# Investigating geology, mineralization and environmental sensitivity along Mohns Ridge using seismic, electromagnetic and bathymetric data

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## Summary

Mohns Ridge is currently the subject of much interest owing to the occurrence of hydrothermal vent fields and critical metal-bearing seafloor massive sulphide (SMS) deposits along this segment of the ultraslow-spreading Arctic Mid-Ocean Ridge. To target where potentially mineable SMS deposits may form or have formed, there is a need to clearly image surface morphology and subsurface permeability, fluid zones and heat sources, along with documenting ecosystems and environmental baselines. Here we present components of an integrated approach towards achieving this. First, we report two-dimensional (2D) seismic and controlled source electromagnetic (CSEM) imaging along part of Mohns Ridge to demonstrate how this might help improve geological understanding of, and exploration for, SMS deposits. Second, we provide a bespoke study that assesses environmental sensitivity close to the Mohns Treasure SMS bodies.

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## Introduction

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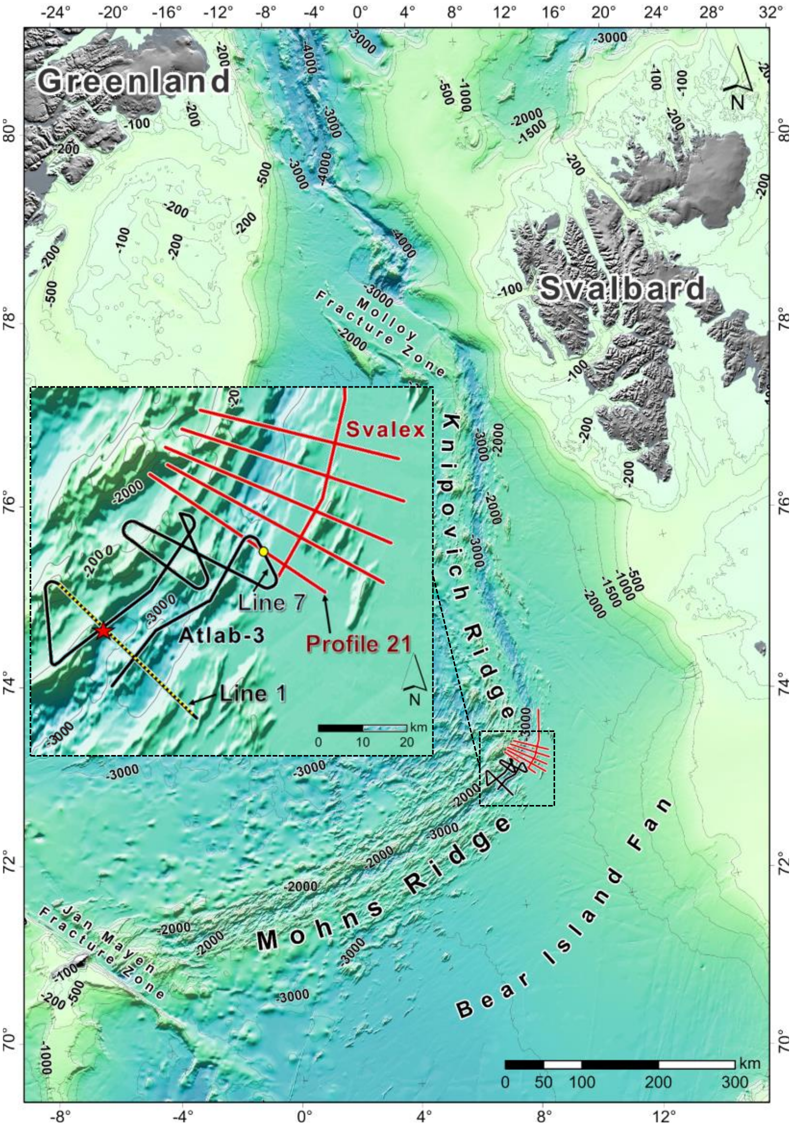

**Figure 1.** Regional bathymetric map of the Arctic Mid-Ocean Ridge in the Western part of the Norwegian Sea with the two exploration surveys used in this study: Svalex from 2001 in red and Atlab-3 from 2022 in black. The red star marks the SMS body Mohn's Treasure

