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MarMine

Cruise Report

Arctic Mid-Ocean Ridge (AMOR)

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Authors:

Martin Ludvigsen, Kurt Aasly, Steinar Ellefemo, Ana Hilario, Eva Ramirez-Llodra, Fredrik Søreide, Ismael Falcon- Suarez, Cyril Juliani, Amanda Kieswetter, Anna Lim, Christian Malmquist, Stein M. Nornes, Emil Paulsen, Hauke Reimers, Øystein Sture

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Table of contents

List of Figures

Abbreviations

General

CTD	Conductivity, Pressure, temperature sensor
DPR	Daily progress report
DSM	Deep-sea mining
EXPL	Exploration area
FFI	Norwegian Defence Research Establishment
LC	Loki's Castle vent field
MT	Mohn's Treasure area
NIVA	Norwegian Institute for Water Research
NTNU	Norwegian University of Science and Technology

Geology

AMOR	Arctic Mid-Ocean Ridge
AVR	Axial Volcanic Ridge
CH_4	Methane
Cp	Chalcopyrite
Py	Pyrite
SMS	Seafloor Massive Sulphide
Sph	Sphalerite

Biology

VT	Video transect

Technology

AUV	Autonomous underwater vehicle
DP	Dynamical positioning
HHXRF	Handheld X-ray Fluorescence
HiPAP	High precision acoustic positioning system
HiSAS	High precision synthetic aperture sonar
MBES	Multibeam echo sounder
MRU	Motion reference unit
PG	Photogrammetry
SCM	Self-Compensated Magnetometer

SSS	Side Scan Sonar
ROCS	Remote Operated Core Sampler
UHI	Underwater Hyperspectral Imager
XLR	Smallest of the two mounted ROVs on Polar King
XLX	Largest of the two mounted ROVs on Polar King

Executive Summary

The overall objectives for the MarMine project are to assess and develop new knowledge about exploration and exploitation technologies, and to define the process mineralogical properties of typical seafloor marine mineral deposits along the AMOR. If marine deep-sea mining (DSM) would be realized, environmental sustainability must be assessed. Like for oil and gas fields, one can expect a marine mineral exploitation operation to contain four phases: exploration, installation, operation and decommissioning.

The cruise would hence have four goals:

1. Obtain geological samples for mineral characterization, and for assessment of mining and mineral processing potential
2. Test new exploration technologies and methods
3. Provide a baseline analysis of the biological systems present on active and in-active hydrothermal vents
4. Explore area of particular interest based on previous analysis of the resource potential and identification of permissive tracts

There are considerable technology gaps for exploration and operation in DSM. The MarMine project aims at contributing to closing such gaps. For exploration purposes, two technologies have been brought forward for this cruise, the AUV and ROV mounted UHI and the ROV mounted drill system. Hyperspectral imagery was collected using the UHI both AUV and ROV mounted. The mineralized rock had a clear hyperspectral signature, but further analyses remain to confirm the results and develop this method. The ROCS proved efficient. Using this tool, a core sample can be collected at 2600 meters' depth within a few hours. However, the mineralized chimney fragments observed on the surface of the mounds at Loki Castle were a mixture of unconsolidated sediments and chimney fragments and hence not suitable for shallow core drilling. Hence, the ROCS was tested in pillow lava basalt. The UHI and the rock drill are tools intended for local scale characterization of previously identified hydrothermal vent fields. For identification of new vent fields, AUV is an important tool for medium and small scale surveys. To learn more about the signature of a hydrothermal vent in the instrument suite applied for the cruise, the vehicle was used on the Loki Castle site.

During the cruise, several hundreds of kilos of rock samples were collected, packed and stored for further analyses. The samples were preliminary checked using HHXRF, showing variable copper and/or zinc contents with traces of gold and silver. The samples will be further investigated in the lab for a detailed mineral characterization.

On the Mohn´s Treasure, a number of video transects together with sample collections were performed. The fauna was distinctively different from the active site Loki Castle. The dominant fauna were sponges and crinoids on rocky substratum and stalked crinoids on sediments. Echinoderms (small asteroids and holothurians) were also observed on sediment. However, the hydrothermal vent characteristics of Mohn's Treasure were not very pronounced.

The Axial Volcanic Ridge (AVR) was defined, based on a former analysis in 2012-2014 confirming high potential for hydrothermal vents. In AVR areas the AUV was deployed for mapping the seafloor bathymetry, sediment acoustic reflectivity (backscatter), salinity, temperature, pressure, turbidity, magnetism and methane content using Multi-Beam Echo-Sounder (MBES), CTD, turbidity sensor, Self-Compensating Magnetometer (SCM) and CH_4-sensor. Based on established bathymetric maps, geological features were selected for visual inspection using the ROV. These surveys showed a dramatic bathymetry similar to alpine terrain, defined by high peaks and ridges formed by plate drift and volcanic activity; no clear evidence of hydrothermal vents was found during these surveys.

1 Background

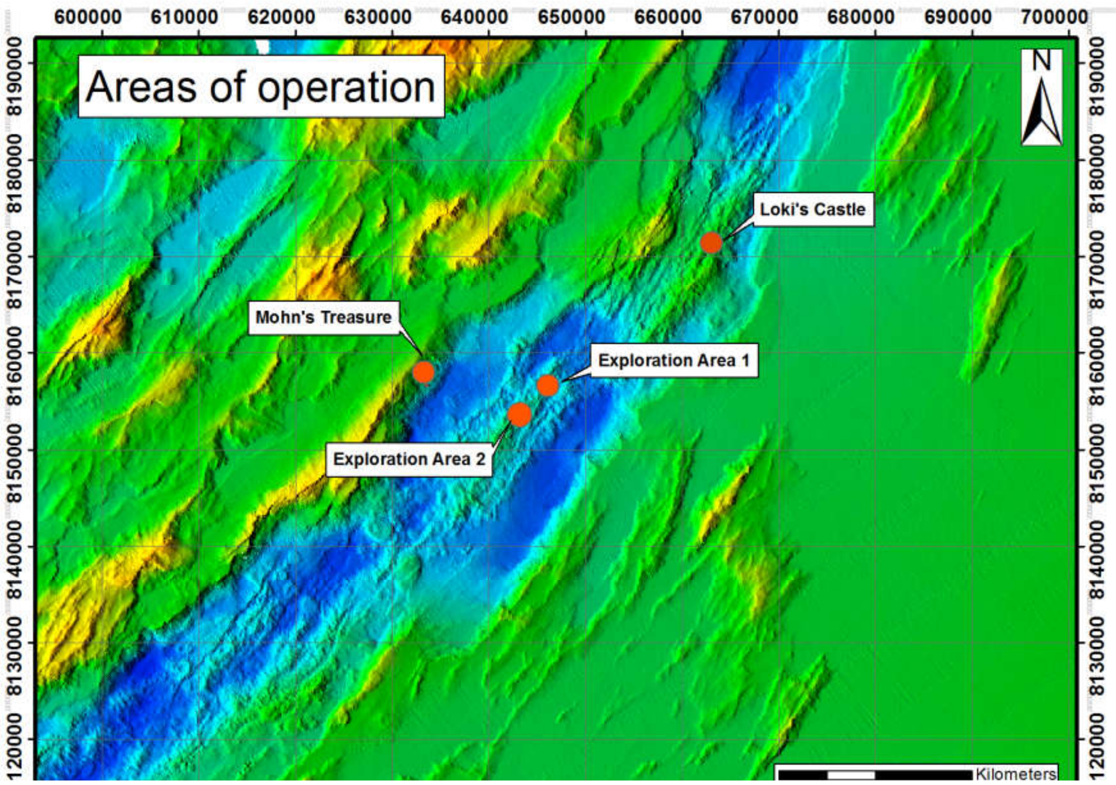
The pre-project to MarMine focused on establishing an estimate of the undiscovered mineral resource potential on the extended Norwegian continental shelf, focusing on seafloor massive sulphides (SMS) deposits along the Arctic Mid-Ocean Ridge (AMOR). The ridge is largely unmapped and preliminary indications of resource potential present considerable uncertainty, see Ellefmo and Søreide (2014a).

The MarMine project attempts to address the technological aspects related to SMS deposits ranging from exploration technology through mining and mineral processing technologies.

The cruise intends to do both biological and geological sampling, which will be analysed thoroughly in the following years. Another goal is to reduce the uncertainty and update the estimates from the pre-project.

1.1 Area of Operations

The area of operations can be divided into three areas along the ridge. The first is Loki's Castle, which is a known site for active hydrothermal venting (Pedersen et Al, 2010), while the second is described in the literature as an inactive vent site (Pedersen et Al, 2013). Finally, a third area was picked for exploration based on the findings from the above-mentioned pre-project.



Figur 1 Figure 1. Area of operations.

1.1.1 Loki's Castle

Loki's Castle is a site of known active hydrothermal venting where sulphide-carrying fluids are expelled from chimneys as black smoker fluids. The fluids have been previously measured to a temperature of about 320°C. The vent field consists of multiple chimneys located on the top of two mounds at approximately 2400 m depth. They are found on the top of an Axial Volcanic Ridge (AVR) that rises about 1300 m above the valley floor (Pedersen, et al., 2010). According to Pedersen et al. (2010), the mineral assemblage in the chimneys consists mostly of sphalerite, pyrite and pyrrhotite. However, the presence of chalcopyrite in the sediments surrounding the chimneys suggests that the temperature of the fluids have been higher in the past.

