R09
Py-3
Py-2
GS20-ROV11-R04
Py-1
Py-2
GS20-ROV11-R02
Py-2
Cpy
n = 5
n = 4
n = 1
n = 1
n = 1
n = 7
n = 3
n = 4
n = 2
n = 2
n = 1
n = 1
n = 6
n = 2
n = 2
n = 2
n = 2
n = 6
n = 1
n = 4
n = 3
n = 4
0 250 500 750 1000 1250 1500
Co (ppm)
0 250 500 750 1000 1250 1500
Cu (ppm)
0 100 200 300 400 500 600
Ni (ppm)

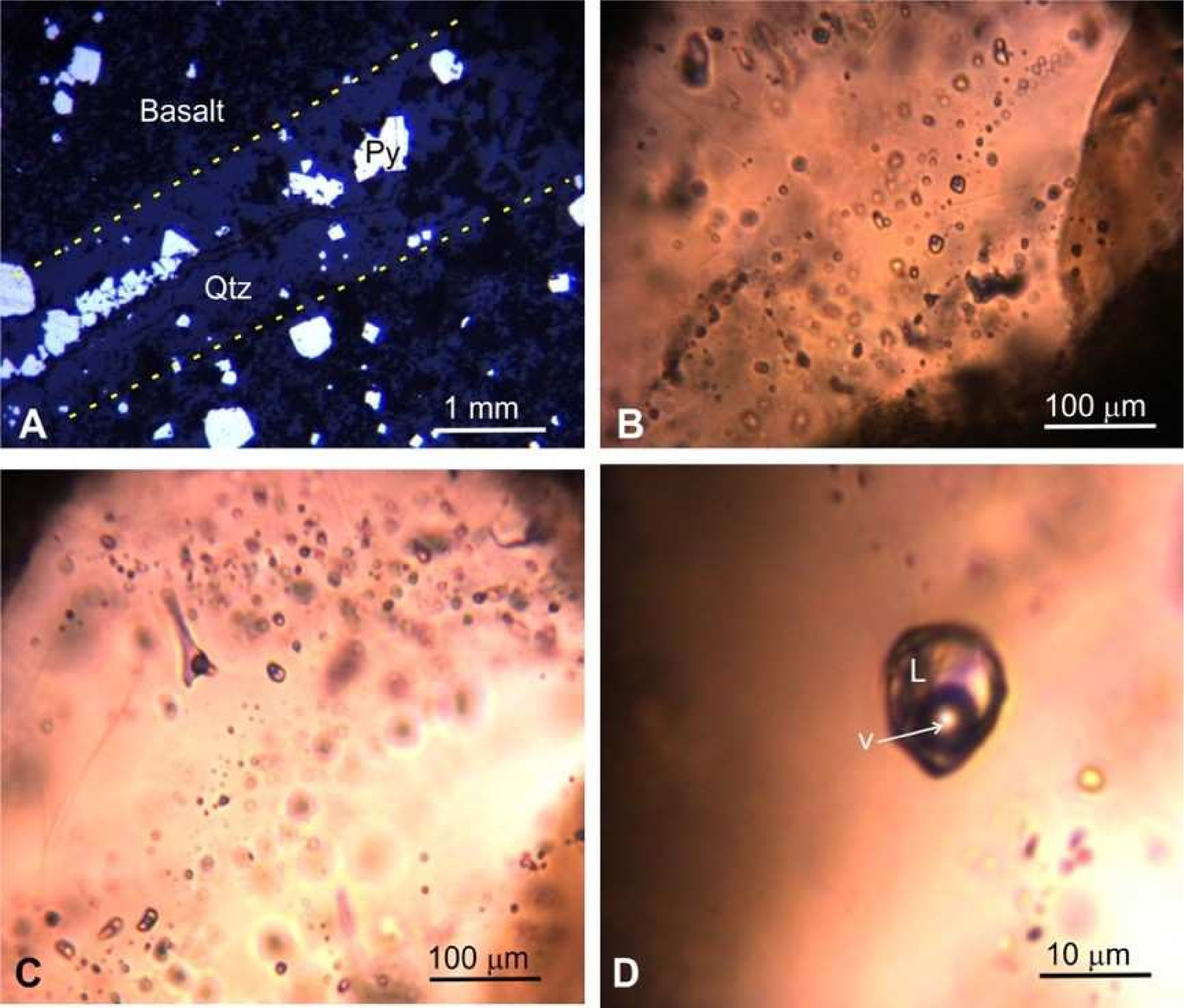
Stable isotopes in hydrothermal systems

^{32}S	^{33}S	^{34}S	^{36}S
31.97207	32.97145	33.96786	35.96708
95.02%	0.75%	4.21%	0.02%
Stable	Stable	Stable	Stable

