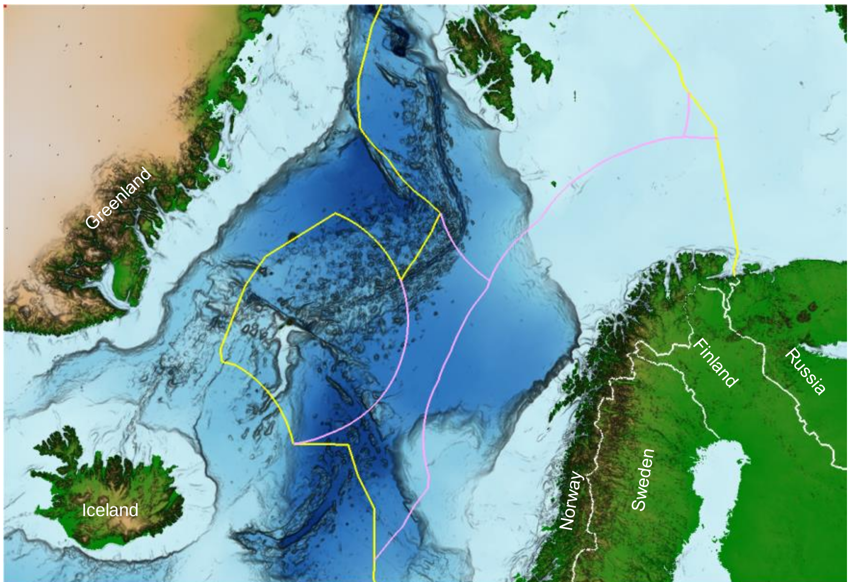
NORWEGIAN PETROLEUM DIRECTORATE

Deep Sea Minerals on the Norwegian Continental Shelf– Developments in Exploration

Brekke, H., Stenløkk, J., Eriksen, S. H., Bjørnstad, A., Sandstå, N. R., Solvi, K. and Schiager, P.

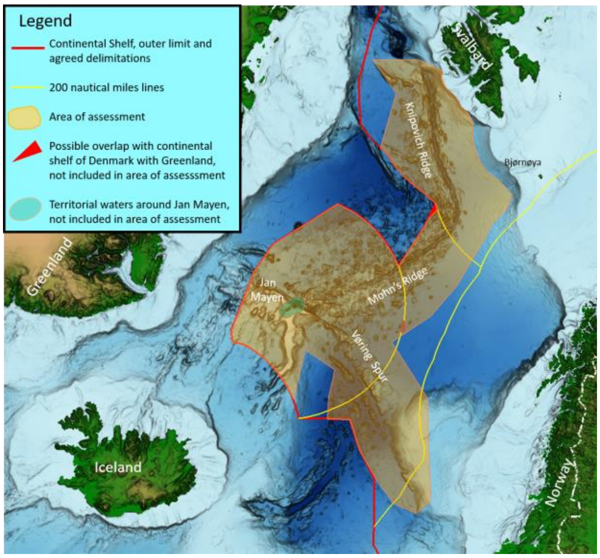
Norwegian Continental Shelf, Norwegian Sea Region



Major parts of the Norwegian Continental Shelf in the Norwegian Sea Region are at more than 1000 meters depth. On this map, the outer limits of the Norwegian Continental Shelf shown by yellow lines. These deep ocean areas are the main areas for the exploration and possible exploitation of metal-bearing deep sea minerals on the Norwegian Continental Shelf. The 200 nautical miles zones overlap parts of the continental shelf area – the relevant 200 nautical miles lines are shown in pink.

Opening process – assessment study area

NPD



The Subsea Minerals Act: 1 July 2019

Competence lies with the Ministry of Oil and Energy (MPE)

The NPD is the expert agency of the MPE

The MPE has initiated the opening process as stipulated in the Act

The NPD is tasked with the assessment study, including mapping and estimating resources

In 2014, the Government started working on a legislation to deal with the management of the mineral resources on the continental shelf. This resulted in the Subsea Minerals Act entered into force 1 July 2019. The Ministry of Petroleum and Energy (MPE) was mandated the application of the act. In accordance with the act, the MPE has initiated an opening process for deep sea minerals activity, in which the first step is the carrying out of an impact assessment study. As the expert agency of the MPE, the NPD is tasked with this impact assessment study including the mapping and assessment of the continental shelf mineral resources.

Mapping and exploration

Now turning to the activity regarding mapping and exploration of these resources.

Types of mineral deposits on the NCS

NPD

Sulphides

Crusts

There are two types of metal-bearing deep sea mineral deposits on the Norwegian Continental Shelf: polymetallic sulphides (often termed Seafloor Massive Sulphides (SMS)) and polymetallic crusts (those of the Pacific Ocean frequently termed Cobalt Rich Crusts).

The polymetallic sulphide deposits are formed on and within the seabed by volcanic hydrothermal activity associated with seafloor spreading.

The polymetallic crusts are deposited as delicate lamina onto surfaces of bare rock on the seafloor by constituents precipitated directly out of the cold enclosing seawater.

The third type of deposit found in the world oceans, the polymetallic nodules (ofte termed Manganese Nodules) is not present on the Norwegian Continental Shelf in the Norwegian Sea Region.

Deep Sea Minerals – Research and Exploration

NPD

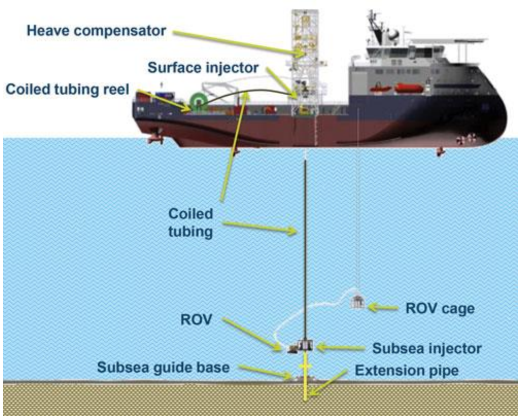
- 1999 – 2020: University of Bergen (UiB), annual scientific research cruises
- 2011 – 2020: NPD and UiB, joint annual scientific research cruises
- 2016: NTNU scientific research cruise (MARMINE)
- 2020: NPD and University of Tromsø, joint scientific research cruise
- 2018 - 2020: NPD, annual cruises for exploration and data acquisition based on commercial tenders

Systematic accummulation of knowledge about the deep sea mineral resources on the continental shelf started with the University of Bergen's marine scientific research program on black smokers. This research has been going on since 1999 based on annual scientific research cruises – still ongoing. In 2011, the NPD joined these university cruises with funding and program. In 2016, NTNU carried out their own scientific research cruise (MARMINE) funded by the NFR. Since 2020, the NPD has also had joint scientific cruises with the University of Tromsø.

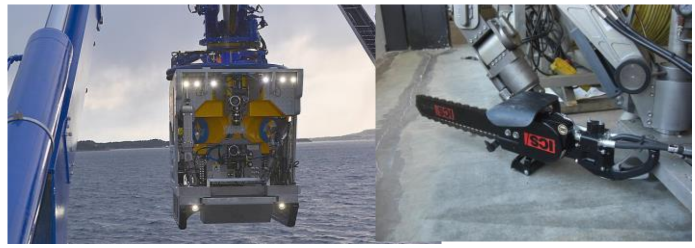
And since 2018, the NPD has carried out their own cruises, based commercial tenders, for the exploration of deep sea minerals.

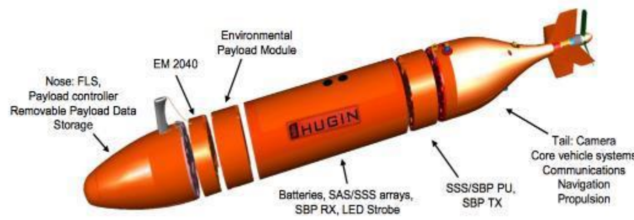
Mapping and exploration technology

NPD



NPD 2020 SMS coring campaign using coiled tubing





Geophysical acquisition using AUV; Crust and SMS sampling by ROV

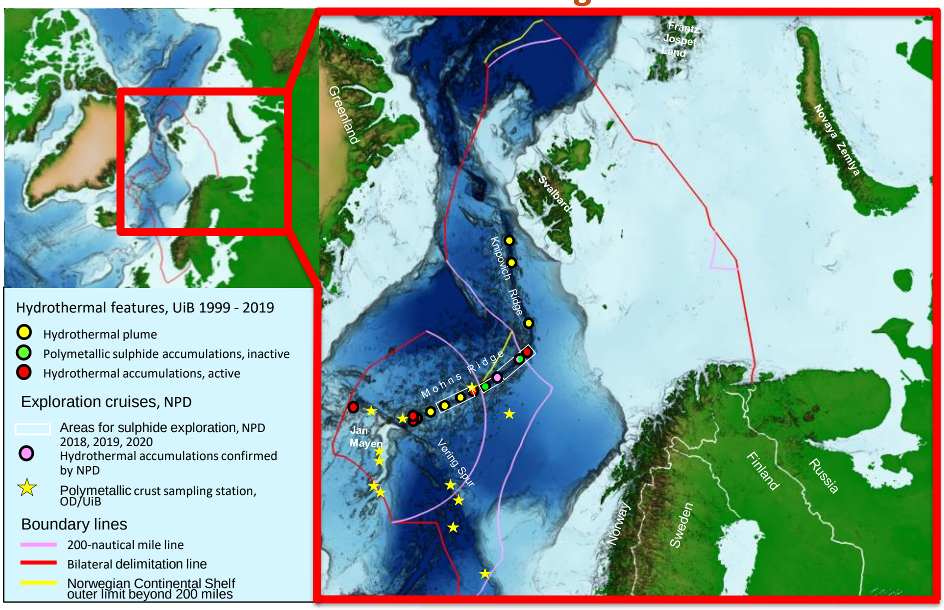
Exploration for deep sea minerals involves the acquisition of geophysical data (including bathymetry) and the collection of rock samples. The acquisition of geophysical data have mainly been done by Automated Underwater Vehicles (AUV) mounted with the relevant set of sensors. The relevant data are MBES, Side-Scan, Magnetometry, Self-potential, SBP, and water parameters (eH, pH, temperature, Methane, turbidity).

Rock sampling has mainly been done by using a Remotely Operated Vehicle (ROV), simply picking samples from the seabed outcrops, or, in the case of crusts, with a hydraulic chain saw mounted on the ROV.

In 2020, NPD tested coiled tubing technology for the core drilling of sulphide deposits. That was the first time this technology was applied at such large depths (around 3000 meters depths). Several cores were successfully recovered, but the test also revealed room for technical improvements.

Seabed Minerals Research on the Norwegian Continental Shelf

NPD



8 08.01.2021 NGF Winter Conference 2021

The current status of exploration of deep sea minerals on the Norwegian Continental Shelf is summarized in this map figure.

The red, green and purple dots show the location of hydrothermal sulphide deposits that are confirmed by inspection by ROV dives. The yellow dots are measured anomalies in the near bottom water column, which strongly indicate hydrothermal vent activity somewhere on the nearby seafloor, but not confirmed by ROV.

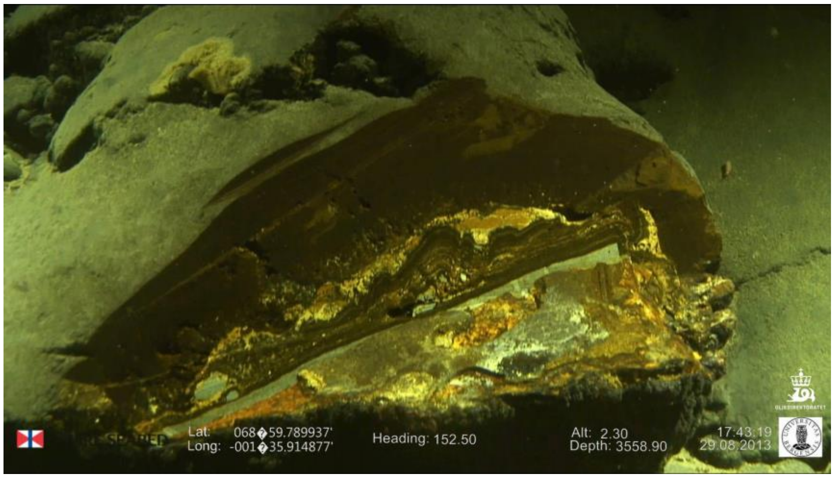
The yellow stars show the locations where crust samples have been collected.