1.1.2 Mohn's Treasure

The Mohn's Area is located south-west of Loki's Castle on the western flank of the spreading ridge. A dredge operation conducted in 2002 brought up sediments containing pyrite and chimney fragments with fluid channels, however no seawater anomalies were detected in the area, indicating that the deposits stem from an extinct site (Pedersen et Al, 2013). The area of Mohn's Treasure is situated on a plateau formed by a mass wasting which originated in a large fault scarp where the vertical displacement is almost a thousand meters.

1.1.3 Exploration Area

Two additional exploration areas were chosen for their potential to host active vent fields, based on their location and morphology. Both are located on an AVR just south of Loki's Castle and about 12km east of Mohn's Treasure. Area 1 is situated in the northern part of the AVR, while Area 2 is found just south of Area 1. Both have been chosen based on critical considerations and assumptions made from observations from other hydrothermal vent fields, among these are the location in the neo-volcanic zone, the morphology of the AVR and the characteristics and presence of faults.

1.2 Operational Goals

An overall goal for the MarMine cruise was to develop new knowledge about SMS deposits on the extended Norwegian continental shelf. The MarMine project is mainly focused on exploration and exploitation technologies, including mining and mineral processing of the ores, as well as environmental issues regarding deep-sea mining. The cruise objective was to collect necessary data and samples to be able to fulfil the project objectives.

The cruise goals were:

- To collect minimum 200 kg of (mineralized) rock samples
- To test exploration methods for SMS deposits. I.e. UHI and rock drill
- To sample biology and perform video transects
- To explore new areas identified in the previous resource potential assessment.

1.2.1 Geology

Geological sampling

The operational goal for the geological sampling was to collect minimum 200 kg of rock samples from confirmed SMS sites. These samples are intended to be used for mineralogical- and rock mechanical characterization (MarMine project WP4, delivering results to WP2 and WP3). Further, experiments will evaluate the mineral processing potential and performance (MarMine project WP2).

Additionally, smaller samples will be selected for mineral- and geochemical characterization from the new areas.

1.2.2 Exploration methods

The exploration activities focused primarily on refining scientific knowledges of areas subject to form SMS deposits using diverse technological approaches. The operational goals of the exploration part of the MarMine cruise has been to

- Test the potential new exploration technologies and assess its appropriateness. This includes the AUV-mounted UHI and the drilling rig.
- Collect multivariate cross platform data with possible non-linear correlations that will be used to develop and test multivariate analysis techniques that merge and enhance signatures of deep ocean floor characteristics
- Perform an initial test and validation of the pre-project hypotheses (Ellefmo and Søreide 2014b), regarding the identification of favourable areas for finding SMS-deposits along the AMOR and to collect data that can form the basis for an update of the resource potential estimate.

1.2.3 Biology

An ecological baseline study is essential to assess impact of mining activities and the recovery potential of the ecosystem. Such studies, as proposed by Collins et al. (2013) to the International Seabed Authority, follow a 3-stage method:

1. Physical characteristics (including bathymetry and hydrography
2. Biological characteristics (faunal and environmental variables)
3. Targeted ecological studies (population structure, life histories and population connectivity of dominant taxa)

This information is essential to develop management measures related to deep-sea mining activities (Van Dover et al., 2010; Boschen et al., 2013).

The main biological goal during the MarMine cruise was to conduct, for the first time, ecological baseline studies on the Mohn's Treasure site. The aim was to provide the first description of the benthic communities in Mohn's Treasure and compare them to biological and ecological data available from Loki's Castle (Pedersen et al., 2010a). Mohn's Treasure is a massive sulphide deposit at 2600 m depth. Mohn's Treasure has not been sampled biologically so far (Pedersen et al., 2010b; Rapp, 2016). The benthic communities and their distribution in relation to habitat types (e.g. rocks, rocky walls, sediment) will be described from video transects. The faunal communities, from microbes, to meio-, macro- and megafauna, were sampled using the ROV-manipulators, ROV deployed push-cores, a suction sampler and scoops. In particular, during the cruise, a number of specific objectives were addressed:

- Characterization of the microbial communities and their functional diversity in an inactive site.
- Description of the composition and structure of the meiofaunal and macrofaunal benthic communities and how they relate to the habitat and environmental variables.
- Description of megafaunal benthic communities along different habitat types on an inactive site.
- Trophic structure analysis of the dominant species in an inactive site.
- Identify key biological components that can be used to identify conservation units.

The biological goals are directly linked to the geological analyses that will provide a detailed bathymetry of an extremely poorly known site and further information on the abiotic characteristics of the habitat.

1.2.4 Exploration of New Areas

It was an operational goal to explore areas close to the AVR and obtain more information of geological properties and their potential for minerals.

1.3 HSE

The cruise was completed without any HSE incidents. MarMine strives for high standards in HSE work. All fieldwork was carried out in compliancy with the HSE regulations defined by NTNU and its main contractor Reach Subsea, as described in the guidelines HMSR-07: "Fieldwork, field-course, research cruise, on-site inspection and excursion". The objective was to ensure that all relevant activities were conducted in a safe manner. A HAZOP was completed prior to the operation in collaboration with Reach Subsea.

All accidents or unwanted events had to be reported through the NTNU reporting system.

HSE is implemented throughout all aspects of our operations, from the safe handling of all instruments and equipment to personal protective equipment (PPE). The PPE includes hard hats, life vests and safety boots mandatory for all personnel being outside on deck while at sea.

The vessel HSE systems of safety observation card was implemented and used during the cruise; the vessel "permit to work" system diligently used during each non-standard activity such as "working at height" "hot work" , etc.

1.4 Vehicles and vessel

The cruise was performed with three underwater vehicles operated from the ship. Two integrated Remotely Operated Vehicles (ROVs) and an Autonomous Underwater Vehicle (AUV), briefly described below.

1.4.1 Polar King

The Polar King is a Construction Support Vessel (CSV) specially designed for operation under severe weather conditions with high manoeuvrability and station keeping capabilities. The vessel provides services including offshore construction, Inspection, Maintenance and Repair (IMR) operations. It is equipped with two integrated work class ROVs, one Perry XLR (build number 02) and on Perry XLX (build number 57).

Three cranes are available on the aft deck, one offshore construction crane rated to 150 T– which has a range of 3000m and two smaller deck cranes – which can be used for mobilization and demobilization. During the cruise, the construction crane was used for transporting samples from the seabed and taking gravity core samples.

Figure 2. Polar King multipurpose subsea vessel.

1.4.2 Work class ROV XLR and XLX

Polar King is equipped with two Triton Work class ROVs with Tether Management System (TMS), both of which were used in the operations. The XLR (called XLR 02) is the smaller of the two, and was used for general exploration and sampling. The larger XLX ROV (called XLX 57) was outfitted with the drill, and was primarily used for this purpose.

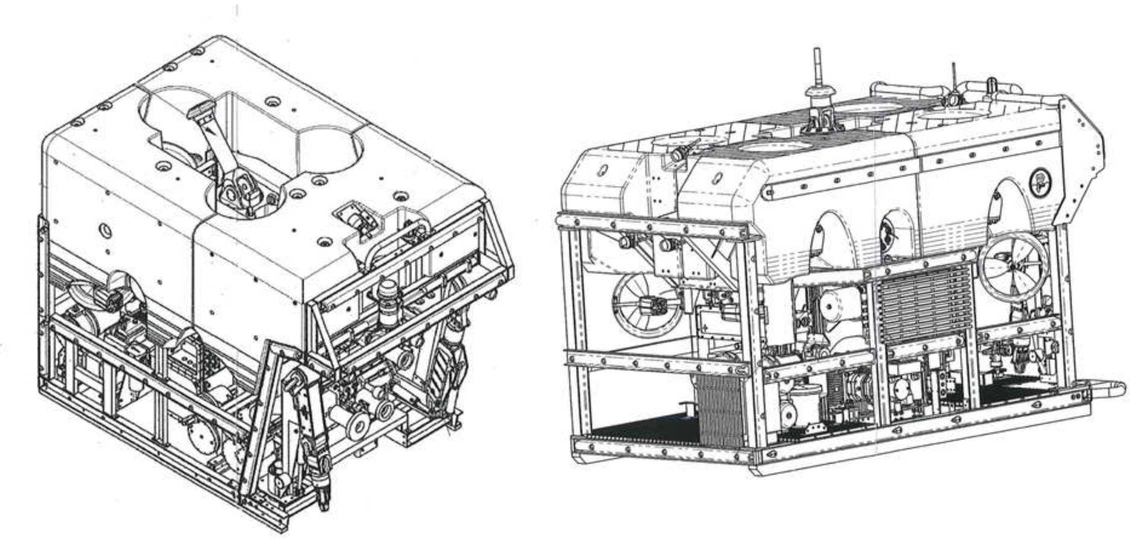


Figure 3: Schematics of the two ROVs. XLR on the left, XLX on the right.

Table 1: ROV XLR02 and XLX57 specifications.