$$\delta^{34}S = \left(\frac{\left(^{34}S/^{32}S\right)_{sample} - \left(^{34}S/^{32}S\right)_{standard}}{\left(^{34}S/^{32}S\right)_{standard}} \right) \times 1000$$



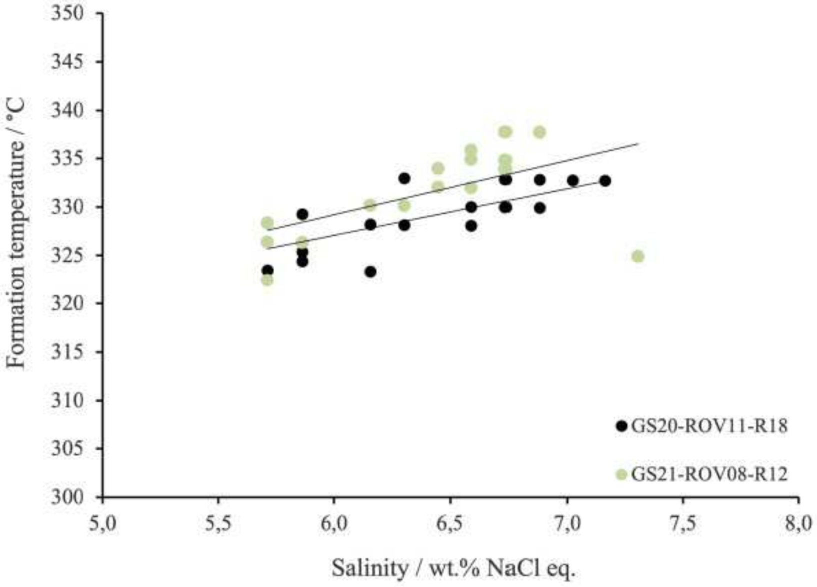
$\delta^{34}S$=+11.1 to +15.9 ‰ V-CDT

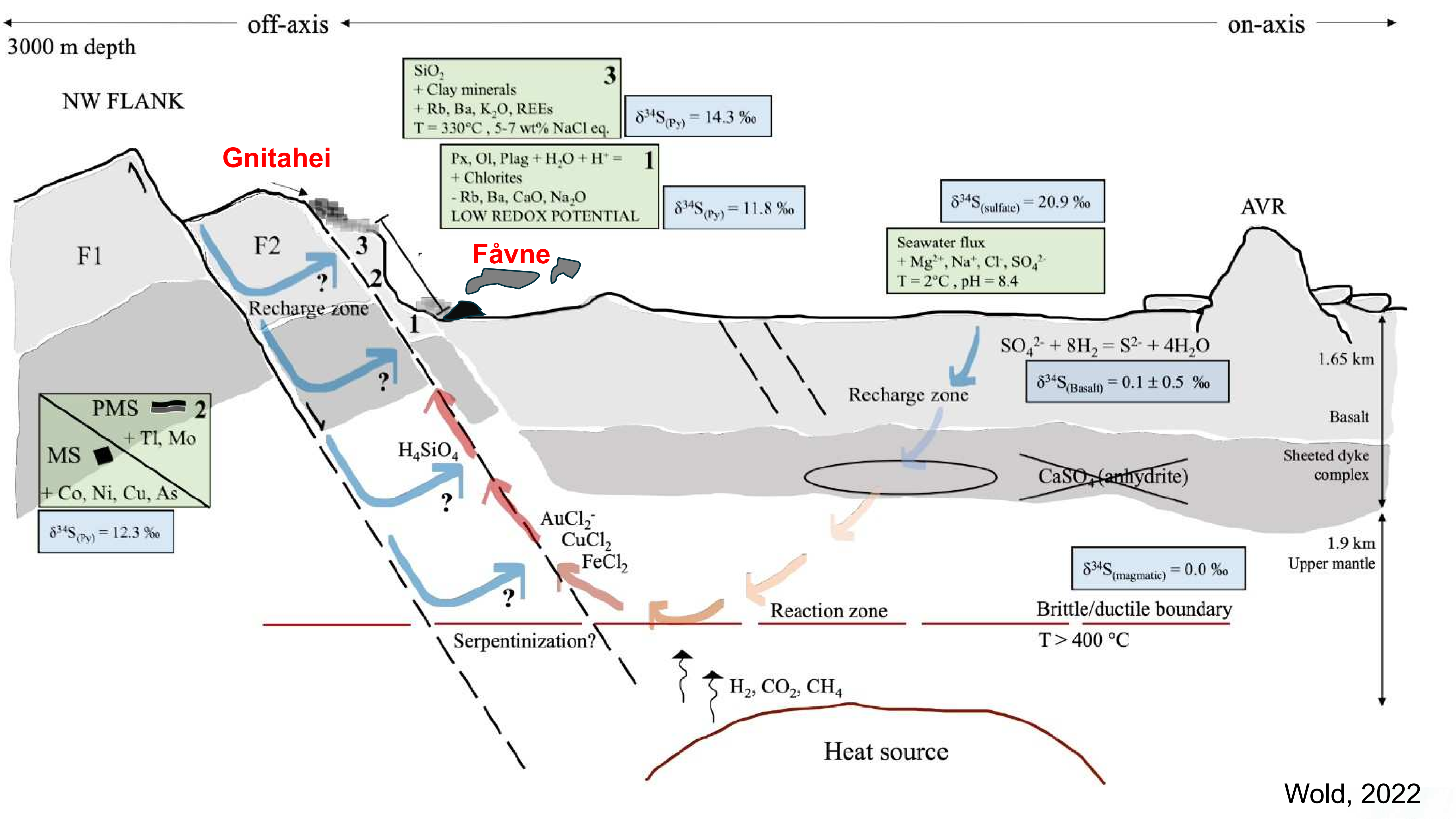


Silicified part of the deposit

Salinity=5.7 – 7.3 wt.% NaCl eq.
T_h=300-320°C
T_f=320-340°C
Density=0.75 g/cm^{-3}

- Au-Cl-complexes
- Cu-Cl-complexes




off-axis
on-axis
3000 m depth
NW FLANK
Gnitahei
Fåvne
F1
F2
SiO2
+ Clay minerals
+ Rb, Ba, K2O, REEs
T = 330°C , 5-7 wt% NaCl eq.
3
δ34S(Py) = 14.3 ‰
Px, Ol, Plag + H2O + H+ =
+ Chlorites
- Rb, Ba, CaO, Na2O
LOW REDOX POTENTIAL
1
δ34S(Py) = 11.8 ‰
δ34S(sulfate) = 20.9 ‰
Seawater flux
+ Mg2+, Na+, Cl-, SO42-
T = 2°C , pH = 8.4
AVR
Recharge zone
SO42- + 8H2 = S2- + 4H2O
δ34S(Basalt) = 0.1 ± 0.5 ‰
1.65 km
Basalt
Sheeted dyke
complex
CaSO4 (anhydrite)
PMS
2
+ Tl, Mo
MS
+ Co, Ni, Cu, As
δ34S(Py) = 12.3 ‰
H4SiO4
AuCl2-
CuCl2
FeCl2
1.9 km
Upper mantle
δ34S(magmatic) = 0.0 ‰
Reaction zone
Brittle/ductile boundary
T > 400 °C
Serpentinization?
H2, CO2, CH4
Heat source
Wold, 2022

Active vs. extinct submarine hydrothermal systems

	Active	Extinct
Cu grade	Moderate-high	Low-moderate
Zn grade	Moderate-high	Low
Co grade	Low-high	Low
Ore minerals	Icb, Cpy, Sph, Po, minor Py/Mrc	Py/Mrc dominated, minor Icb, Cpy, Sph, Po
Gangue minerals	Anhydrite, amorphous silica, minor barite	Quartz, minor barite