Polymetallic Crusts

Now, a short note on the crust deposits

Polymetallic Crust Cut by Chain Saw

NPD



Here is a typical crust deposit on the Norwegian Continental Shelf cut by a hydraulic chainsaw. The crust is about 20 cm thick, which is a substantial thickness compared globally.

Observations from crust analyses

NPD

- Chemical analysis of numerous crust samples confirms:
- Norwegian-Greenland Sea crusts has clear Arctic Ocean affinities
- Contain an elevated concentration of numerous elements when compared to other oceanic regions.
- Potential as metal ores, especially the REE-enriched population

By Stian Rolfsen Gilje, NPD/UiB

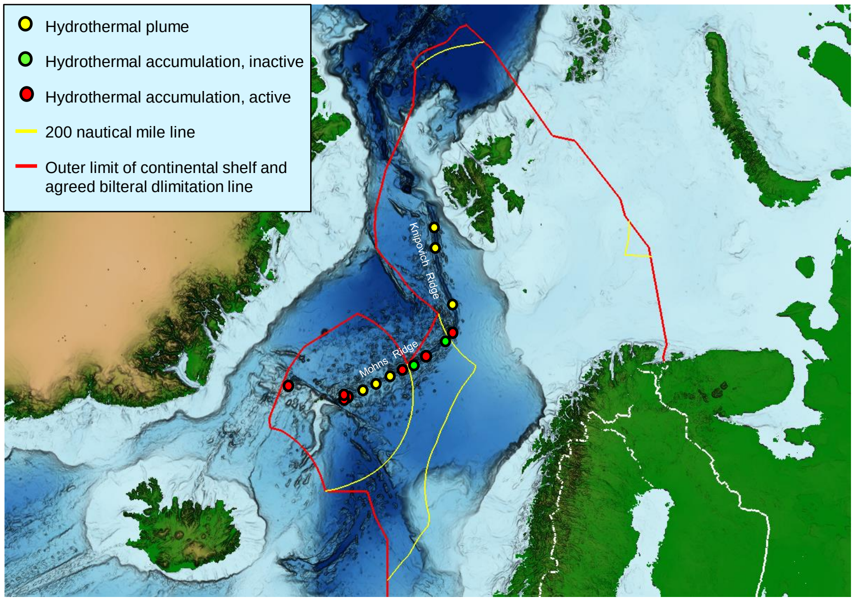
The general observations are that the crusts on the Norwegian Continental Shelf reflect a water chemistry with clear affinities with the Arctic Ocean, separate from the other world oceans. They contain clearly higher concentrations of the elements Li, Sc, V, and Th, compared to crusts of other oceans. One group of the crusts also show clearly elevated (double of the Pacific) level of Lanthanides (REE).

Polymetallic Sulphides

12 08.01.2021 NGF Winter Conference 2021

The rest of the presentation will concentrate on the sulphide deposits.

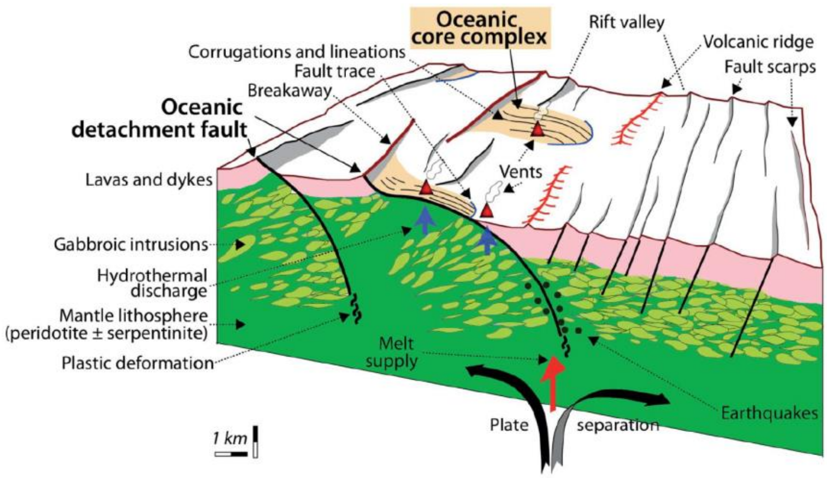
Known hydrothermal features within the NCS



Here is a map figure showing the locations of the confirmed and indicated hydrothermal vent deposits to date. The confirmed deposits are associated with both active and extinct vents, almost all of which are located along the spreading axis of the Mohn Ridge.

Plate separation at slow-spreading ridges – the "Chapman Model"

NPD



Maffione et al., 2013

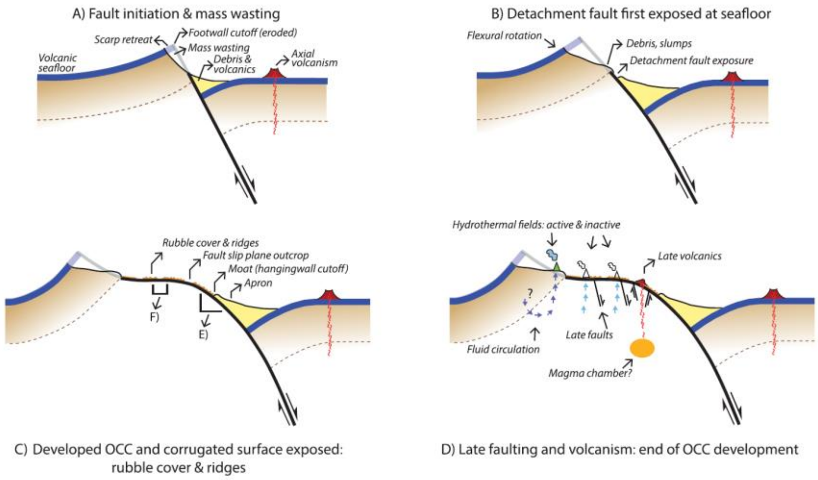
14 08.01.2021 NGF Winter Conference 2021

The Mohn and Knipovich spreading ridges are in the category of slow-spreading ridges. A widely accepted tectonic model for the plate separation process in such slow-spreading ridges is shown in this slide. The model depicts the general situation that such ridges are asymmetrical, i.e. that one of the flanks of the axial rift valley dominates the process. This is the left flank of the model in the slide. The large bounding faults with large displacements are found along this dominant flank. Some of these bounding faults may develop into what is called oceanic detachment faults. Through time, these detachment faults tends to roll backwards and elevate the deeper levels of the footwall up to the seafloor forming oceanic core complexes of deep-level mafic and ultramafic rocks (green and yellow in slide).

The faults on the other flank (to the right in the slide) are depicted as more or less antithetic to the large bounding faults and accommodate the total displacement over a larger number of faults. Due to the smaller displacements, the mafic and ultramafic levels of the footwalls of these faults are not brought to surface. The upper level of basalt volcanics (pink in slide) thus stays juxtaposed across the fault plane.

This fault process allows melt (and thereby heat) to rise into the separation zone (arrows in slide). The model also predicts that the configuration of the fault framework controls and creates the conduites for the flow of melt and heat through the upper crust and thereby the location of volcanism and hydrothermal vet activities at the surface. In general, this is reflected by the formation of volcanic ridges in the axial parts of the rift valley, and volcanic and hydrothermal vents concentrated along the large bounding fault scarps of the dominant rift flank.

Development of oceanic core complex

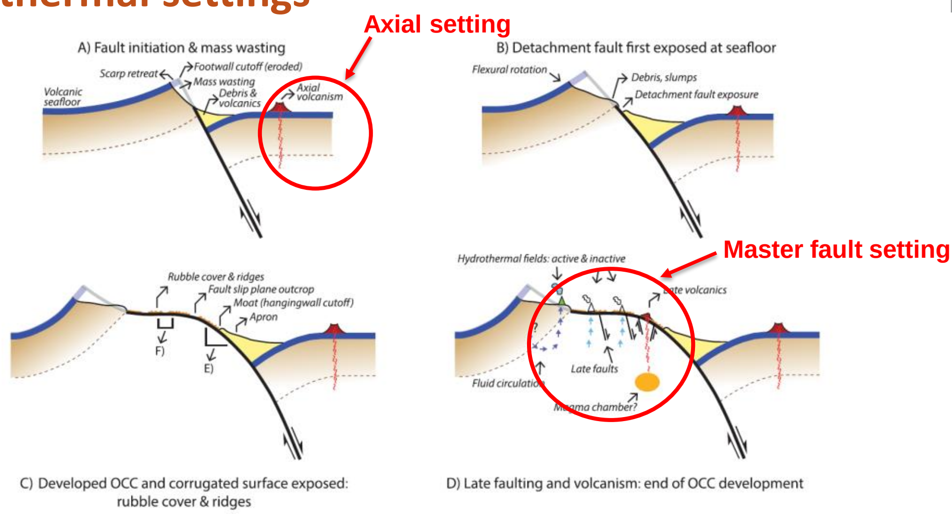


Escartin et al., 2017

This slide shows in more detail the evolution of an oceanic detachment fault and the formation of an oceanic core complex. It also shows details on how such detachments control the surface volcanism and the hydrothermal fluid circulation. The latter is here concentrated on the large bounding fault scarp - in this case the fully developed detachment fault/core complex. If the core complex here consist of ultramafic rocks from deeper levels of the crust, it is clear that the hydrothermal circulation in this case will leach these rocks. This will result in a different chemical composition of the sulphide deposits in this setting than the sulphides associated with activity leaching upper level basaltic rocks, which one would expect to find in the axial volcanic setting.

It is proposed that leaching mafic and ultramafic rocks will give rise to a substantially higher concentration of Co.

Hydrothermal settings



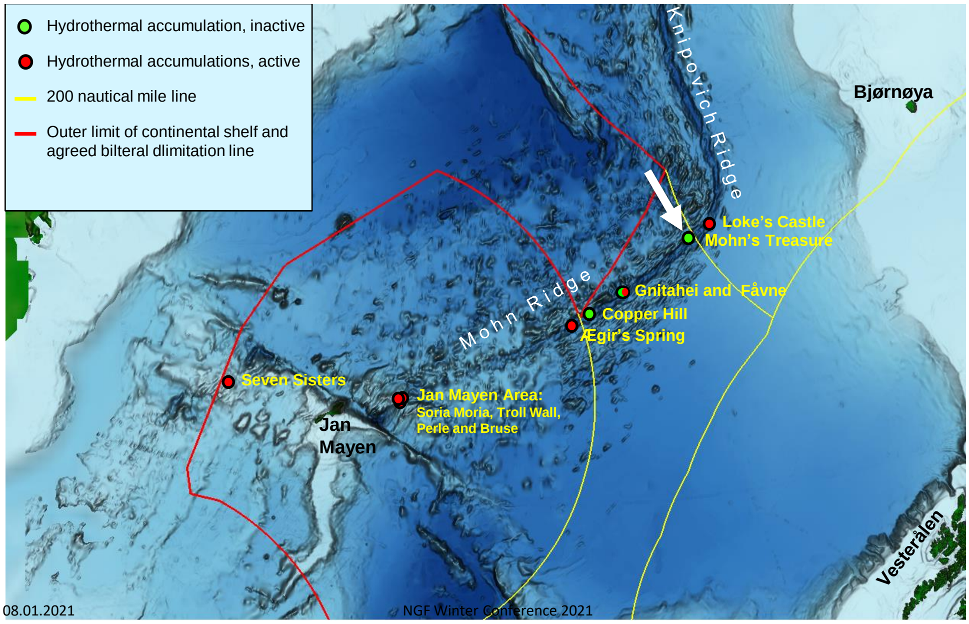
Escartin et al., 2017

From the model described above, we see two settings that may fit with the tectonic framework of the Mohn Ridge in the Norwegian Sea. It is the axial setting of volcanic vents and ridges built on the upper basaltic level of the oceanic crust, and the master fault setting that is located on and along the large bounding faults on the dominant rift flank.