Description	Unit	Triton XLR 02	Triton XLX57
General Particulars			
Manufacturer/Type		Perry/Triton XLR	Perry/Triton XLX
Length	m	2,95	3,55
Width	m	1,70	1,80
Height	m	2,05	2,18
Weight	kg	4000	4800
Payload	kg	150	250
Operational depth	m	3000	3000
Vehicle frame carrying load	kg	3000	3000
TMS & Umbilical			
Manufacturer/Type		Perry/Top Hat Type IV	Perry/Top Hat Type V
Tether length	m	370	650
Umbilical length	m	3450	3105
Standard Equipment			
Low light navigation camera		Kongsberg OE13-124	Kongsberg 15-110c
CCD colour camera		Kongsberg 14-366	Kongsberg 14-366
Manipulator/Utility camera		Schilling Wrist Camera	Kongsberg OE15-358
Lights		Bowtech LED AC4200	Bowtech LED AC4200
Number of lights on Vehicle		6, dimmable in pairs	6, dimmable in pairs
Total lighting capacity	W	1500	1500
Lighting circuits		3	3
Grabber manipulator		Whittaker, M5	Schilling, Rigmaster
Working manipulator		Schilling, Titan 4	Schilling, Titan 4
Sonar		Kongsberg Simrad, Mesotech MS1000, Ms1171 Sonar head	Kongsberg Simrad, Mesotech MS1000, Ms1171 Sonar head
Depth sensor		Paroscientific Digiquartz	Paroscientific Digiquartz
Compass		CDL TOGS	Octans 3000 FOG
General navigation system		Tritech, IGC	Teledyne, Workhorse Navigator
Connection points			
Outlet (12, 24 and/or 250 VDC – 5 A)		12/24/48VDC outlets in JB	11 off 24VDC
Outlet (110 and/or 220 VAC – 1 A)		120vAC @20A	120vAC @20A
Spare quad or two data channels through fibre		4x RS232 / RS485	4x RS232 / RS485
Spare video lines		4	4
Number of low flow outputs		7+14, total 21 spare outputs	10

Pressure	bar	210-240	220
Flow	l/min	8-15	15
Number of high flow hydraulic output		2	2 optional RCU
Pressure	bar	210	210
Flow	l/min	70	70
RCU		Optional	Optional
Optional equipment			
38 mm hard-line cutter, high pressure water jet, grinder, integrated RCUs, ROV tool basket, dirty oil pack			
Launching/Handling systems			
Manufacturer/Type		ODIM Integrated in the vessel	ODIM Integrated in the vessel
Launch/Recovery		A frame over the side	Moonpool and Cursor
Active heave compensation	m	Hs 4,5	Hs 4,5
Operational depth	m	3000	3000
Manoeuvring			
Forward speed	m/s	1,33	1,30
Backward speed	m/s	1,31	1,38
Vertical speed	m/s	1,39	1,50
Lateral speed	m/s	1,04	1,14
Forward thrust	N	9500	10787
Backward thrust	N	9500	10787
Vertical thrust	N	9500	8825
Lateral thrust	N	9500	10787
Number of thrusters and position		7 vectored, 4 axial, 3 vertical	8 vectored, 4 axial, 4 vertical
Auto heading		± 2 degrees	± 2 degrees
Auto depth		± 150 mm	± 150 mm
Auto altitude		± 150 mm	± 150 mm
Auto roll		± 5.0 degrees	± 5.0 degrees
Auto pitch		± 5.0 degrees	± 5.0 degrees
Auto station keeping in 3 knots		Yes	Yes
Power			
Overall available power	kW	145	130
Overall available power	HP	125	150
Propulsion	W	110	95
Number of hydraulic circuits		2	2
Pressure	Bar	220	210
Flow	l/min	70	70

1.4.3 AUV Hugin HUS

The MarMine cruise utilized the Hugin HUS AUV, operated by the Norwegian Research Defence Establishment (FFI). The AUV is deployed and recovered using the stinger system shown in image mounted in an 8m*3m container on the stern of the Polar King. The AUV is equipped with a wide range of sensors

- Kongsberg HiSAS 1030 side-scan sonar (SSS)
- Kongsberg EM 2040 multi-beam echo sounder (MBES)
- Magnetometer
- Conductivity, temperature, depth (CTD) sensor
- Turbidity sensor
- Optical camera (still image)
- Ecotone underwater hyperspectral imager (UHI)
- Methane sensor
- Acoustic Doppler current profiler (ADCP)
- Inertial Navigation System (INS)

Figure 4: Hugin in the stinger, while being deployed.

1.5 Survey equipment

Table 2: Survey equipment

Type	Producer company
Navigation and positioning	
Navigation spread: **Primary Online, Spare Online, 2 ROV remotes, Bridge remote, and supervisor Remote.**	Fugro
Set of Fugro Starpack GNSS receivers with corrections over ESAT.	
HiPAP 500 systems	Polar King
CNODE transponders	
Acquisition	
UHI	Ecotone
EM 2040 Multibeam echosounder	Kongsberg
Interferometric Side-Scan Sonar (HiSAS 1030)	Kongsberg
Self-Compensating Magnetometer (SCM)	OFG
3 SAIV 204 CTD profilers	

1.6 Mobilization

The mobilization went largely without any issues, but had some last minute changes to the setup. In particular, the lamp mounted on the ROV was found to provide insufficient illumination for the hyperspectral camera. This was solved by renting a more suitable lamp before departing. The new lamp provided enough light, but the spectrum emitted was not ideal. To provide a comparable dataset across the ROV and AUV hyperspectral images, this must be compensated for during post-processing using data taken on a calibration reference. The problem with the lamp characteristics was the only problem found during the mobilization that directly affects the results of the cruise.

In addition to this, there was an incident during the first dive test of the AUV, Hugin, in the fjord outside Bergen. Polar King is equipped with Voith Schneider Propellers (VSP), which generated an unexpected current behind the ship when engaged. While the AUV was clear of the propellers, the strong current caused the engine section to be damaged. Fortunately, a spare motor section was brought along, which was installed to replace the damaged part. The damaged part was also repaired during the following day, to once again have a spare available.

1.7 Methods

In the course of the cruise, diverse methods were used to fulfil the set objectives. These methods can be divided into 4 main categories: visual/optical, remote sensing, sampling, and express laboratory methods. All these methods served both for geological and biological analysis purposes and are described under the biology and geology sections below.

1. Visual/optical methods:
   - Video/photo transects
   - 3D photogrammetry
   - Photo mosaic
   - Underwater Hyperspectral Imaging (UHI)
2. Remote sensing:
   - Multibeam echosounder bathymetry
   - High Resolution Interferometric Synthetic Aperture Sonar (HISAS) imaging
   - Magnetometry
   - Conductivity Temperature Depth (CTD) logging
   - Turbidity and CH4 logging
3. Sampling:
   - Suction sampling
   - Scoop sampling
   - Grab/manipulator sampling
   - Push-core sampling
   - Gravity core sampling
   - Core drilling
   - Water sampling
4. On-board laboratory methods
   - Hand Held - X-Ray Fluorescence (HHXRF) analysis (elemental content of minerals)
   - Microscope analysis (biology)

1.7.1 Geology and Exploration

On-site operations required preliminary selections of best site emplacements to be investigated for sampling and explorative transects. The process involved analyses of bathymetric data as well as geological interpretations using recognizable morphostructural features in both low and enhanced resolution maps.

The exploration on-site involved ROVs to primarily identify, situate and sample massive sulphide evidences. Secondary studies consisted in visualizing and describing the geological environment with an attempt to better refine further interpretations on seafloor maps.

Although a big portion of the data and samples was analysed during the cruise, most of the analyses will be done in laboratories onshore afterwards. Thus, preservation of the samples and quality check of the data became an important task.

Original rock samples collected for mineralogical, geochemical and textural characterization were split into manageable sections, and then double bagged in 150 µm thick and 20 or 40 cm wide plastic tubes, flushed with nitrogen and vacuumed (twice) to prevent oxidation before they were stored in freezer at -21 C. Remaining rock samples were stored in water containers on deck to prevent oxidation. Figure 5 shows an example where the nitrogen flushed plastic tube is being vacuumed.

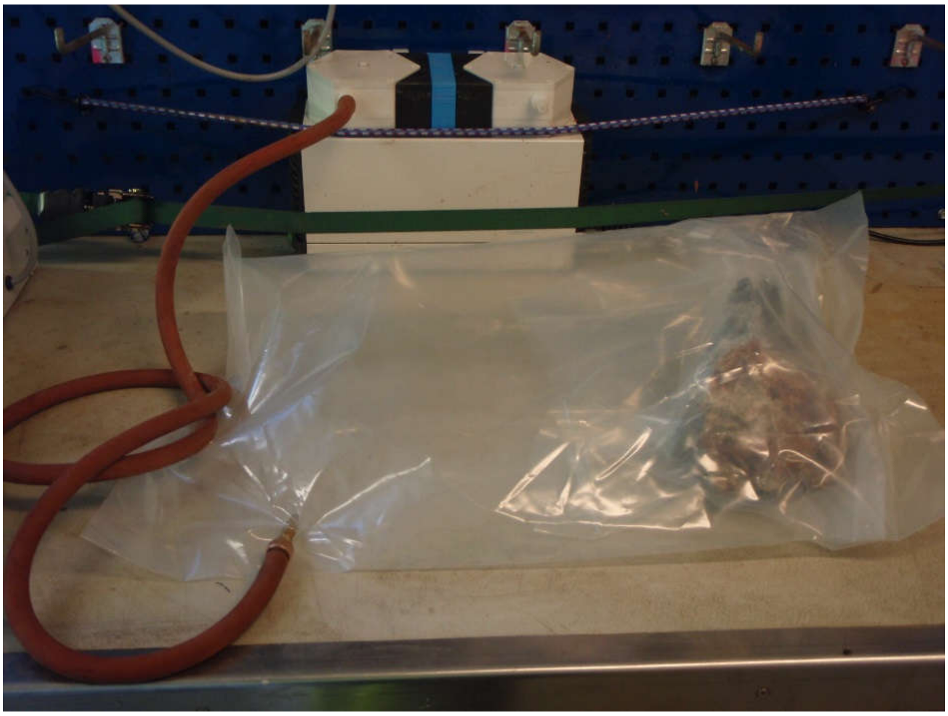


Figure 5 Plastic tube flushed with nitrogen gas being vacuumed. Photo: NTNU MarMine / Kurt Aasly

Material for rock mechanical characterization was kept as boulders (minimum) that allows to core over 10 cm lengths, 5 cm diameter samples for the planned characterization. The samples were double bagged, flushed with nitrogen and vacuumed (twice) before they were stored in a fridge at +4 C to prevent development of micro-cracks.