## Seismic and CSEM imaging: methods, results and discussion

The seismic and CSEM datasets used in this study come from two surveys (Figure 1). The first is the Svalex 2D seismic survey undertaken in 2001 as part of a student programme organised by the University of Bergen. The second dataset consists of 2D seismic and CSEM data acquired as part of the Atlab-3 project led by the Atlantic Laboratory (ATLAB) consortium organised by the Norwegian University of Science and Technology (NTNU). Profile 21 in Figure 1 is the southernmost line in the Svalex data that crosses the ridge perpendicularly. These data were reprocessed in 2023 (Vinje *et al*., 2023) using state-of-the-art processing and imaging technologies, resulting in the seismic profile shown in Figure 2. A comparison with the legacy processing can be found in Vinje *et al*. (2023).

Close to the centre of Mohns Ridge is the Axial Volcanic Ridge (AVR) with irregular basaltic structures, ridges and blocks. The complex 3D structure of the AVR and the axial valleys on each side is a severe problem for 2D seismic acquisition and imaging as used here. Out-of-plane reflections will move into the 2D image plane, resulting in un-collapsed events and misplaced energy. In areas with less off-plane variation in the geology, good imaging is achieved.

The overall asymmetry of Mohns Ridge at either side of the AVR is clear in Figure 2, showing that the north-western side of the ridge is more elevated and rugged than the flatter and sediment-covered south-eastern flank. This is consistent with an ultraslow-spreading zone where extension is driven by weak magmatic and more dominant tectonic processes (e.g., Buck et al., 2005). Sub-horizontal sediments of the Bear Island Fan (Figure 2), dominate in the south-east and reach a thickness of 800 m. In contrast, sediments on the north-western flank of the ridge have been rotated counterclockwise, again emphasising the asymmetry across the whole ridge system. The north-western part of the profile is dominated by rotated fault blocks (A to E in Figure 2), forming half-grabens, partly filled with pre-rift and syn-rift sediments. The sediments appear to have been tilted by faulting and simultaneously folded during dragging along the fault footwall.

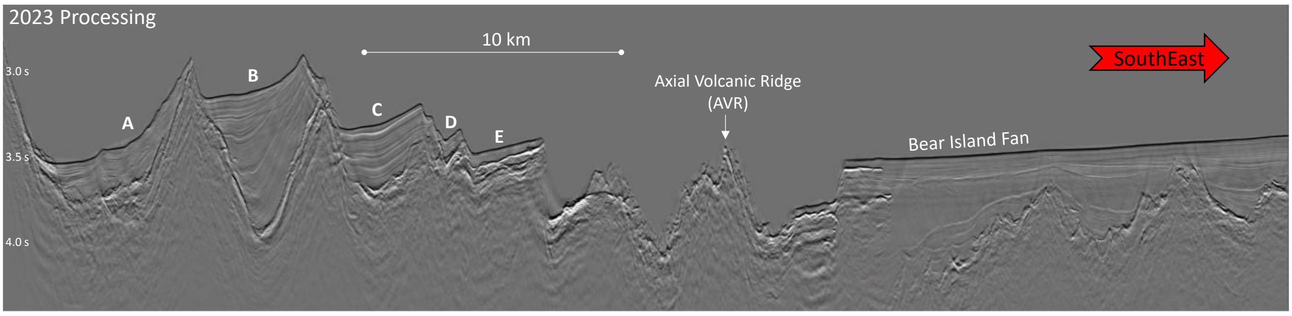

**Figure 2:** Profile 21 of the Svalex data reprocessed in 2023 across Mohns Ridge including the central Axial Volcanic Ridge with rotated fault blocks A to E. The data were acquired in 2001and reprocessed by CGG in 2023.