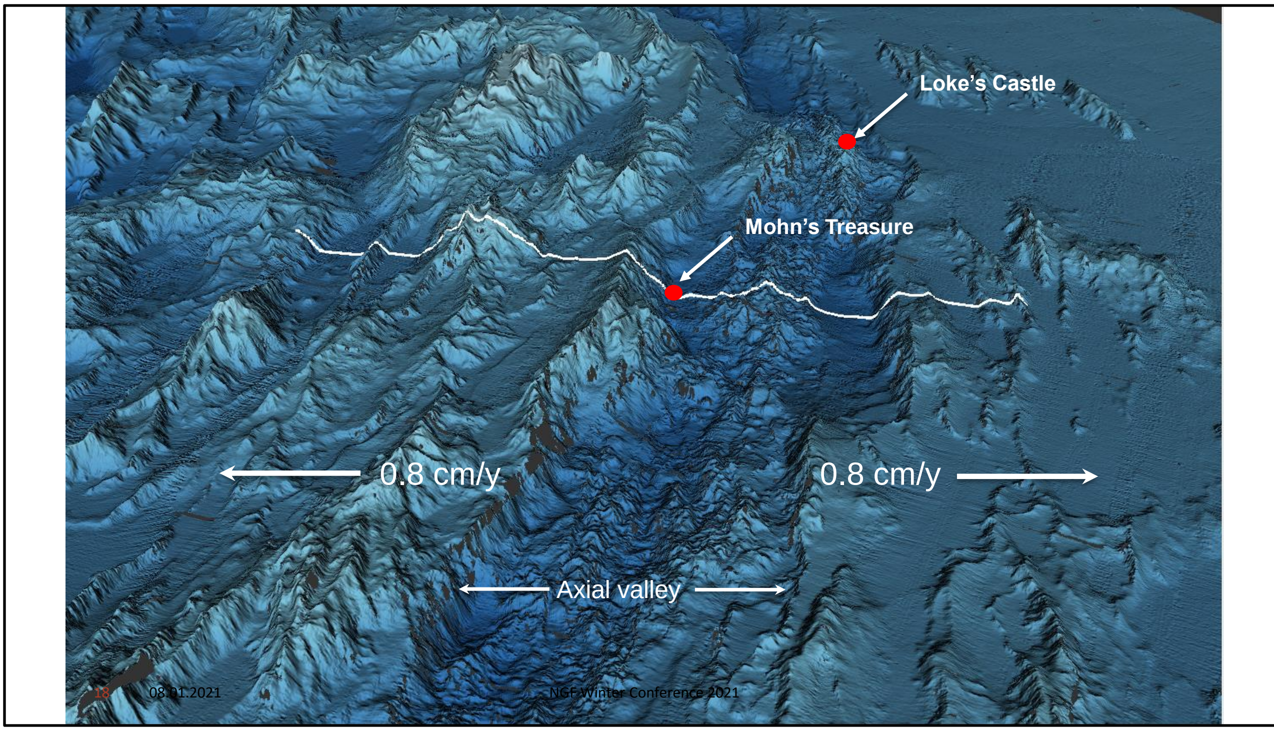
As demonstrated later, the Mohn Ridge, is assymmetric with the north-west flank of the rift valley as the dominant flank.

Known hydrothermal sulphide accumulations

NPD



This map shows the locations of the known hydrothermal sulphide deposits identified along the Mohns ridge system. We shall now look in more detail on the Mohn's Treasure deposit, here marked by the white arrow. Note also the Loke's Castle deposit just to the north-east.

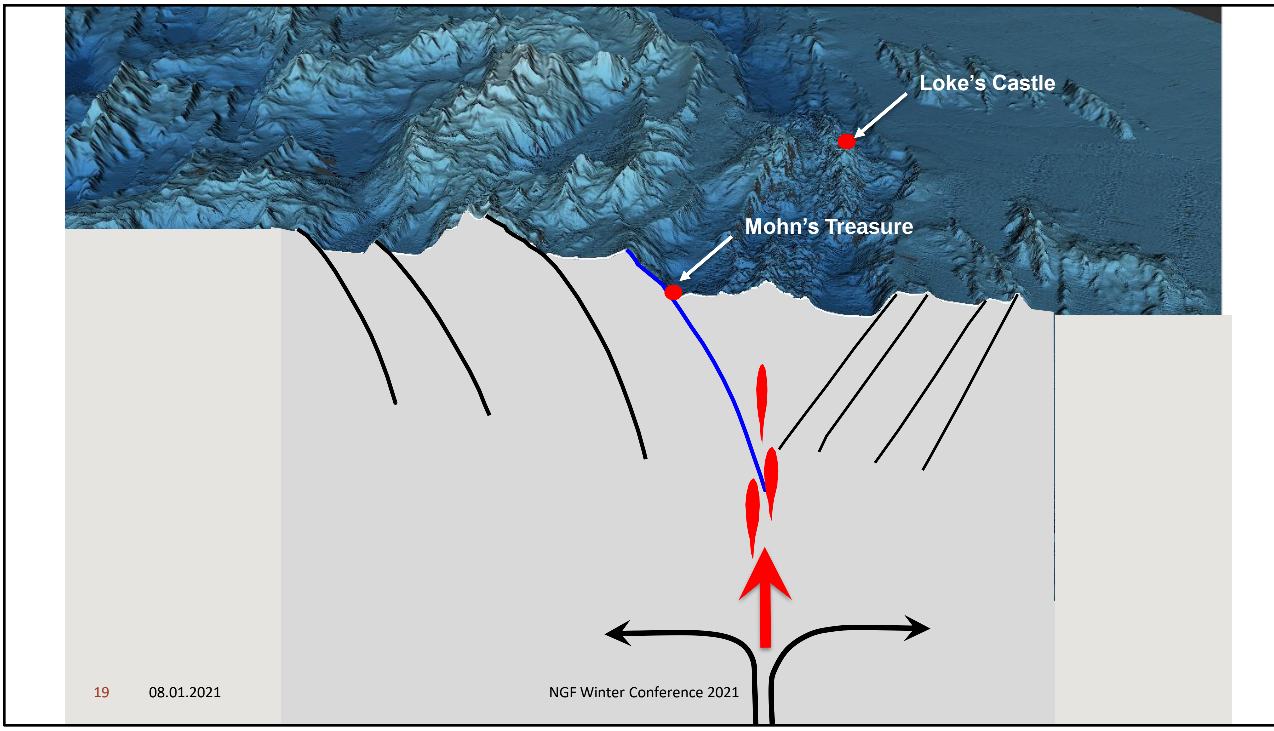


This is a 3D view of a MBES data-set of the northern part of the Mohn Ridge, looking north-eastwards along the axial rift valley. The spreading rate of the Mohn Ridge is 1.6 cm/y, i.e. 0.8 cm/y to each side of the spreading axis.

We can see that the NW flank (right hand side of the valley) is made up of large, very pronounced bounding faults. The faults along on the SE flank are less pronounced, partly due to a thicker cover of sediments. However, they can be seen to more numerous and of less topography than those on the NW flank. This shows that the Mohn Ridge is asymmetric with the NW flank of large bounding faults as the dominant flank. The floor of the rift valley is low lying compared to the flanks and is dominated by slightly oblique, transverse volcanic ridges.

The locations of the Loke's Castle and the Mohn's Treasure are shown in the northern part of the rift valley. The Loke's Castle is located on a volcanic ridge on the floor of the valley, i.e. in an axial setting according to the terminology introduced above. The Mohn's Treasure is located at the foot of on of the large bounding faults on the dominant flank of the rift valley. This is what is termed a master fault setting.

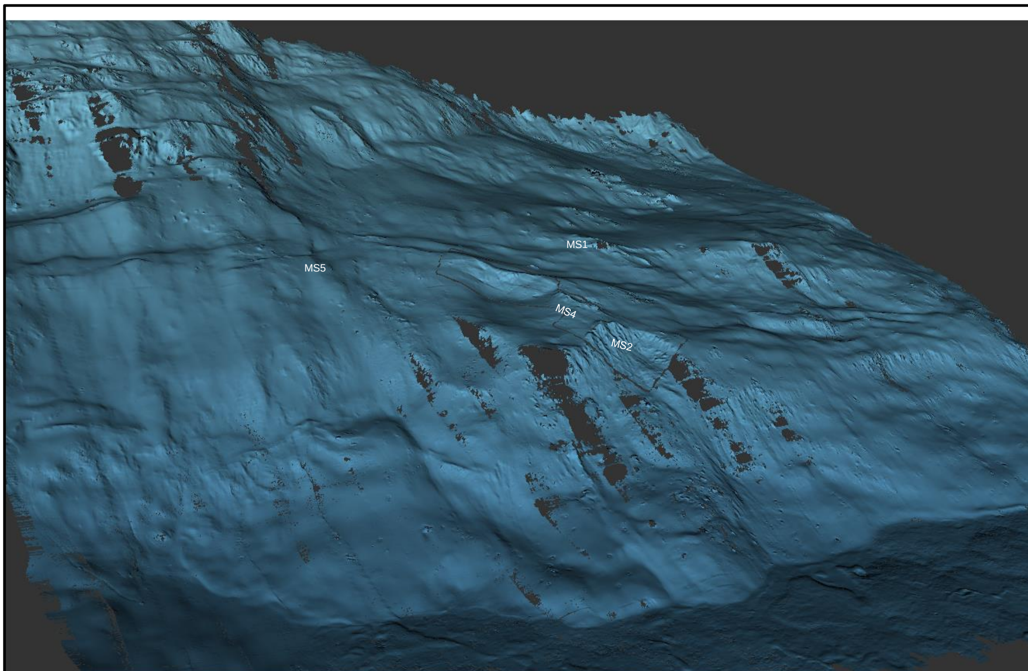
In the next slide shows this setting in combination with a profile along the white line.



The slide shows an interpretation of the tectono/magmatic setting of the Mohn's Treasure deposit. The topography fits well with the interpretation of a present (blue) and past (black) large bounding faults on the NW flank of the rift valley. The topography shows these fault scarps to be in the order of 1200 – 1500 meters, indicating large scale displacements when active. However, none of them seems to form fully developed oceanic detachments and oceanic core complexes. The SE flank is defined by more numerous faults with less throw.

The Mohn's Treasure is located at the foot of the present bounding fault with an escarpment of about 1200 meters.

Following the model described above, the present interpretation includes the rising of melts and heat into the basal zone of the large faults. The bounding fault is believed to have been the conduit of the heat setting up the circulation of the hydrothermal fluids that formed the Mohns Treasure sulphide deposits in this location.



NPD

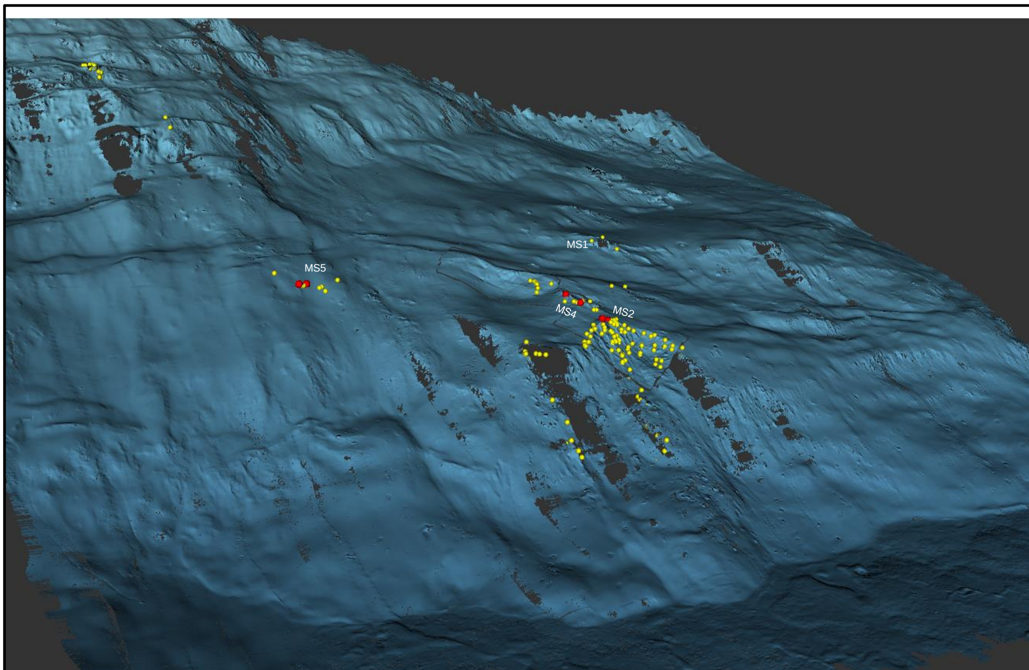
Mohn's Treasure area

This is a 3D view of a high resolution (1x1 m) MBES data-set depicting the Mohn's Treasure area. The entire hill slope is the fault scarp of the footwall of the large bounding fault described in the previous slide. In the lower part of the slide, one can see how this footwall juxtaposes the hanging wall, which constitutes the flat ocean floor of the rift valley. The footwall scarp is modified by smaller fault and slide scarps.