Some samples were bagged, flushed, vacuumed and stored in room temperature as references and to make it possible to assess the influence the freezing on the development of micro cracks in basalt.

Sampled sediments where drained using a vacuum pump trap kit and a 20-25 µm aperture filter and packed according to the same procedure to the one described for the rock samples. See Figure 6 for the setup.

Figure 6 Drainage of sediment samples before bagging, flushing, vacuuming and freezing. Photo: NTNU MarMine / Kurt Aasly.

Video/photo transects

Video/photo materials obtained during the ROV dives were used for both geological and biological purposes. They were conducted with the XLR ROV at selected locations at Loki's Castle and Mohn's Treasure. The ROV was flown at < 1 m above the seafloor at a constant speed of 0.4 knots (0.2 ms^{-1}). Because the video camera was not high resolution, photographs were taken at regular intervals (approx. 10 seconds apart), providing higher resolution for further analysis. The field of view was calibrated with line lasers that were (i) turned on at the transect start for the first three photos, (ii) and turned off for the reminder of the transect because the lines interfered with the particles in the water (Figure 7. Calibration of photos for video/photo transects.).

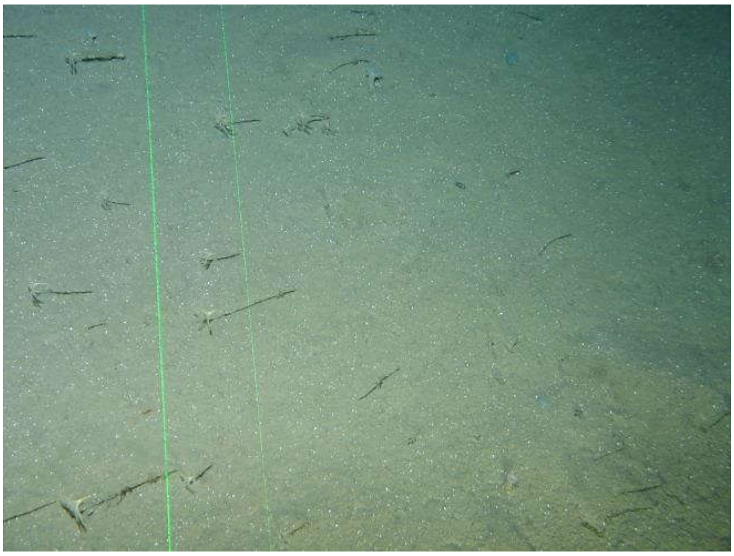


Figure 7. Calibration of photos for video/photo transects.

3D Photogrammetry

The XLR ROV was equipped with an AVT 1380C camera for collecting still images for photogrammetry. Photogrammetry uses overlapping 2D still images to reconstruct a 3D model of the recorded scene. The AVT 1380C camera has a relatively low resolution (1360*1024 pixels), high light sensitivity and good depth of focus. It was set up to take one image every two seconds. A photogrammetric survey was conducted on one of the vents of Loki's castle: 354 images were collected over the course of 45 minutes and used to construct a 3D model of the vent.

Photo mosaic

The same still camera (AVT 1380) was used to collect 2D still images of higher quality for some of transects. These data were used to make photo mosaic of the transects.

Underwater Hyperspectral Imaging (UHI)

A Hyperspectral Imager is a specialized camera which observes the electromagnetic spectrum in more detail than regular red-green-blue (RGB) cameras. Whereas a traditional camera outputs three colour bands per pixel, hyperspectral cameras yield much more. This provides a greater granularity within the same spectrum as RGB and/or a wider spectrum. A technology such as this enables us to distinguish features that would not be visible in an RGB-image, or indeed to the human eye. Hyperspectral imaging has been conducted successfully from airplanes and satellites for quite some time, but moving the technology underwater is only just starting.

Figure 8. The UHI sensor and the AUV with the sensor mounted. The AUV has a roll angle of 90° in the picture.

The Ecotone Scientific UHI is a line scanner. While a regular camera records rectangular images, the UHI images are lines with a width of 1920 pixels and height of a single pixel. To produce a recognizable picture, the scanner needs to be moved forward at a steady speed, and the lines are then combined into a larger image in post-processing. The light of a line is sent through a diffraction grating to separate the different wavelengths of a pixel into up to 960 colour bands. Splitting the available light into so many bands does however require a lot of light. In order to increase the recorded, both spectral and spatial binning of the pixels can be employed. In the scans conducted during this cruise, the spectral-spatial binning was set to either 8-1 or 4-2, leading to a spectral resolution of 120 or 240 colour bands. The corresponding spatial resolution is 1920 pixels and 960 pixels, respectively. The sensor and its mounting is seen in Figure 8.

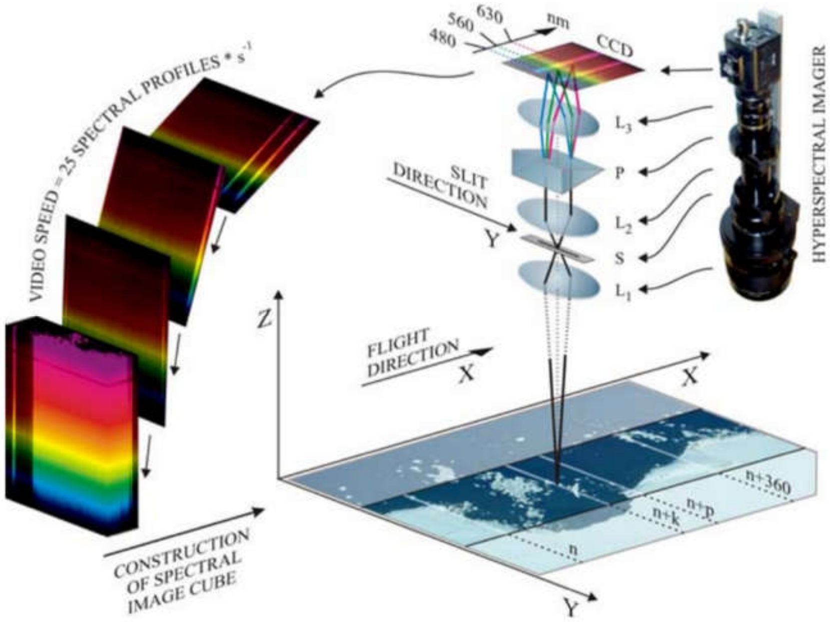


Figure 9. Diagram of UHI principles.

Magnetometry

Magnetometry is an essential method for seafloor massive sulfides exploration. Hydrothermal processes that lead to accumulation of SMS deposits also significantly change the magnetic properties of these rocks. This means that magnetic anomalies can indicate potential sites of recent or former hydrothermal activity, making magnetic study an essential method in exploration of both active and extinct hydrothermal fields.

The Earth's magnetic field is a vector quantity, which means at each point in space it has an intensity and direction. To completely describe the field we need three components. A Self-Compensating Magnetometer (SCM) was rented from Ocean Floor Geophysics and installed inside of the Hugin AUV. The magnetometer used in the survey recorded three orthogonal intensity components (X, Y and Z) along three directions and the total field strength. All these elements are measured in nanoTesla (1nT=10^{-9} Tesla).

The observed magnetic field contains several components:

- The geomagnetic field. The Erath's magnetic field that is generated in the fluid outer core by a self-exciting dynamo process.
- Anomaly field. Caused by local changes in magnetization of rocks.
- Vehicle induced field. Caused by vehicle movement in the Earth's field at various orientations, and the electromagnetic field from the electronics that vehicle contains.
- Diurnal changes. Short-term changes, caused by the ionosphere or geomagnetic storms.

To produce useful data from a magnetometer, first of all, it is necessary to compensate for the host vehicle motion related field. To acquire information about this generally called vehicle induced magnetic field, the host vehicle was flown in a specific calibration square manoeuver as shown in Figure 10 (Source: Ocean Floor Geophysics). The calibration procedure was conducted for every AUV dive, as magnetic signature of the vehicle changes in time and with changing latitudes. The rest of components are not depending on the local varying field of interest and will be removed and analysed in post-processing after the cruise.