Line 1 of the Atlab-3 survey passes close to the SMS body known as Mohns Treasure (Figure 1), discovered in 2002 by dredging (Pedersen *et al*., 2010). Both 2D seismic and CSEM were acquired along this line. A total of 23 CSEM nodes were deployed on the seabed in depths ranging from 1660 to 3140 m (Figure 3), with a nominal spacing of 2000 m; the actual spacing was irregular due to the rough seabed. The CSEM source was a transmitter dipole transmitting a signal with a base frequency

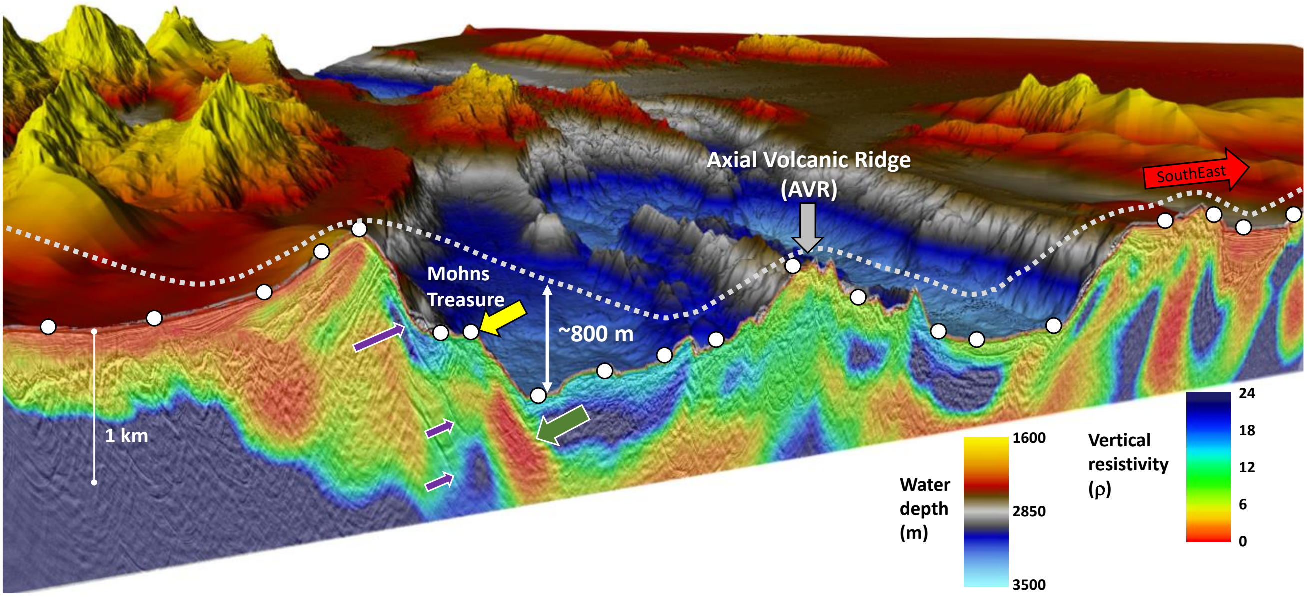

***Figure 3:*** *Vertical resistivity, seismic and bathymetry along Atlab-3 Line 1 viewed towards the north-east showing the AVR, the rift valleys on each side and Mohns Treasure on the western flank. Purple arrows identify faults and the green arrow a zone of low resistivity close to Mohns Treasure (yellow arrow). The EM source track and node locations are shown as a white dotted line and white circles respectively.*

of 0.5 Hz. Due to the rough seabed topography, the distance from the EM source to the seabed ranged from about 35 m to more than 800 m (Figure 3).

The CSEM data were inverted with a finite-difference-based inversion method (Scholl and Miorelli, 2019), with the seismic section being used as a structural guide (Scholl et al., 2017) via the cross-gradient method (Gallardo and Meju, 2003).

The Atlab-3 2D seismic data acquired along Line 1 were processed and imaged using a similar workflow as for the Svalex data. The seismic data in Figure 3 are co-rendered with the bathymetry of the sea bottom and the vertical resistivity derived from the CSEM inversion of the magnetic y-component Hy data.

The combined seismic and CSEM result (Figure 3) provide subsurface indications for the mineralized zone around Mohns Treasure, as demonstrated by the coinciding zones of low resistivity (i.e., high conductivity) and faulting (Figure 3). This represents a useful solution for understanding the geological context of SMS bodies in this region, appropriate for exploration. In potential future regional exploration for SMS deposits, these tools may help constrain geographically limited areas to be explored by manned or unmanned submersibles or by dredging.