The existence of polymetallic sulphide deposits in this area was discovered by dredging of samples by the University of Bergen in 2002, but the exact location was not established. Anna Lim at NTNU identified three possible sites in the area based on magnetic modelling – a large anomaly covering the area of MS2 and MS4, and two smaller anomalies located at MS1 and MS5. These sites were visited and partly confirmed by NPD in 2019.

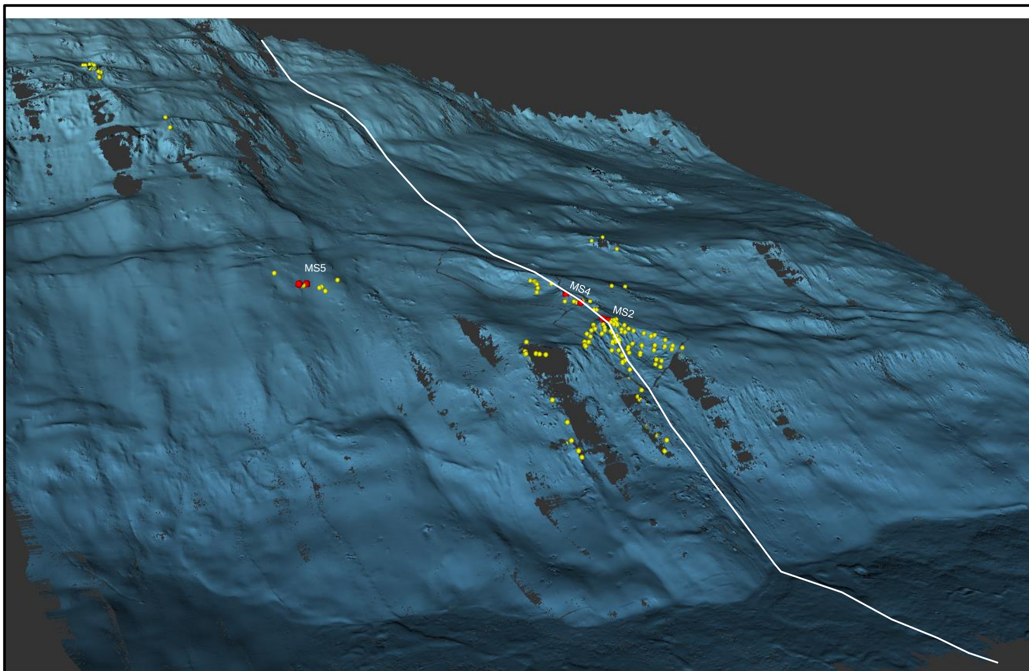
In 2020 the sulphide deposits in the area of MS2 and MS4 were confirmed by NPD by visual inspection, outcrop sampling and core drilling. No sulphide deposits were confirmed in MS1 and MS5, leaving the area of MS2 and MS4 as the being the Mohn's Treasure.

The location of the Mohn's Treasure deposit dominated by sigmoidal slide scarp (marked MS2). The top rim of the slide scarp is built by 10 – 20 thick accumulation of extinct, massive sulphide chimneys. Fragments and *in situ* sulphide chimneys are found downslope throughout slide scarp down to about 100 meters below the top rim, indicating a minimum depth of mineralization of the bedrock. This means that the slide occurred during the hydrothermal activity at the Mohn's Treasure. The deposit extends into the small ridge marked MS4.



Coring and sampling locations, Mohn's Treasure

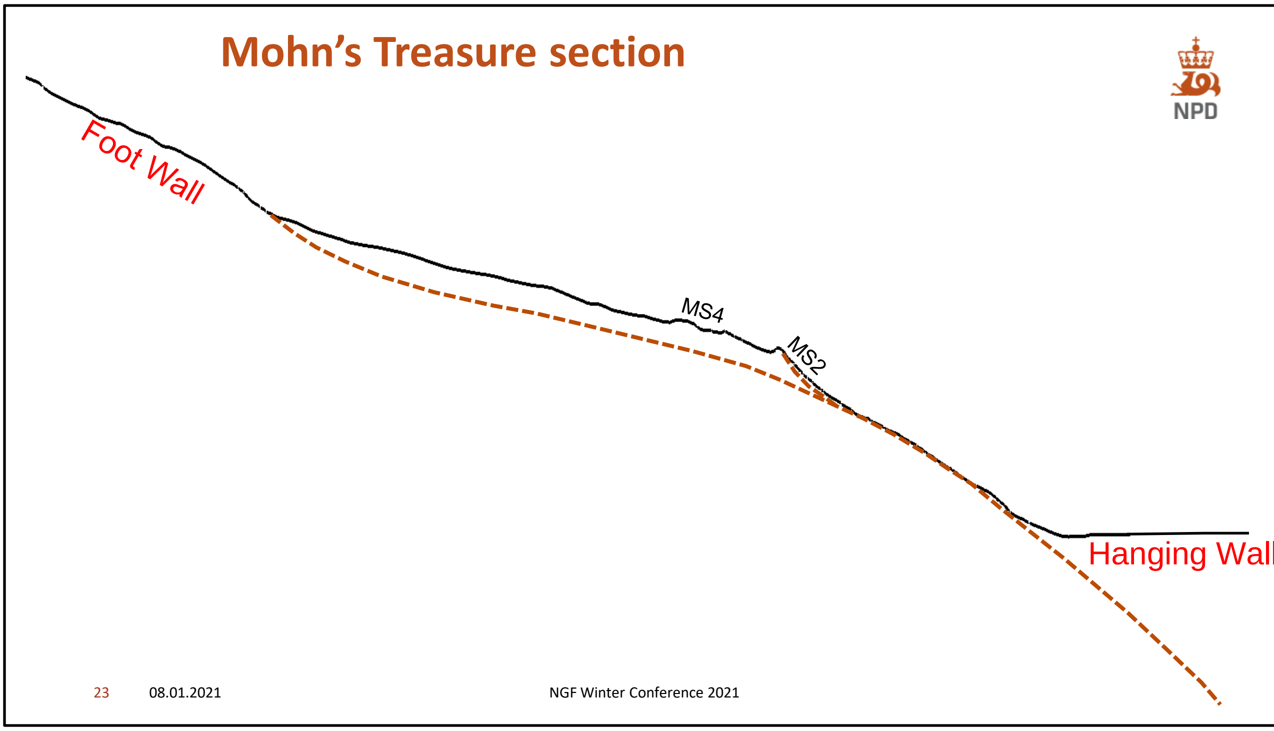
Outcrop sampling by ROV (yellow) and core drilling locations (red) in the Mohn's Treasure area during the NPD 2020 cruise.



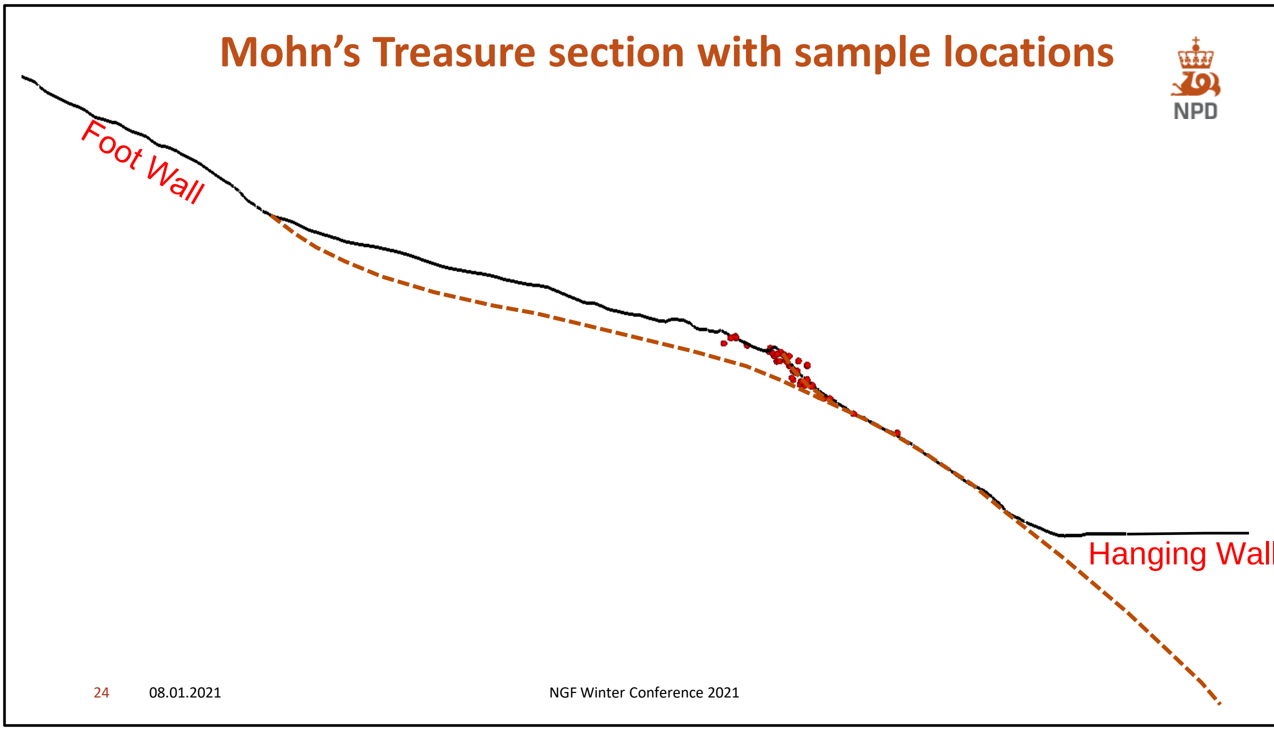
NPD

X-section location

An interpretation in section of the setting of the Mohn's Treasure deposit within the footwall of the large bounding fault has been made along the white track in this slide. The section is shown in the next slide.

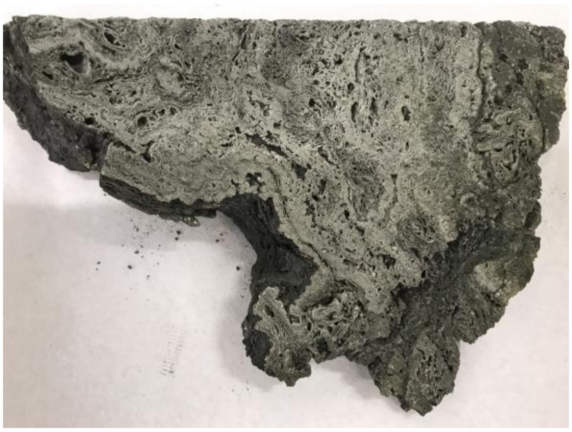


An interpreted section showing the position of the Mohn's Treasure deposit (MS2 and MS4) in relation to the overall rift valley fault configuration. The slide giving the scarp at MS2 is proposed to have slid on a deeper fault plane within the large bounding fault.