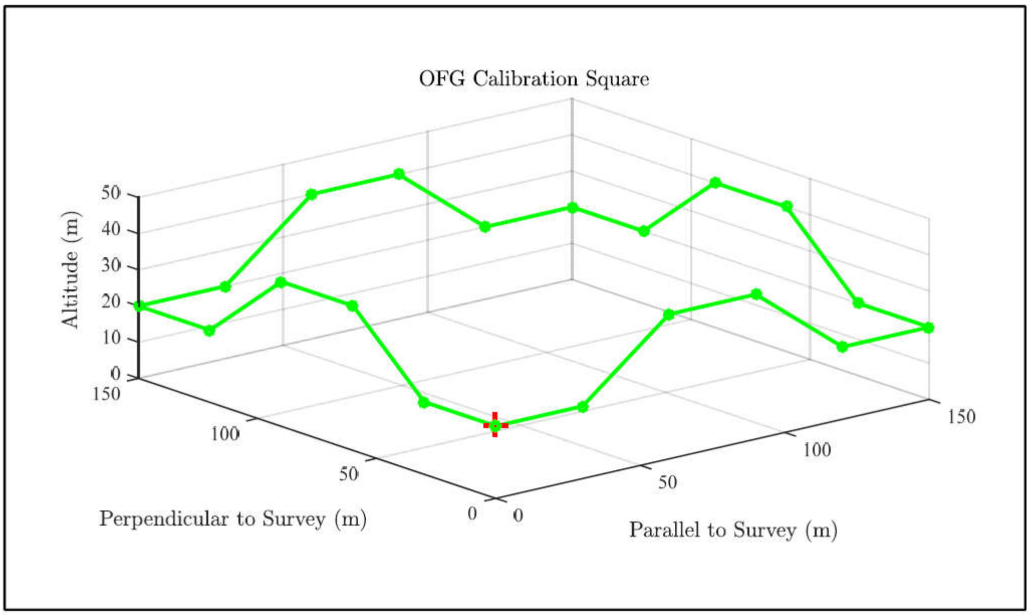


Figure 10. 3D representation of the path for a typical calibration square, flown in both clockwise and counter clockwise directions.

Water column data

Another important method in hydrothermal vent exploration is logging of water column parameters. These are: conductivity, salinity, temperature, depth/pressure, sound velocity, water density, methane (CH_4), and turbidity. All of them were recorded by the AUV. A CTD profiler was used for every dive conducted by both ROV and AUV, and it was repeatedly mounted on the crane to obtain a sound velocity profile for better acoustic positioning of the AUV. Data were recorded in physical units and simultaneously transmitted via a cable to the ROV for on-line use, saving valuable dive time. Not all of these parameters were recorded directly, but some of them are calculated; all of them are widely used in real-time as well as post acquisition interpretation, though.

Hand Held X-Ray Fluorescence Spectrometry (XRF)

X-Ray Fluorescence spectrometry is a non-destructive analytical method used for immediate analysis of the elemental composition of rock samples. The XRF analyser determines the chemistry of a rock/soil sample by measuring the fluorescent X-ray it emits (secondary X-ray) after being excited by a primary X-ray source. The technique is based on the fact that each element presents in a sample produces a unique specific set of fluorescent X-rays ('a fingerprint'), that allows compositional identification and quantification.

Most atoms have several electron orbitals (K shell, L shell, M shell, for example). When x-ray energy causes electrons to transfer in and out of these shell levels (see Figure 11), XRF peaks with varying intensities are created and will be present in the spectrum, a graphical representation of X-ray intensity peaks as a function of energy peaks. The peak energy identifies the element, and the peak height/intensity is generally indicative of its concentration (Source: Thermo Fisher Scientific).

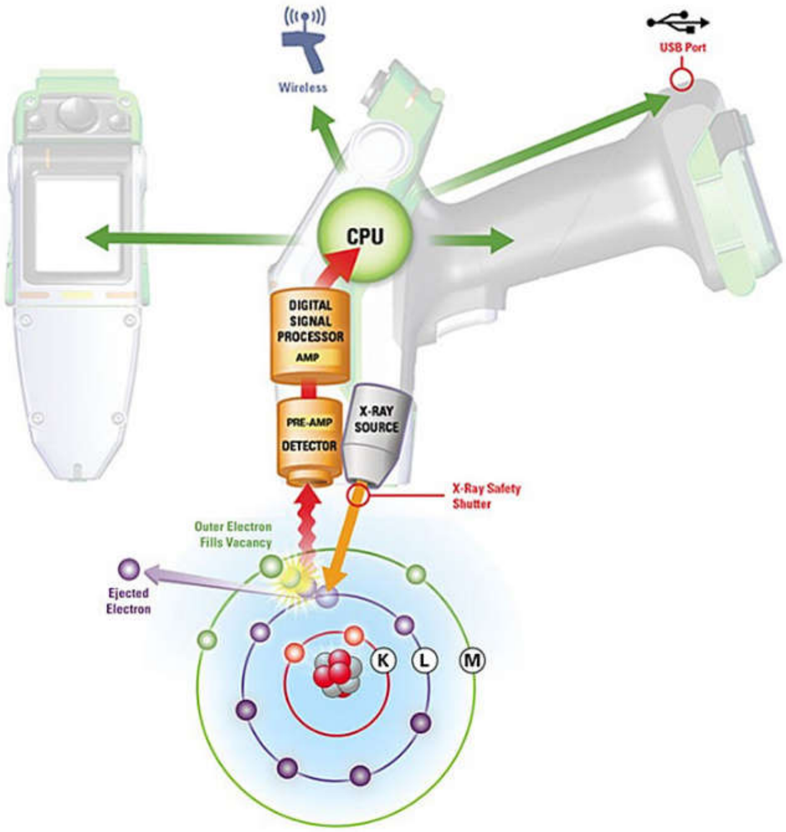


Figure 11. X-ray Fluorescence analysis.

Each time samples were delivered on board of the vessel, first of all they were analysed with a Hand held XRF analyser for content of Cu, Zn, Au, and Ag, which are expected to be present in mineralized areas. The method is suitable for both qualitative and semi-quantitative analysis and allowed us to indicate an average percentage of metals of interest present in the rock samples. Analysis results were stored locally on the HHXRF and a backup was taken on a regularly basis to secure the data. Figure 12 shows the HHXRF in use in the sampling handling container before the sample is packed.

A system check including a detector-calibration was performed on the HHXRF prior to all analysis campaigns. Standard procedure was to analyse for + 120 seconds and thereby using the built in filters for the mining calibration. The “Mining” calibration is intended for use on e.g. geological materials and mill feed to mineral processing plants.

Figure 12. The handheld XRF was used to get a rough indication of the element content of the sampled rock samples. Photo: NTNU MarMine / Lars Ivar Tumyr.

Gravity core sampling

The gravity coring method is fairly simple, but very efficient and reliable for collecting sediment cores from the seabed using gravity to penetrate the seabed – driven by a weight added to the rear part of the coring pipe. In this cruise a 3 m long and 105 mm diameter core was dropped from 5 m above the seafloor, using the main crane of the vessel to control altitude and position, and also for bringing the core back onto the vessel after sampling (see Figure 13). The sediment was later removed for the core catcher fitted inside the main body SS-pipe line, which completes the gravity core set up.

The gravity corer was operated freely using the construction crane with no specialized LARS. A proper LARS would have improved both the efficiency and the safety of the gravity coring operations.

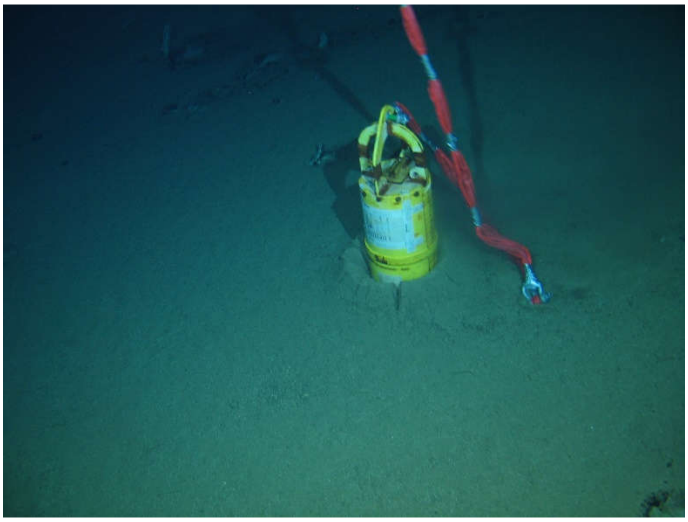


Figure 13. Instantaneous caption of the gravity corer deployment from the ROV camera. Notice that the SS-pipe line is dig into the sediment.

Remotely operated core sampling

From the first half of 2016 Williamson & Associates has developed for NTNU a Remotely Operated Core Sampler system capable of recovering 1000mm of core sample with a diameter of 75mm. ROCS is an ROV mounted box drill that uses the fluid power, electrical power and telemetric interface of the host ROV to operate in depths up to 4000m.

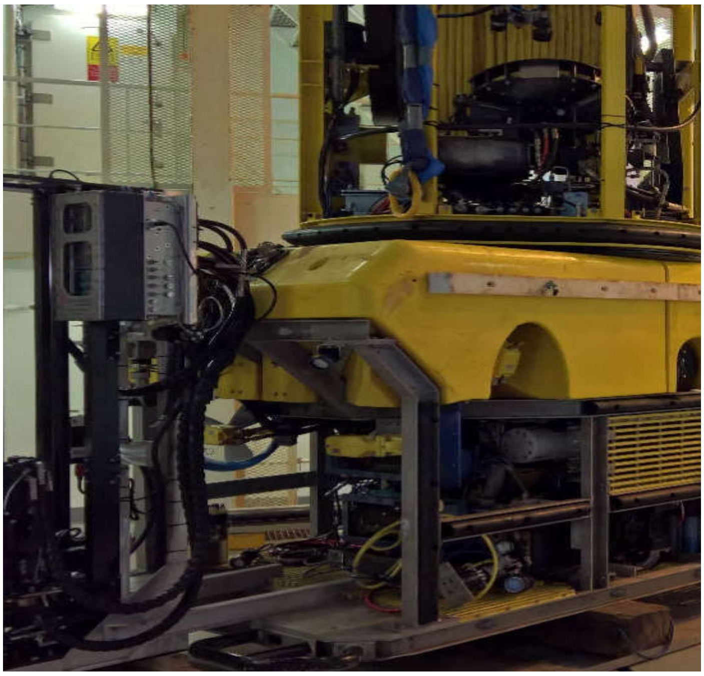


Figure 14. The XLX57 ROV equipped with the ROCS drill (front).