## Environmental sensitivity analysis: method, results and discussion

Hydrothermally active habitats represent some of the most biologically unique environments on the planet (Zeng *et al.*, 2021) and provide valuable insights into the processes of evolution. It is critical that natural capital is considered at all stages of the mining lifecycle. The level of resolution and confidence in natural capital assessments will depend on the data available, which are generally very limited in the deep sea. Early within the exploration cycle, and particularly when looking at regional screening, direct "on site" biodiversity data is often not available. In such cases, an analogue-based methodology may be used to initially assess environmental sensitivity, which will improve as more data is implemented when available.

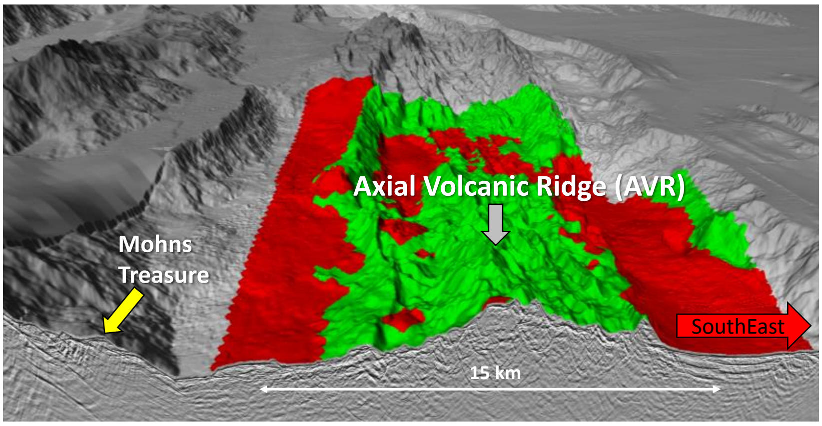

***Figure 4*** *Cross section of the seismic data perpendicular to the AVR south-east of Mohns Treasure with the bathymetric map of the seabed overlain by the environmental sensitivity map that display ecologically sensitive sites in red and less ecologically sensitive areas in green (no buffer applied)*

An environmental sensitivity assessment for an area along Mohns Ridge is shown in Figure 4. The University of Bergen acquired high-resolution multibeam echo sounding data in 2021 which resulted in a high-density (10x10) m bathymetric map of the seabed.. This seabed map was used to identify and classify geomorphic features and substrate types as habitat parcels, including axial valley floor, volcanic bed rock, sediment, fault scarps, seamounts and guyots. The biodiversity value of each habitat was calculated using the UK's statutory biodiversity metric (Natural England, 2023) modified for application in the deep sea, and quantified within the Taskforce on Nature-related Financial Disclosures (TNFD) ecosystem service categories (Cordingley *et al.*, 2023; TNFD, 2022). The habitat parcels associated with geomorphological features such as seamounts and guyots display the highest biodiversity and ecosystem services unit scores. A final environmental sensitivity assessment accounts for services put into the environment versus the resources that may be present. Buffers are added around the more sensitive areas to account for potential adjacent environmental impacts of mining-related activity. Figure 4 shows a map with no buffer. Using a 500 m buffer, approximately 66% of the area of interest at Mohns Treasure is characterised as high risk and 92% under a 2 km buffer. These classifications include areas with medium to high mineral resource probability based on proximity to fault scarps and inactive or active hydrothermal features.

## Conclusion

Responsible deep-sea mineral exploration must look at both the mineral resources and their environmental context at all stages of the exploration cycle and integrate these to provide the right data to enable authorities and operators to make appropriate decisions that consider the value of both the mineral resources and the ecosystem within which they are found, from regional down to prospect and target levels. The quality of exploration for SMS deposits will continue to improve as more becomes known about their geological and environmental settings, both at the surface and in the subsurface. Technological development and better knowledge of both potential mineral resources and the deep-sea ecology, such as that undertaken here, will help limit irreversible negative impacts in highly sensitive environments along with supporting responsible decision making in the assessment of deep-sea exploitation and mining.

## Acknowledgements

We thank the ATLAB consortium and its coordinator Ståle Emil Johansen for cooperation and fruitful discussions throughout the Atlab-3 project period from August 2022 until the present day. We are also grateful to Green Minerals for providing the Svalex data. We would like to thank our colleagues Hao Jiang, Sarah Hill and Federico Buriola for the seismic processing and imaging, and finally CGG Earth Data for funding this work.

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