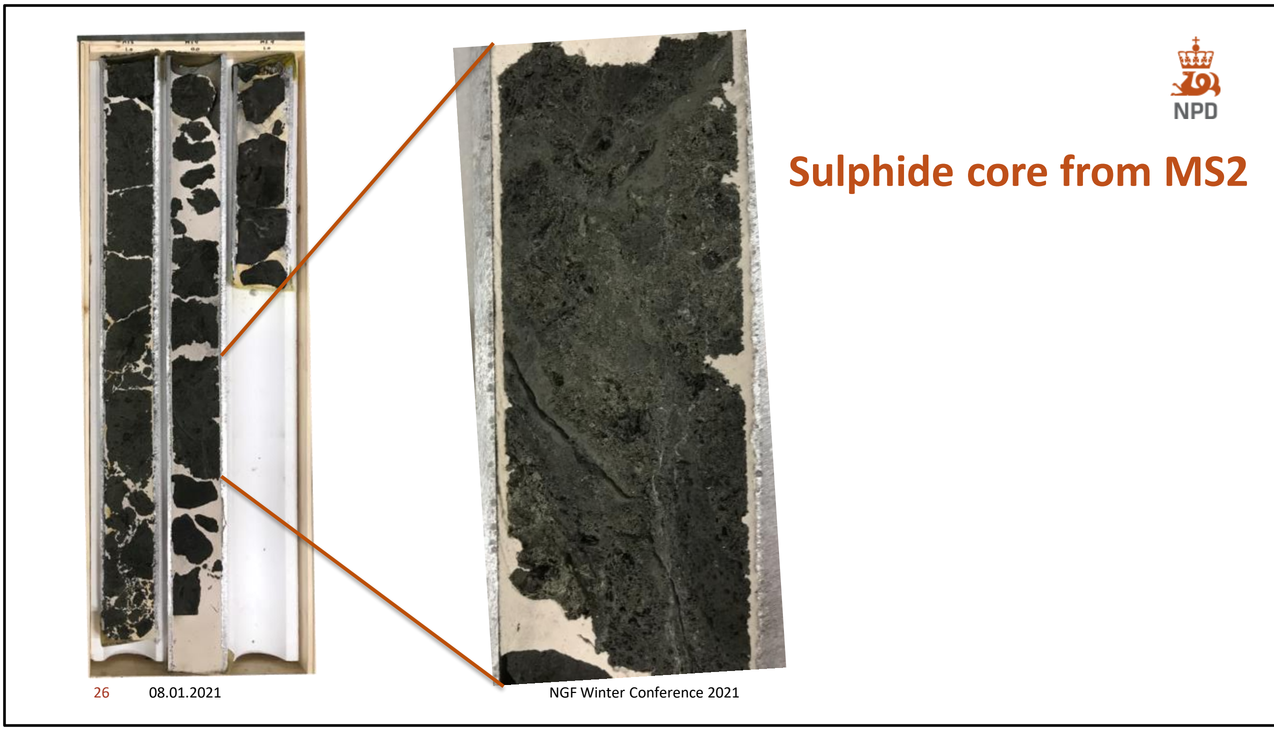


The sample locations plotted on the same section shown in the previous slide.

Sulphide specimens sampled by ROV at MS2



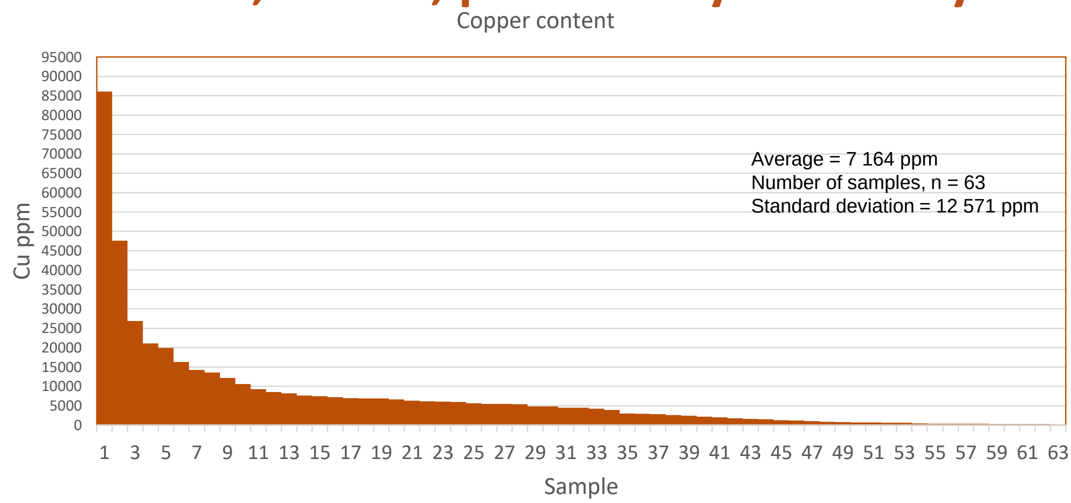
Two outcrop samples of massive sulphides from the MS2 area of the Mohn's Treasure. The left sample is a cut showing the delicate structure of the interior of an extinct sulphide chimney. The right sample shows the common appearance of local vent pipes extending from the main chimneys.



Drill core of massive sulphides from the top rim area of the slide scarp in the MS2 area of the Mohn's Treasure deposit.

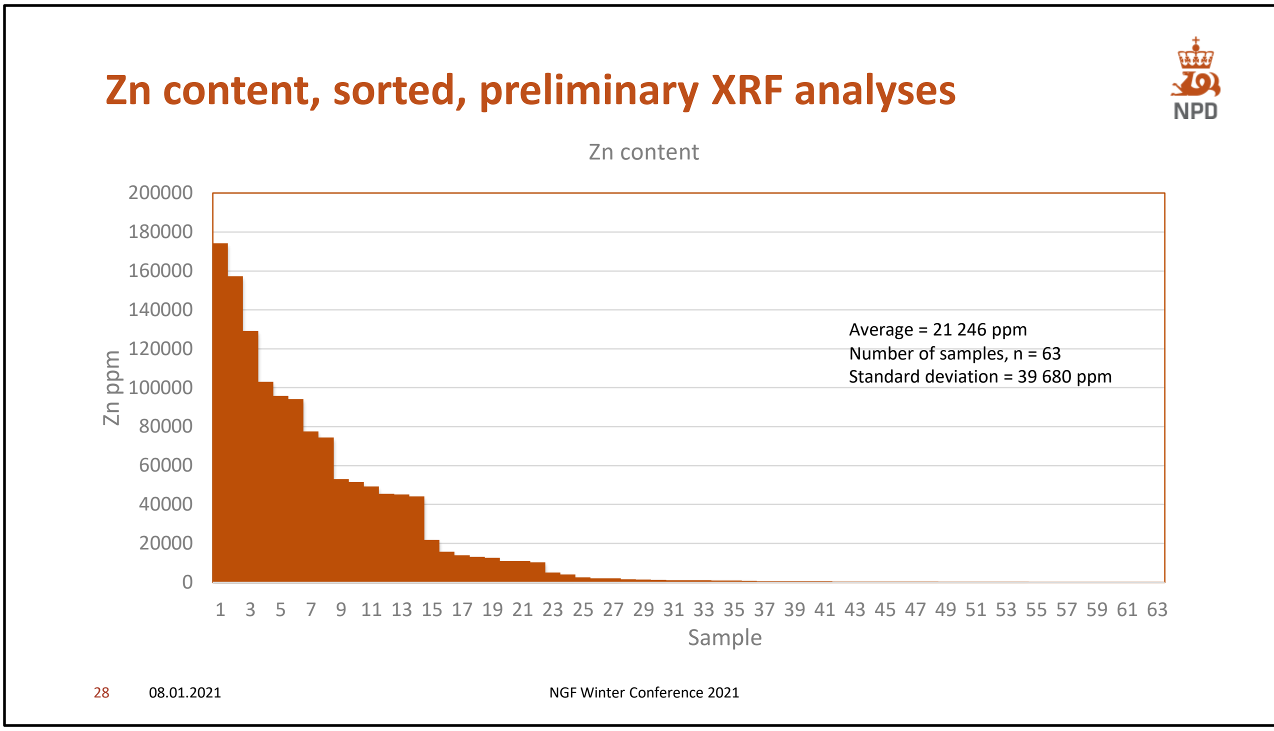
Cu content, sorted, preliminary XRF analyses

NPD



27 08.01.2021 NGF Winter Conference 2021

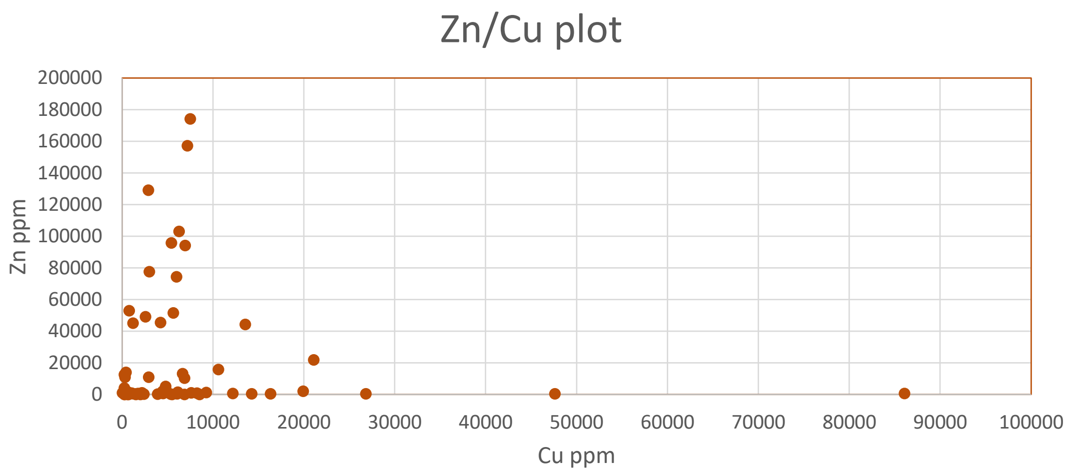
The preliminary analyses show a maximum content of 8.5 % Cu in the Mohn's Treasure deposit.



The preliminary analyses show a maximum content of 17 % Zn in the Mohn's Treasure deposit.

Zn vs Cu, preliminary XRF analyses

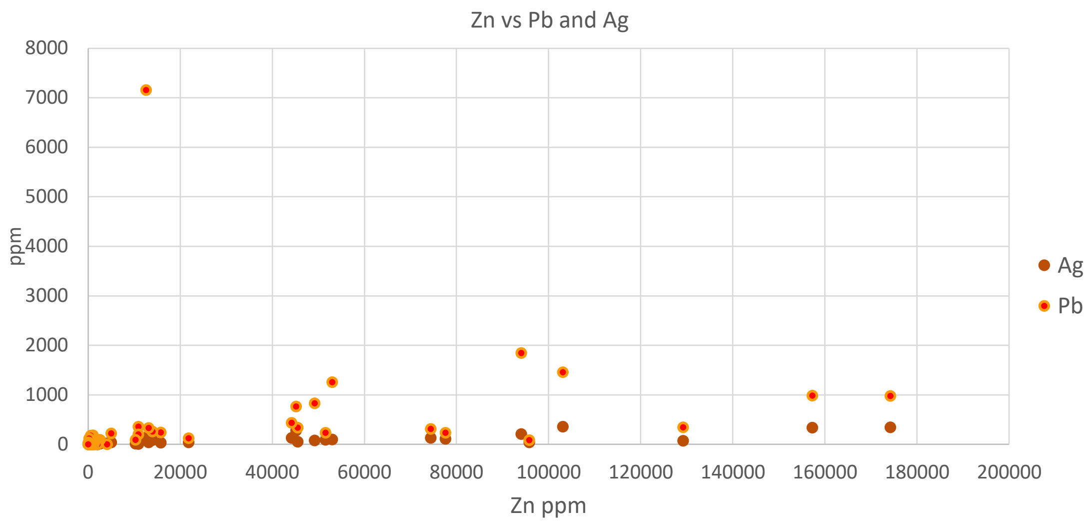
NPD



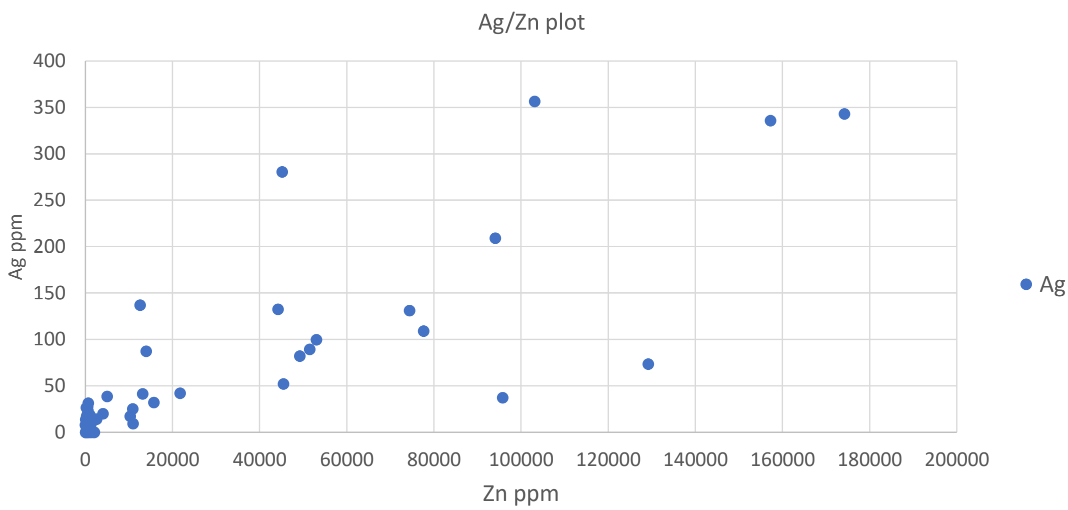
29 08.01.2021 NGF Winter Conference 2021

The plot shows, not surprisingly, that low values of Cu correspond with high values of Zn, and *visa versa*.