This system was mobilized aboard the Polar King for the MarMine cruise. The mobilization process was relatively smooth and the system integrated well with the Perry XLX ROV.

Subsea Positioning

All positioning of surface and subsea vehicles are done online using the Fugro SEIS navigation package. A redundant set of Fugro Starpack GNSS receivers with corrections over ESAT provided vessel positioning. The G2 differential correction service was used as primary position for the entire cruise giving absolute vessel 2D accuracy of 4cm at one sigma level and not relying on proximity to shore differential stations. Two redundant Kongsberg Seapath systems provided ship attitude and heading.

Two redundant Kongsberg HiPAP 500 USBL systems provided subsea positioning. The sound velocity profile, gathered by CTD on the XLR ROV, was processed and uploaded in both systems prior to commencing work on each dive. Stated accuracy at a working depth of 2800m for a HiPAP 500 system in calm water is 5m at one sigma level. Real-time subsea positioning during the MarMine cruise are within this accuracy and slightly worse in rougher weather. When carrying out average position fixes of 10 and more USBL measurements we achieved standard deviations from 2m to 4m.

Real-time USBL positions of all subsea vehicles were recorded in the online software suite at 1Hz. This log was then smoothed by a running a univariate smoothing spline in 2D. The smoothed track was used in GIS and to geotag all subsea still images.

During the mobilization, an integrity check of both navigation and attitude sensors was carried out. All systems showed good agreement and the results are detailed in the mobilization report. The integrity of the USBL systems was verified by carrying out a 360 spin of the vessel. No offset or alignment errors were identified and the results are detailed in the mobilization report.

MBES Processing

Prior to the cruise, we had a bathymetry data set collected using vessel mounted MBES. The data were collected by UiB and the Norwegian Petroleum Directorate in 2002. This data set could support gridding to 100 m grid size. In the highly variable conditions on our sites, this was insufficient for planning AUV mission close to the seabed. For all unknown areas, the first stage of bathymetry mapping was always to provide MBES data, typically at seabed altitudes of 100 meters. These AUV surveys were sometimes referred to as course surveys or reconnaissance surveys. For these missions, bathymetry models gridded to 1 meter grid spacing was developed. Based on the AUV collected bathymetrical data, fine surveys were performed. For the fine scale surveys, we used HiSAS 1032, the TileFish camera or the UHI.

The Multibeam dataset on the Hugin HUS AUV was collected using an EM2040 multibeam sensor. The multibeam was processed in CARIS HIPS using exact AUV navigation post-processed in Navlab and the CUBE algorithm. The dataset was too noisy for a pure CUBE processing run and manual cleaning was required in order to produce grids off sufficient quality.

After Dive1, it was apparent that the complex bathymetry was very challenging for the AUV. When running in fixed altitude mode, the AUV pitched ±35deg to avoid crashing into the seabed. The active pitch beam steering of the EM2040 only works up to ±10deg, and strong pitching artefacts was introduced to the dataset. The CUBE algorithm was not capable of elegantly flagging out the erroneous pings and the AUV datasets had to be cleaned manually. The resulting DTMs will therefore not give a complete coverage of the exploration areas. For AUV dives 2 and onward, the AUV operator ran the survey in fixed depth, which improved the results. However, the high peaks in this subsea terrain forced the AUV to pitch upwards to avoid crashes.

Further investigation into the AUV dives number 1, 2, 3 proved wrong installation parameter settings for the EM2040 sonar head and the later dives are of better quality with less pitching artefacts. We will post cruise investigate if AUV dive 1 through 3 can be post processed with the correct installation parameters. New DTMs will then be produced for these three dives.

The EM2040 was setup to acquire backscatter and water-column data. Backscatter was processed using CARIS SIPS, but due to a possible bug in the Kongsberg reader, the backscatter algorithm did not accept some of lines. Example files will be sent to CARIS support for further investigation post cruise and backscatter for the missing lines will be generated.

The bathymetric models created in Caris were visualized in 3D together with ROV track and video using Navimodel. The AUV CTD and methane logs were also added in Navimodel in order to facilitate data interpretation between vehicles.

1.7.2 Biology

Scoop and suction sampling

A suction sampler was integrated to the ROV and used to sample macro fauna and megafauna from the surface of rocks and sediment. On board, the samples were sieved over a sieving tower containing sieves of 1 mm, 500 µm and 250 µm. All samples were preserved in 96% ethanol in the fridge, with ethanol changed after 24 h or frozen at -20 C.

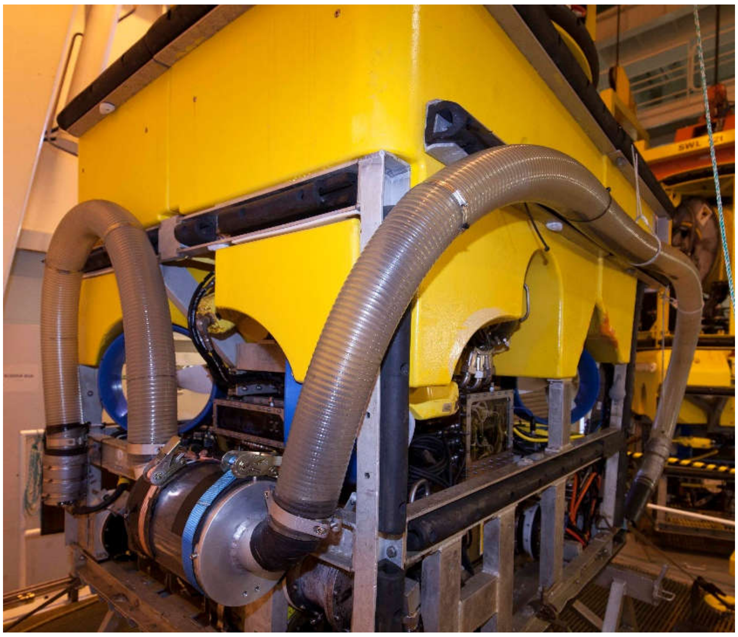


Figure 15: Suction sampler mounted on the XLR02 ROV. Photo: NTNU MarMine / Lars Ivar Tumyr.

A scoop with a lid operated with the ROV manipulator was used to sample small rocks and fauna on the surface and first centimetres of sediment. On board, the samples were sieved and preserved following the same procedure as for the samples collected with the suction sampler.

Push-core sampling

Two types of push-cores were used: a push-core rack from Ifremer with 8 tubes and a rack from GEOMAR with 8 tubes. The system and dimensions of the push-cores were different for each rack. The push-cores were first deployed in the seafloor basket as the ROV did not have a front drawer and if integrated on the front frame, they were in the field of view of the camera used for video transects. However, this operation was very lengthy and the Ifremer rack arrived upside down in one deployment and in one recovery. For the second part of the cruise, only the GEOMAR push-cores were used and deployed in the front of the ROV, when all video transects were finished. The ROV positioned itself on the seafloor avoiding as much as possible sediment disturbance. Then the push-core racks were positioned on the seafloor. The push-cores were deployed in undisturbed sediment one by one, and then retrieved.

- Push-cores #1 to #8: Ifremer, inner diameter 54 mm.
- Push-cores #9 to #16: GEOMAR, inner diameter 74 mm.

Figure 16: Push-core tubes used for sampling. Photo: NTNU MarMine / Lars Ivar Tumyr.

On board, all push-cores were photographed with the push-core number before slicing. The push-core samples were distributed over several disciplines including metagenomics, microbiology, macro- and meiofauna. Three replicates for each analysis were taken at each site. However, as there were not enough cores to have three individual replicates per analysis, some cores were shared: metagenomics and microbes; meiofauna and environmental variables. Once on board the sediment cores were sliced into layers according to protocols for each discipline.

Metagenomics and microbiology

Each core was photographed with the label. The overlaying water was carefully removed with a syringe and the cores sliced at different levels (0-1 cm, 1-2 cm, 3-5 cm, 5-10 cm, 10-15 cm). The sediment of each layer was placed in individual plastic bags and homogenised. Approximately 5 ml of sediment were removed from each bag and placed in a different labelled plastic bag for microbiology. A slicer per layer for each core was cleaned with DNA away before the slicing and kept in sterile bags. The slicing rings were cleaned with DNA away and new gloves were worn between each layer. All labelled bags were stored in the freezer at -20 °C.

Environmental variables

The cores dedicated to meiofauna were first subsampled for sediment grain size, total organic carbon, total nitrogen and pigment concentration. The above standing water was removed and the surface water was sampled with a syringe and stored in the bottle designated for the 0-1 cm layer. A 20 ml syringe was used for granulometry and a 10 ml syringe for Total Organic Carbon, Total Nitrogen and Pigments. Store each subsample in the designated jar (Figure 17).