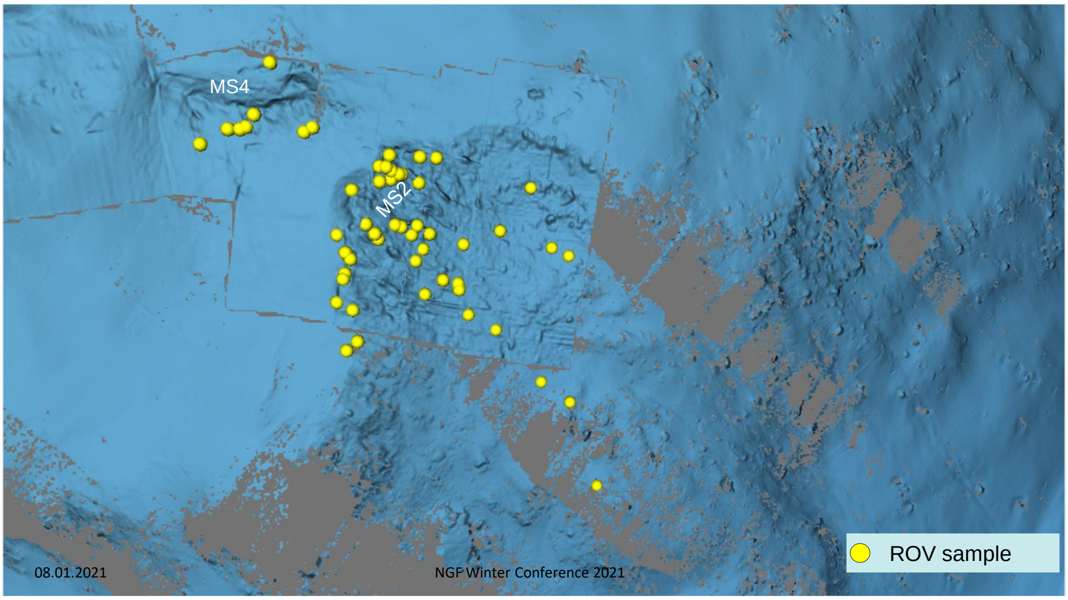
Pb and Ag vs Zn, preliminary XRF analyses



Ag vs Zn, preliminary XRF analyses



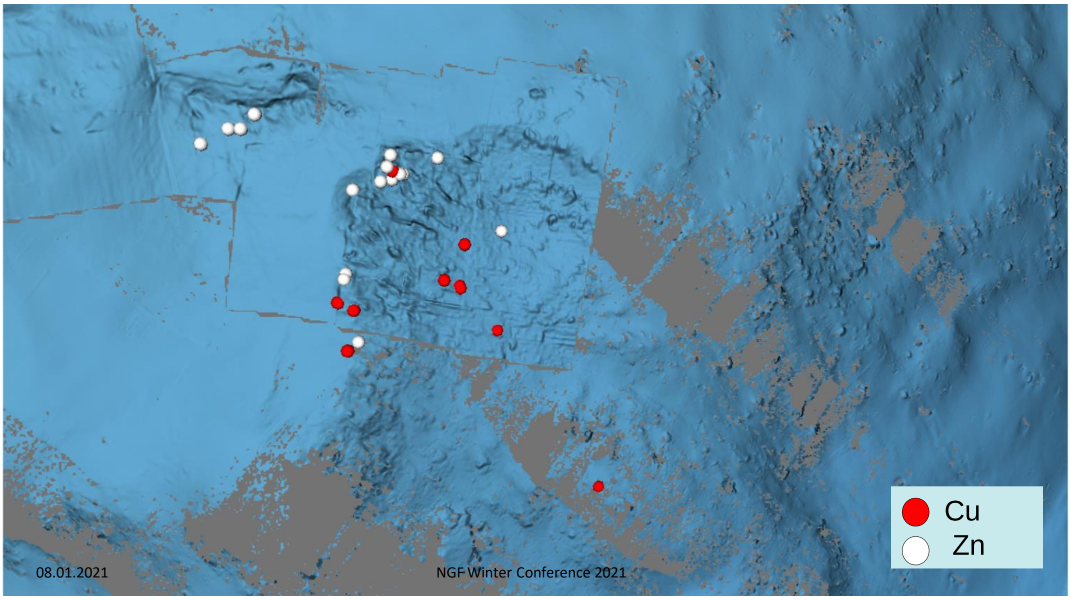
All sulphide samples analysed



32 08.01.2021 NGF Winter Conference 2021

This map shows the location of all the samples from Mohn's Treasure that were subject to preliminary analyses by XRF.

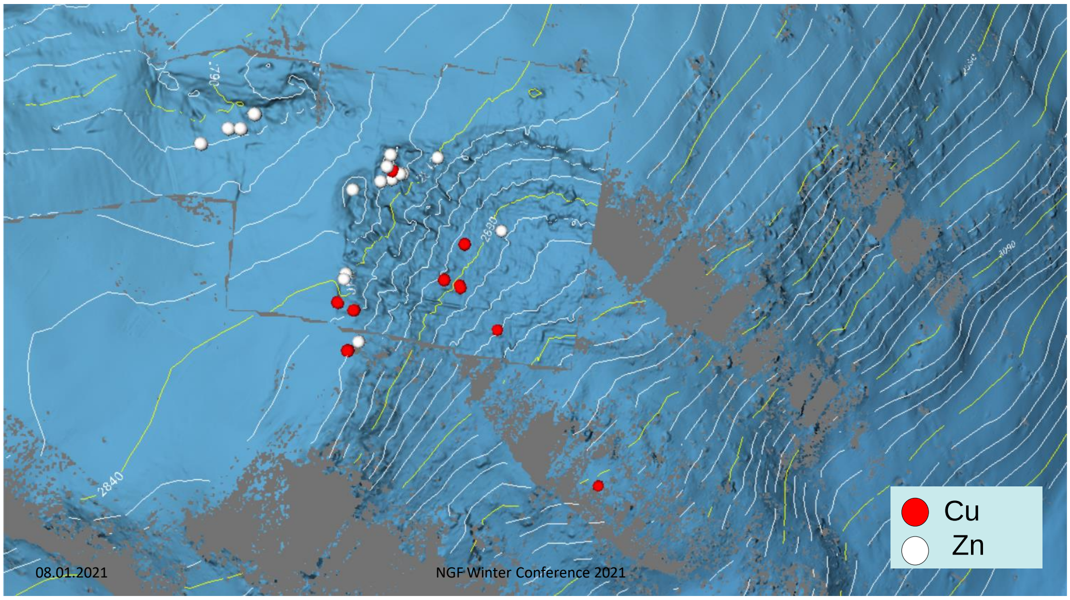
Samples of Cu and Zn contents >1%



This map shows the distribution of the samples that contained more than 1% of Cu or Zn. It may seem that the high Zn values are concentrated in the top parts of the deposits. This may have been an effect of the cooling stages of the vent activity which ic now extinct (no rigorous analysis of whether this is statistically significant has been done).

Samples of Cu and Zn contents >1%

NPD

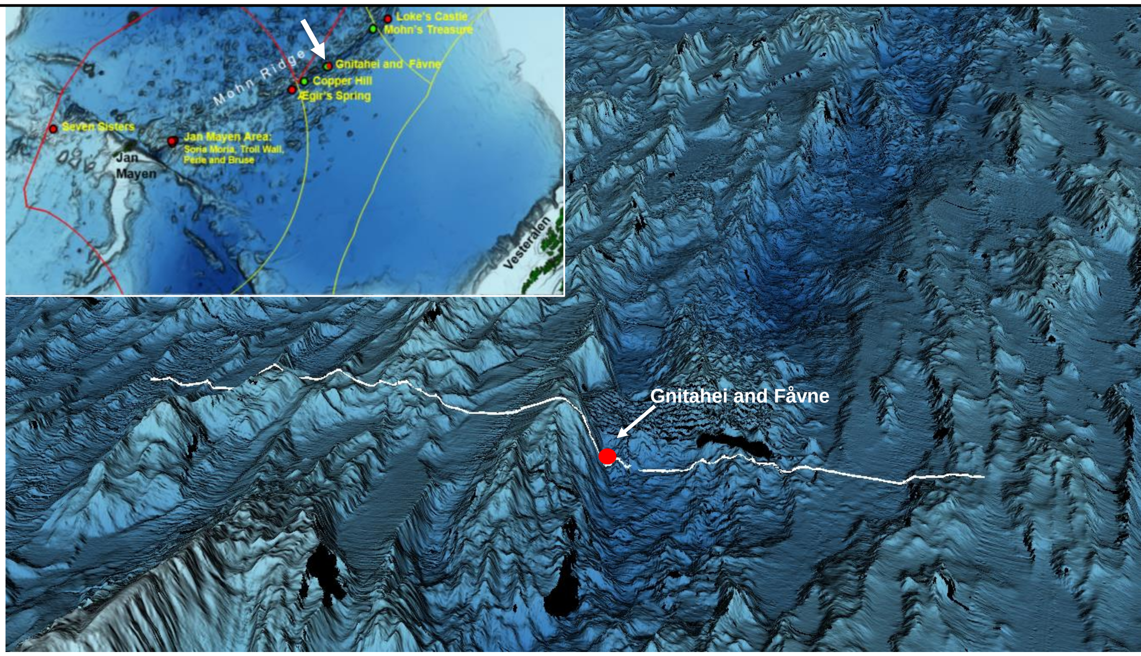


Same map as in the previous slide, but plotted with depth contours at 10 m intervals.

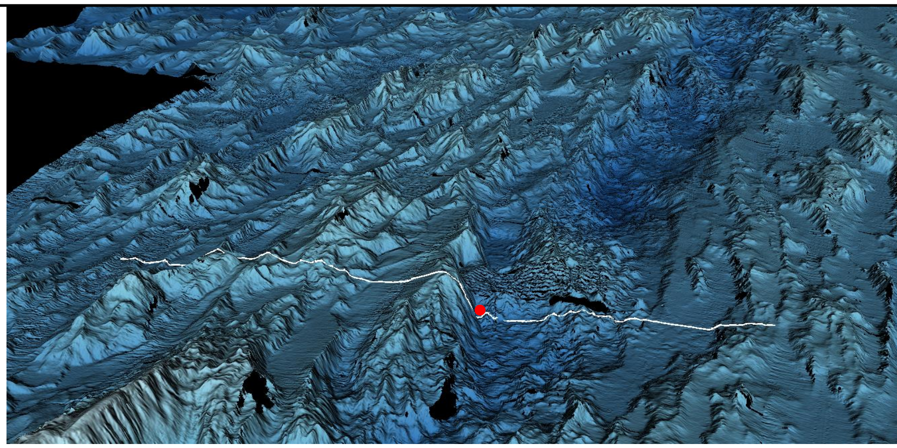
Gnitahei and Fåvne

35 08.01.2021 NGF Winter Conference 2021

Now we shall look at te Gnitahei and Fåvne deposits in more detail.

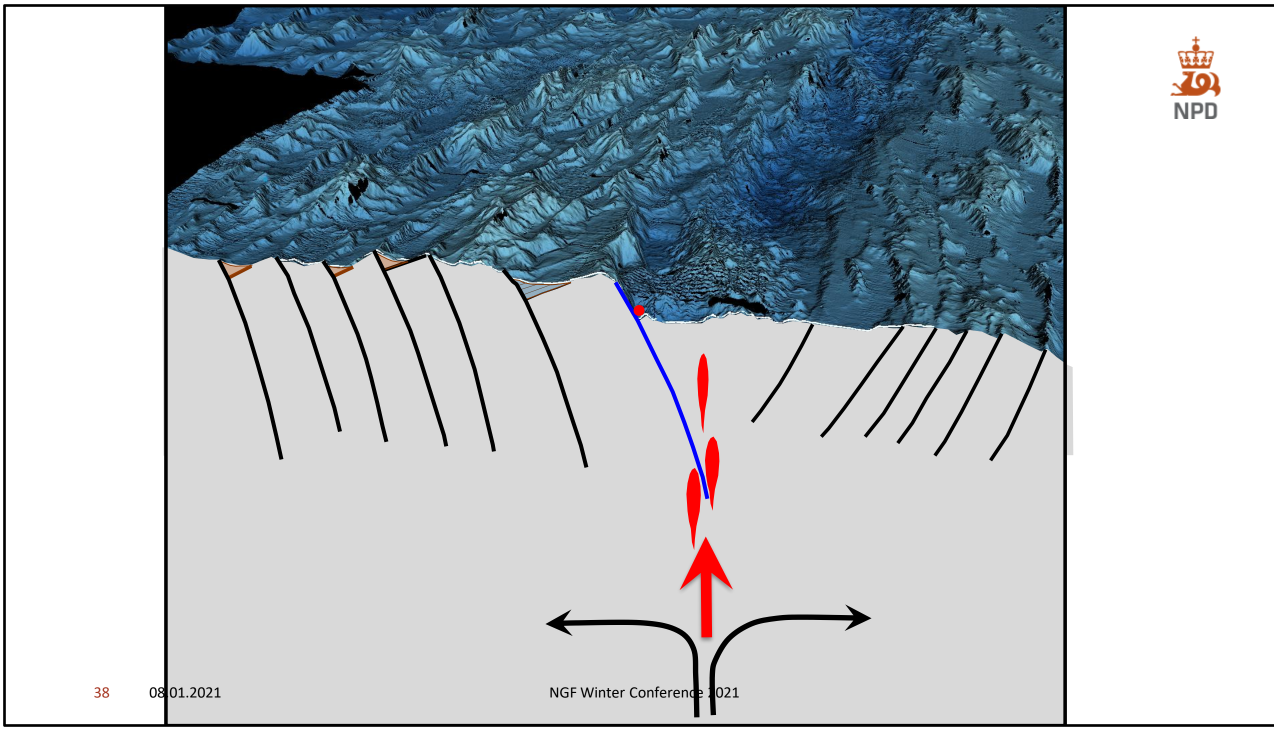


The Gnitahei and Fåvne deposits are also located at the foot of a bounding fault on the NW flank of the Mohn Ridge. However, Gnitahei is extinct and sits within the footwall, while Fåvne is active and sits at the junction between the footwall and hanging wall. The distance between the two deposits is about 700 meters. Here, the area of their location is shown in a 3D view looking north-eastwards along the axial rift valley.



NPD

In the next slide shows the setting of Gnitahei and Fåvne in combination with a profile along the white line.

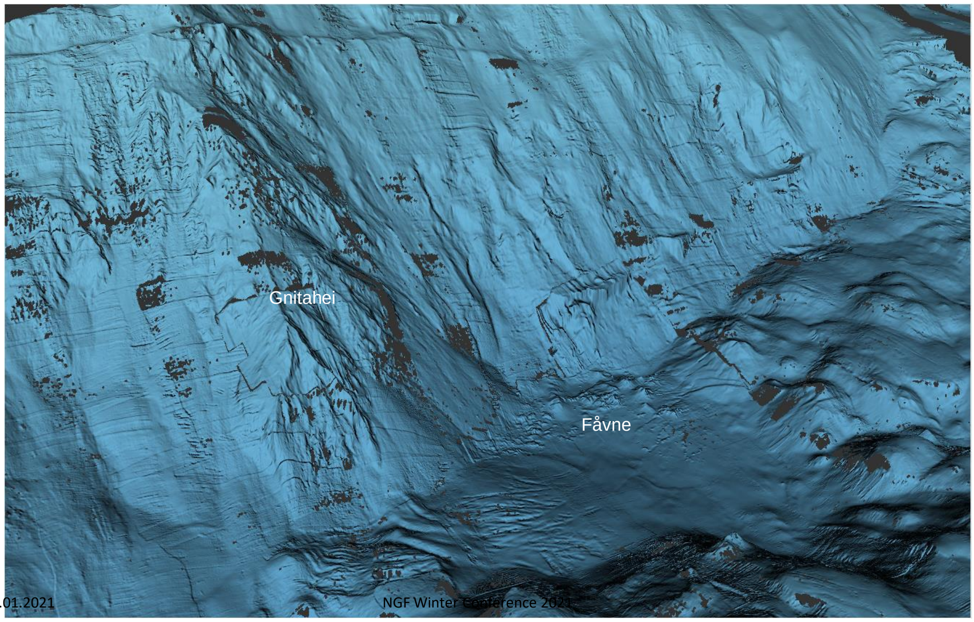


The slide shows an interpretation of the tectono/magmatic setting of the Gnitahei and Fåvne deposits. Like in the area of the Mohn's Treasure, the topography fits well with the interpretation of a present (blue) and past (black) large bounding faults on the NW flank of the rift valley. The topography shows these fault scarps to be in the order of 1000 – 1500 meters, indicating large scale displacements when active. However, none of them seems to form fully developed oceanic detachments and oceanic core complexes. The SE flank is defined by more numerous faults with less throw.

Following the model described above, the present interpretation includes the rising of melts and heat into the basal zone of the large faults. The bounding fault is believed to have been the conduit of the heat setting up the circulation of the hydrothermal fluids that formed the sulphide deposits in this location. However, hydrothermal activity has occurred in two distinct periods on this fault scarp – first during the activity at Gnitahei, and then the current activity at Fåvne, with a long period of no activity in between.

Fåvne and Gnitahei accumulations

NPD

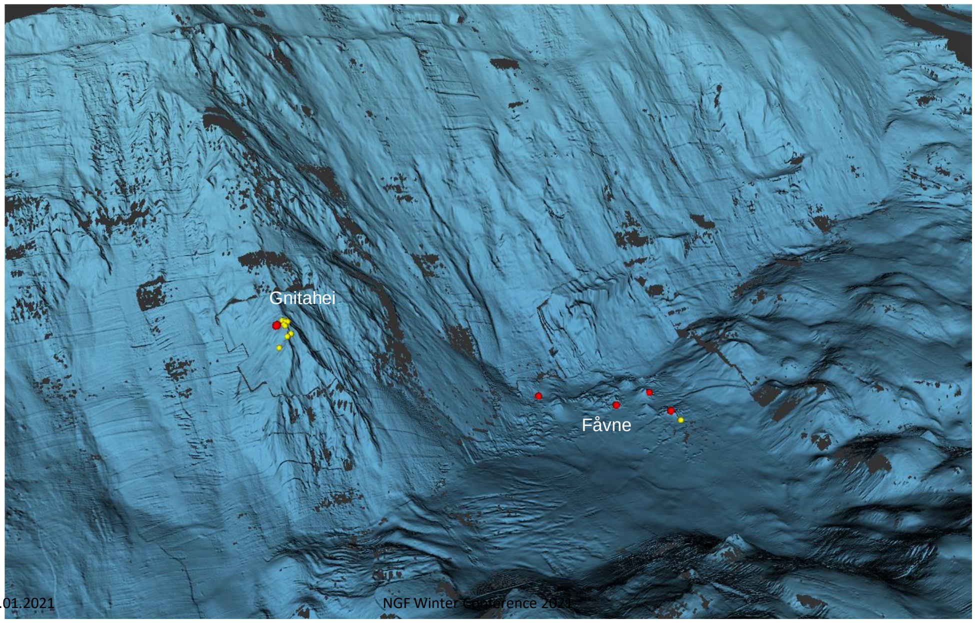


This is a 3D view of a high resolution (1x1 m) MBES data-set depicting the area of the Gnitahei and Fåvne deposits. The entire hill slope is the fault scarp of the footwall of the large bounding fault described in the previous slide. In the lower part of the slide, one can see how this footwall juxtaposes the hanging wall, which constitutes the floor of the rift valley. The footwall scarp is modified by smaller fault and slide scarps.

Gnitahei, which is extinct, sits in a local slide scarp within the lower parts of the footwall of the large bounding fault, very much like the Mohn’s Treasure. However, the Gnitahei deposit has been subject to prolonged erosion, so that the characteristic chimney structures of sulphide deposits are no longer preserved, and whether the slide occurred during the hydrothermal activity is at best uncertain.

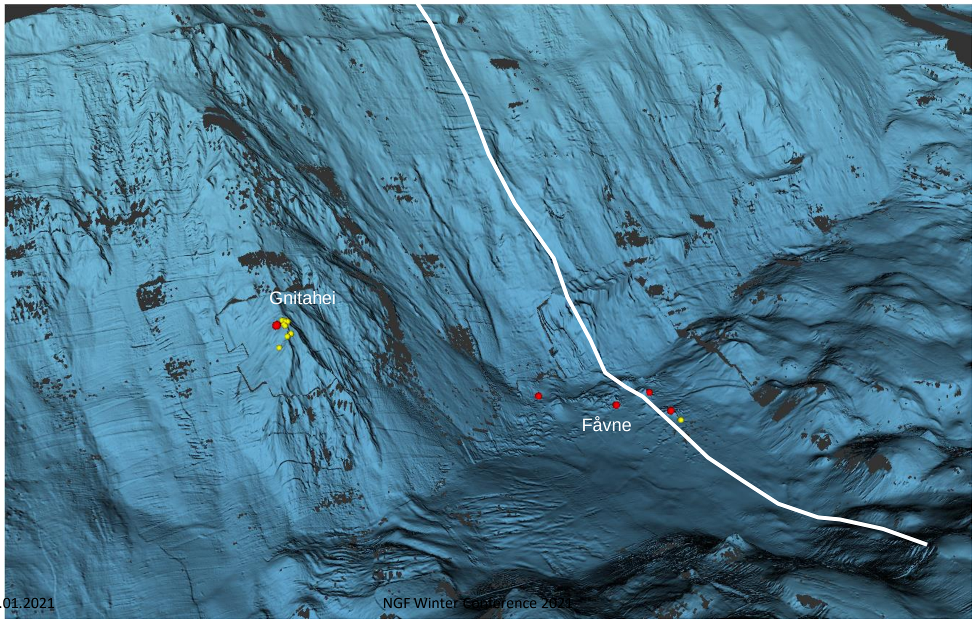
Fåvne, which is active, is charcterized by a group of mounds built by black smokers located on the rift valley floor that constitutes the hanging wall adjacent to the very foot of the hanging wall scarp.

Coring and ROV sampling locations, Gnitahei and Fåvne

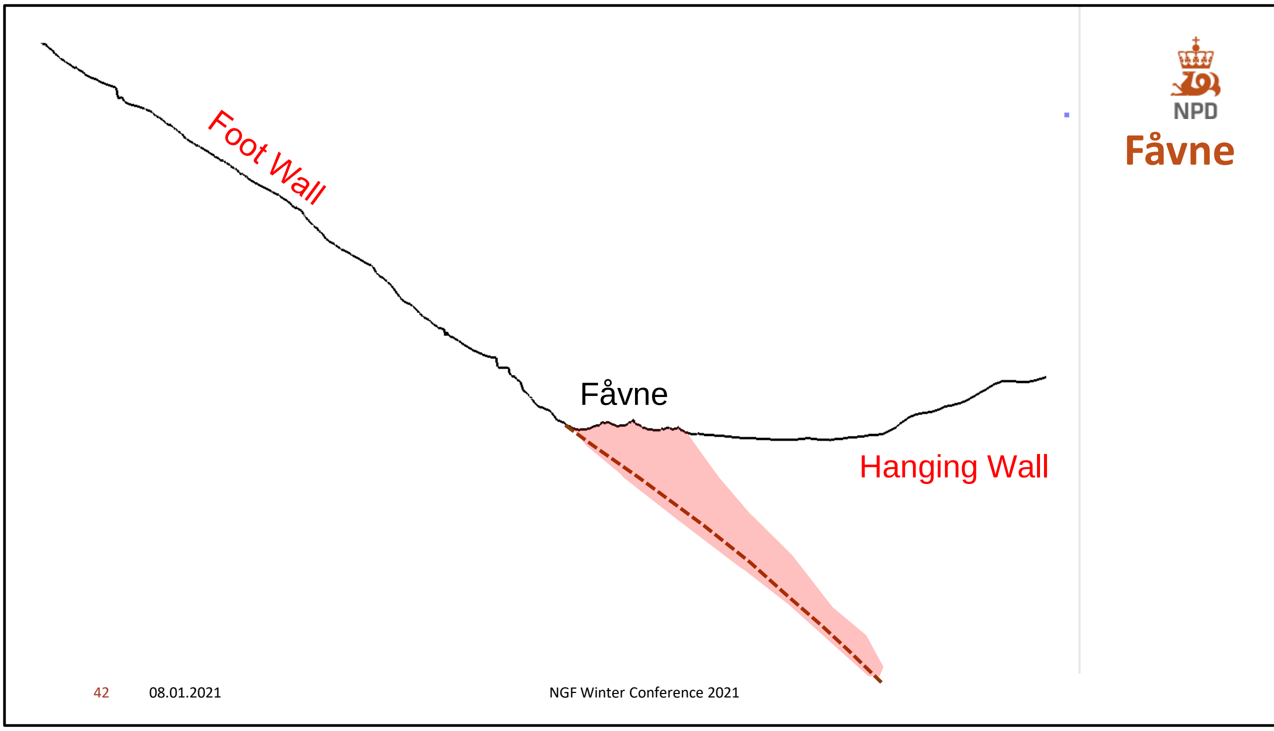


Outcrop sampling by ROV (yellow) and core drilling locations (red) in the Gnitahei/Fåvne area during the NPD 2020 cruise.