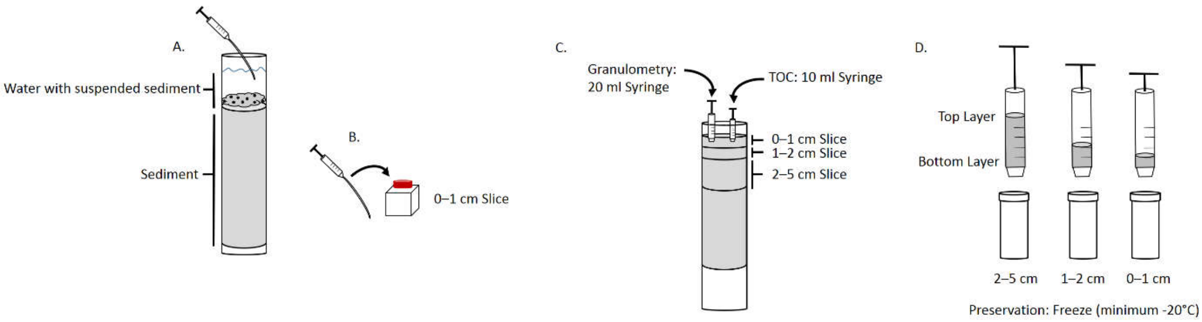


Figure 17: Core processing for environmental variables.

Meiofauna and macro fauna genetic structure

The cores were sliced into two layers (0-2 cm, 2-5 cm) and preserved in DESS. The different layers were then sieved on stacked sieves (500 µ, 250 µ, 180 µ and 32 µ) in order to separate the meiofauna and macro fauna (Figure 18).

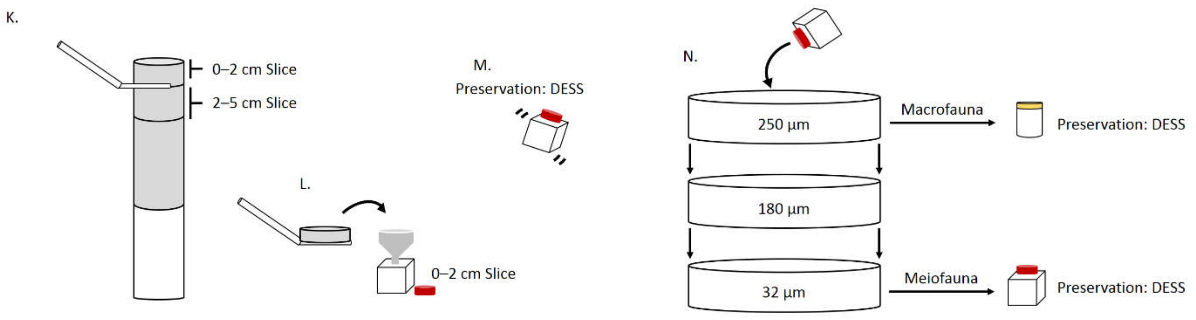


Figure 18: Core processing for molecular studies of meiofauna and macro fauna.

Meiofauna and macro fauna community analyses

The cores were sliced into three layers (0-1 cm, 1-2 cm, 2-5 cm) and preserved in formalin. The different layers will be sieved in the lab on stacked sieves (500 µ, 250 µ, 180 µ and 32 µ) in order to sort the meiofauna and the macrofauna (Figure 19).

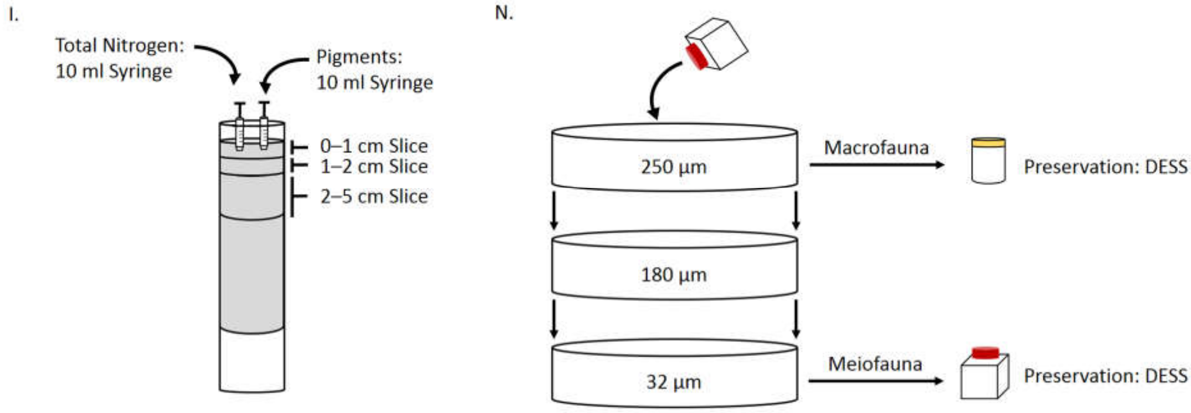


Figure 19: Core processing for community analyses of meiofauna and macro fauna.

2 Summary of Results

2.1 Geology

Three main sites were visited with ROV and in detail investigated and sampled.

Loki's Vent Field was sampled to enable a thorough analysis of the technological potential regarding mineral processing and mining. Sampling includes samples made using manipulator and subsea basket and push cores using the drilling rig.

Grab sampling was planned using the construction crane, a hydraulic grab connected to the ROV HPU with hot stab connections. This procedure was abandoned because of massive leaks for the hot stab system. The method also proved very time consuming.

The Mohn's Treasure area was visited and sampled to increase the understanding of its characteristics as a potential extinct vent field. Sampling includes samples made using the ROV manipulators and subsea basket, push cores, gravity core and a drill core. All samples will be further analysed onshore, in the laboratory.

2.2 Biology

The Loki's Castle was surveyed with two video and photo transects that provided background information for comparison for habitat and fauna to the Mohn's Treasure communities. Most of the biological sampling, however, was conducted in the unexplored Mohn's Treasure. In this inactive site, the environmental variable and benthic communities, from microbes, to meio-, macro- and megafauna were sampled. A total of 10 video/photo transects were conducted (two in Loki's Castle and eight in Mohn's Treasure). The Mohn's Treasure transects and surveys provided a good overview of the habitat and benthic megafauna. The sediment environmental variables, microbes and meiofauna were sampled, with 55 push-cores that were processed on board, sectioned at different levels and preserved in different methods (frozen, formalin, DEES) depending on future analyses. Additionally, the push-cores for microbial analyses were shared for metagenomics analyses. The push-cores for meiofaunal molecular analyses where sieved and the sample retained in the 250 µm sieve was preserved for macro fauna identification. Three scoop samples were sieved for macro faunal analyses and the suction sampler and manipulator were used to collect megafauna, both from the sediment and rocky habitat in Mohn's Treasure. These samples were preserved in 96% ethanol for barcoding, frozen for stable isotope analyses (holothurians and stalked crinoids) and in formalin for morphological analyses (holothurians and stalked crinoids). All samples have been distributed to the different national and international partners and experts for laboratory analyses and the results will be published in an MSc thesis (E. Paulsen, NTNU) and in a minimum of three papers.

2.3 Technology

During the cruise, the ROV mounted core drill was tested. The system was developed by Williamson for taking sub surface samples of the areas of interest to the project. The mineralized material on the active vent proved to be too loose for core drilling. For this reason, the drill was modified to exhibit reduced rotation in the sampling procedure. The sample recovery was 67% and 37%. Later the core drill was used with a proper drill bit for hard rock on approximately 2600-meter depth and a core sample of basalt was recovered.

A tool for in-situ mineral and seabed identification beyond visual video is useful in this type of investigations. The UHI was mounted on both the ROV and the AUV and can be developed to provide information obtainable using conventional cameras. This is the first time an UHI has been used on AUV for research. Further analysis will show the spectral response of the seabed. Data were collected along proper transect using both AUV and ROV.

2.4 Exploration

All sites have also been visited with AUV to acquire multisensory data that will be used in future analysis and exploration strategy development. Based on acquired data, potential hydrothermal vent fields have been selected and target checked using the ROV.

3 Detailed Results

3.1 Dive Schedule

The following table presents the time and location of the dives performed, split into ROV and AUV dives.

Table 3: Table of dives - ROV

#	ROV	Start	Duration	Location	Field	Aim
1	XLR	2016-08-20 23:11	7h 49m	LC	Geo	Exploration, UHI
2	XLR	2016-08-21 11:05	4h 50m	LC	EXPL.	Sampling
3	XLR	2016-08-21 16:13	10h 00m	LC	Geo, EXPL.	Sampling, UHI
4	XLR	2016-08-23 02:52	7h 17m	LC	Geology	Drilling observ.
5	XLX	2016-08-23 02:23	4h 06m	LC	Drilling	Core drilling
6	XLX	2016-08-23 09:23	1h 07m	LC	Drilling	Core drilling
7	XLR	2016-08-24 10:37	0h 47m	MT	-	(Aborted)
8	XLR	2016-08-24 12:29	28h 01m	MT	Biology	VT, Sampling
9	XLR	2016-08-25 16:34	8h 05m	MT	Biology	VT, Sampling, PG
10	XLR	2016-08-26 00:57	9h 32m	MT	Biology	VT, Sampling
11	XLR	2016-08-27 04:22	7h 59m	MT	Geology	Sampling
12	XLR	2016-08-27 13:14	4h 19m	MT	Geology	Sampling
13	XLX	2016-08-28 06:15	3h 55m	MT	Drilling	Core drilling
14	XLR	2016-08-28 10:55	5h 46m	MT	Biology	Push-core sampl.
15	XLX	2016-08-28 19:56	4h 52m	MT	Drill	Core drilling
16	XLR	2016-08-29 02:22	4h 55m	EXPL	EXPL.	Exploration, PG
17	XLR	2016-08-29 11:02	5h 54m	MT	EXPL.	Exploration
18	XLX	2016-08-29 18:01	4h 00m	MT	Drilling	Core drilling
19	XLR	2016-08-29 23:01	5h 07m	MT	Geo, EXPL.	Exploration, UHI
20	XLR	2016-08-30 18:03	5h 30m	LC	EXPL.	PG
21	XLR	2016-08-30 23:53	6h 32m	EXPL	EXPL.	Exploration
22	XLR	2016-08-31 20:17	7h 03m	MT	Geology	Gravity core, UHI

The abbreviations in the table above are as follows; Loki Castle (LC), Mohn's Treasure (MT), exploration area (EXPL), underwater hyperspectral imager (UHI), video transect (VT), photogrammetry (PG).