Coring and ROV sampling locations, Gnitahei and Fåvne

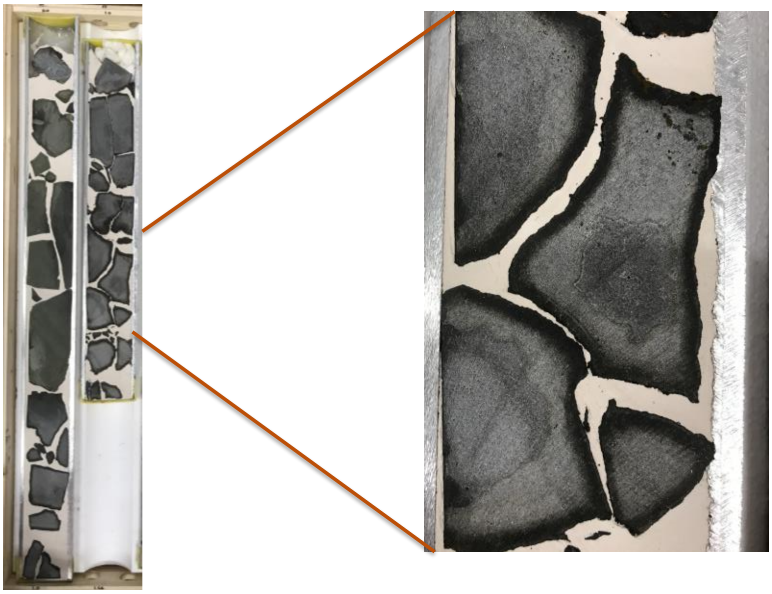


An interpretation in section of the setting of the Fåvne deposits within the hanging wall adjacent to the large bounding fault has been made along the white track in this slide. The section is shown in the next slide.



An interpreted section showing the position of the Fåvne deposits in relation to the overall rift valley fault configuration. The red polygon indicates how the large master fault may act as a conduit for the heat that drives the hydrothermal activity forming the Fåvne deposits.

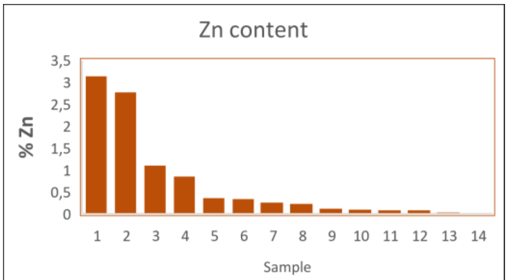
Bedrock to Fåvne hydrothermal mounds

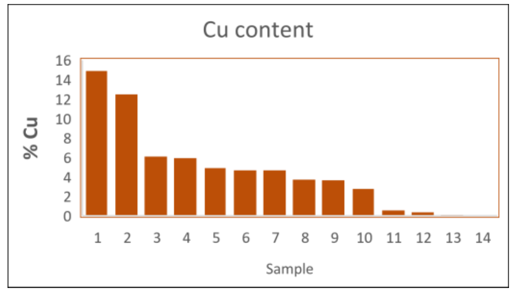


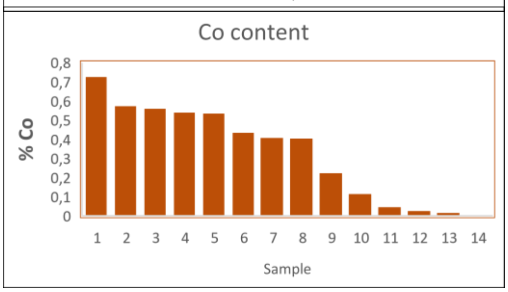
Core drilling into the substrate of the Fåvne black smoker mounds, revealed that it consists of very brecciated basaltic rocks. The fragments have dark coloured altered rims which demonstrate that the brecciation is a result of the hyrothermal activity and not caused by the drilling process.

Analysis of Samples from Fåvne (2018 Cruise)

NPD



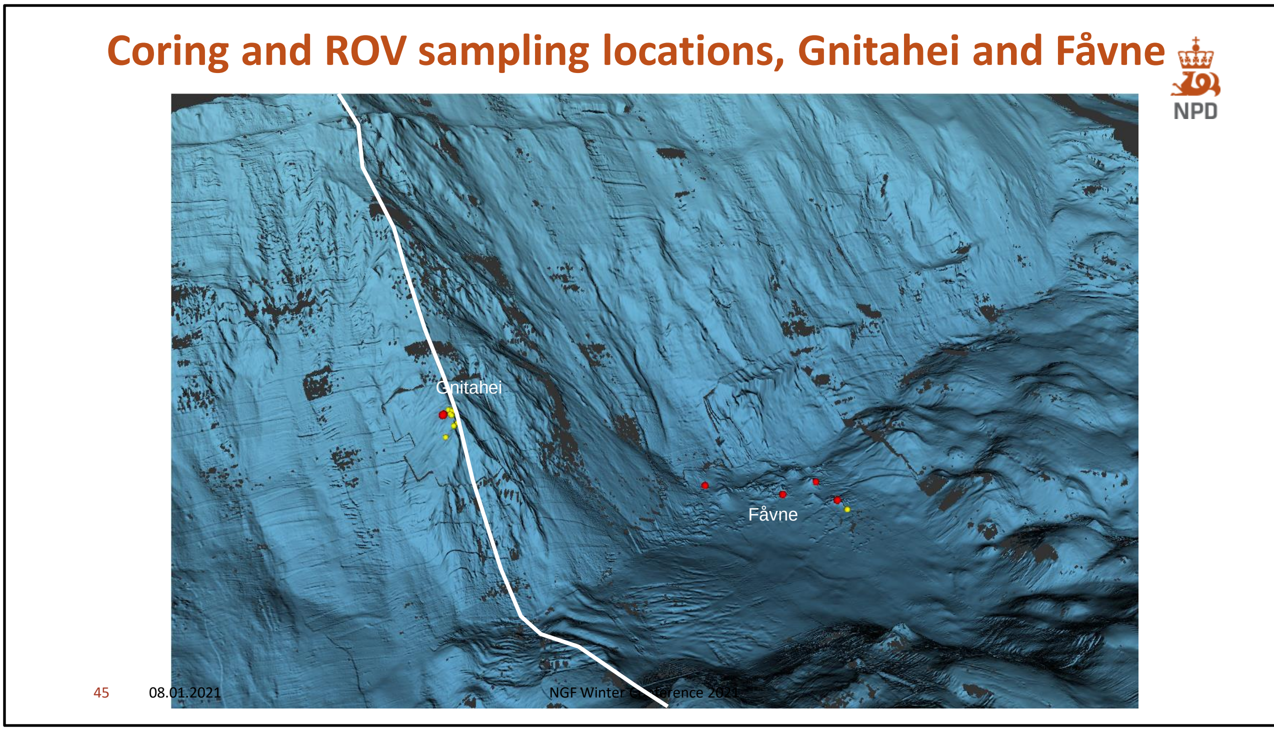




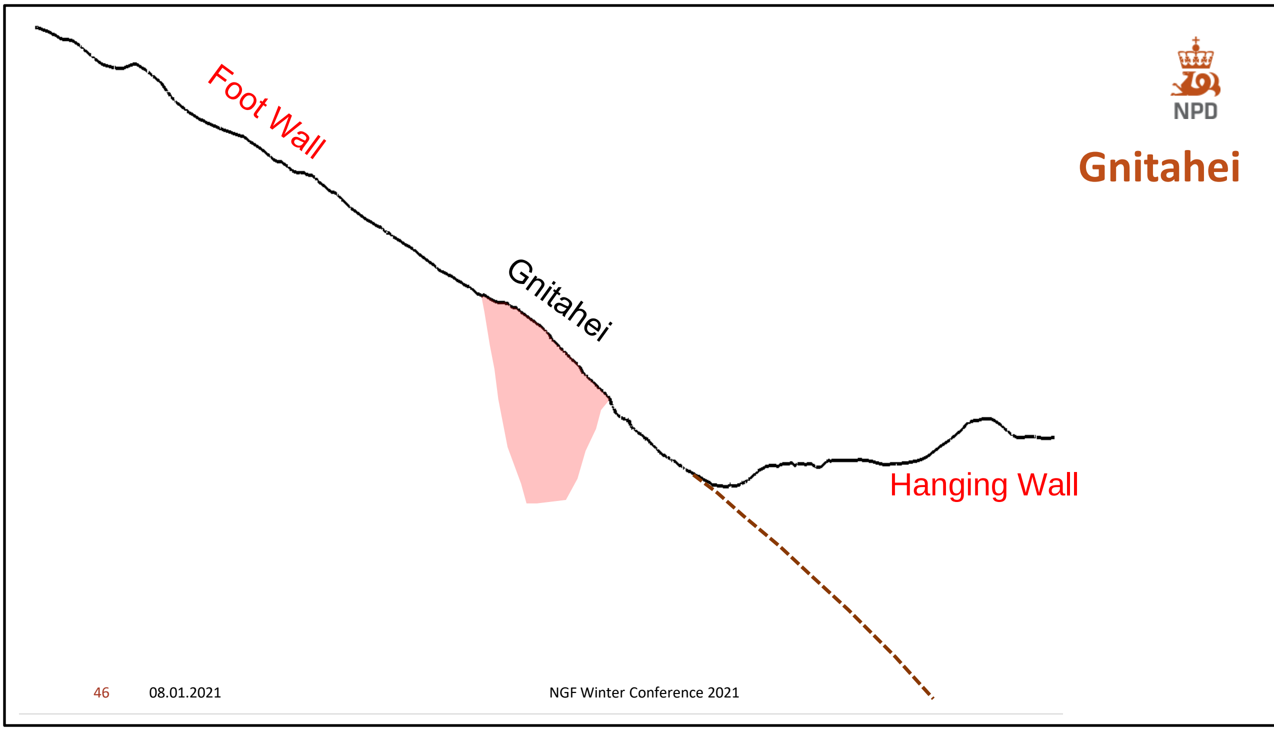
Other:

Lead (Pb)	<2 – 128, Av. 20 (ppm)
Silver (Ag)	0.3 – 34, Av. 7 (ppm)

Analyses of samples from Fåvne show an exceptionally high content of Co. This may indicate that the hydrothermal fluids have passed through ultramafic rocks within the reaction zone beneath Fåvne. No such rocks have been recorded by sampling.



An interpretation in section of the setting of the Gnitahei deposits within the foot wall of the large bounding fault has been made along the white track in this slide. The section is shown in the next slide.



An interpreted section showing the position of the Gnitahei deposits in relation to the overall rift valley fault configuration. The red polygon indicates the location of the hydrothermal fluid circulation during the activity forming the Gnitahei deposits.

Host rocks of Gnitahei

Outcrop samples by ROV from the Gnitahei deposit. The sample to the left is a breccia of fine grained, black basalt impregnated by Zn-rich sulphide. The middle sample is a basalt with very large, kaolinized feldspar phenocrysts. The sample to the right is from part of the surface of the middle sample, showing a “skin” of baryte crystals. Baryte (a sulphate) is known precipitates at low temperatures in the waning stages of hydrothermal activity. This indicates that the rock was in situ.

Summary

- Subsea Minerals act in place
- Opening process, including assessment study, initiated
- Scientific studies and research activity has been going on for years
- Further data acquisition and studies will be carried out in order to:
  - Better understand the geological setting and distribution of the seabed minerals
  - Make better estimates of the resource potential
  - Assess the environmental and social impacts of mineral activity