Table 4: Table of dives, AUV. The dives with shorter duration were results of emergency ascents caused by the vehicle coming to close to the seabed. In this situation, the vehicles performs emergency ascent as an obstacle avoidance measure.

#	AUV	Start	Duration	Location	Sensors
1	-	2016-08-22 10:22	12h 58m	MT	MBES
2	-	2016-08-23 16:48	15h 42m	MT	MBES, SSS, UHI
3	-	2016-08-26 11:42	14h 50m	EXPL1	MBES, SSS
4	-	2016-08-27 18:37	3h 33m	EXPL1	MBES, SSS
5	-	2016-08-28 00:47	3h 9m	EXPL1	MBES
6	-	No dive	-	-	-
7	-	2016-08-30 07:15	5h 2m	LC	MBES
8	-	2016-08-30 13:30	3h 14m	LC	MBES, UHI
9	-	2016-08-31 07:35	10h 42m	EXPL1	MBES
10	-	2016-09-01 05:43	5h 56m	EXPL2	MBES

All AUV dives are performed with CTD, CH_4 (methane), magnetometer and turbidity sensors.

The HiSAS 1030 side-scan sonar was not used after the fourth dive due to a critical malfunction that put the acoustic transmitter out of commission. It is worth mentioning that the UHI was not performed for the entirety of dives two and eight, due to its required proximity to the seabed. The UHI was therefore typically employed at a few survey lines at the end of the dive, in an area that had previously been mapped using multi-beam - to ensure that the bathymetry was known.

3.1.1 Datum

The coordinate systems used for all datasets acquired during the MarMine are:

Horizontal Datum = WGS84 / UTM31 = EPSG:32631

Vertical Datum = MSL Depth = EPSG:5715

Notes:

1) The online navigation software does not carry out any datum transformations. WGS84 realization based on ITRF08 calculated by Fugro G2 navigation solution is thus used directly.

2) Some background datasets are given in EUREF89 / UTM31 (EPSG:25831). These datasets are used directly in the MarMine GIS as the difference between the WGS84 and ETRS89/EUREF89 ellipsoid is smaller than the error introduced by a datum transformation.

3) Due to lack of an accurate tidal model, no tidal reduction has been applied and all depths are instant water depth. The closest primary tidal gauge maintained by the Norwegian mapping authority is at Ny-Ålesund/Spitsbergen. During the cruise duration, the maximum predicted tidal difference at this tidal gauge is 70cm. The tidal difference at site can be regarded to be within the accuracy level of the depth sensor and mean sea level equals instantaneous sea level.

3.1.2 Waypoint numbers

During the cruise, a reference system with waypoints named Snn was defined and maintained by the survey team aboard. S54 would refer to waypoint 54 and be a unique position for the cruise. The numbering was continuously running and common for all the sites and dives performed during the MarMine cruise.

3.2 Geology

3.2.1 Loki's Castle Area

The Loki's Castle vent field is situated at around 2330-m-depth on the crest of an AVR situated at the transition between the Mohn's Ridge and the Knipovich Ridge (Pedersen et al., 2010). It is associated with a 50–100-m deep rift along the crest of a volcano. The vent field consists of two sulphide mounds (≥150 m in diameter, ~20-30-m-height) with five active black smoker chimneys on the top. The hydrothermal mounds were formed by successive massive sulphide depositions and built on basaltic substrates partly covered by thin layers of sediments. The venting area is delimited eastward by a large ridge-parallel trending fault and pronounced fractures on the western side delimiting more volcanically active portions of the ridge. It lies on secondary fractures probably acting as major pathways for hydrothermal fluid circulation. Figure 20 shows the extent of the AUV operations around the Loki's Castle.

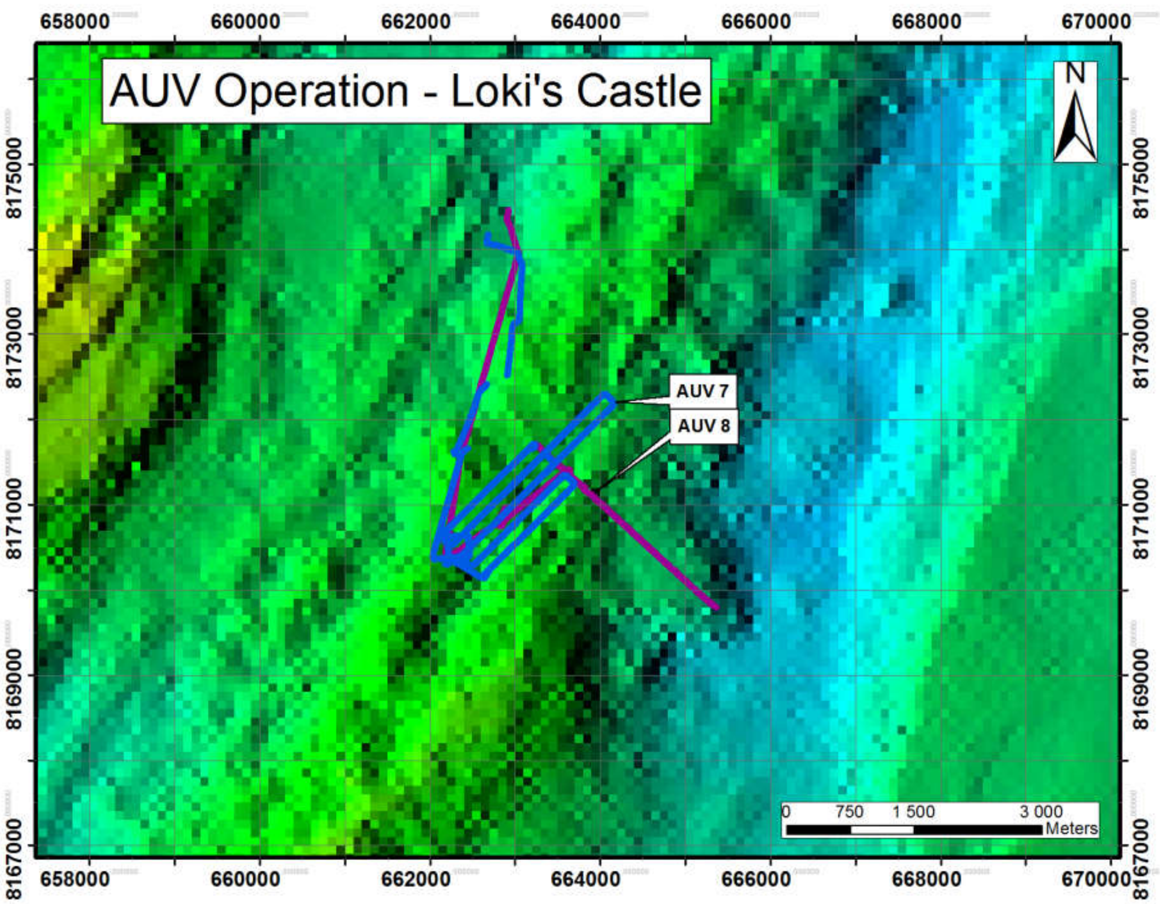


Figure 20 Extent of the Loki's Castle area investigated on the AVR at the northern part of the Mohn's ridge.

Seven ROV dives were carried out at Loki´s Castle. These covered all sides of the two mounds and all the way up to the top. During VT1 to VT3, geological features were noted as well, in order to understand the geology on the seabed. Typically, the pillow lavas are observed on the side of the mounds grading with sediments until the mound starts to slope. Along the slopes, there seem to be a mixture of sediments and increasing content and size of chimney fragments towards the top. Several visits to the vents at the top of the mounds resulted in a series of good quality pictures of the vents.

One vent water sample and one water sample from the seawater close to the vents (near S9) were collected for further analyses on shore. Five small rock samples were collected as reference from the slopes of the mounds. These represent chimney fragments. Figure 21 shows examples of samples collected from LC.

Figure 21: Samples from LC. Chimney fragments with visible fluid channels with mineralization. Photo: NTNU MarMine / Kurt Aasly

Along profiles from S9 towards the top larger samples were collected from the two mounds. On the eastern mound, a very large sample is treated as one sample, although crushed to 28 smaller samples for packing purposes. The sample has an oxides outer crust (Figure 22). A claylike inner crust transforms into a silicified rock towards the core. HHXRF analyses indicate locally anomalies of Cu and/or Zn and Au and Ag.

Further one collective sample was made from the two mounds, consisting of 4-5 samples collected using the ROV manipulators and the subsea basket. Examples of this may also be seen in Figure 22. This sampling fulfils the goal of collecting minimum of 200 kg sample material for further testing.

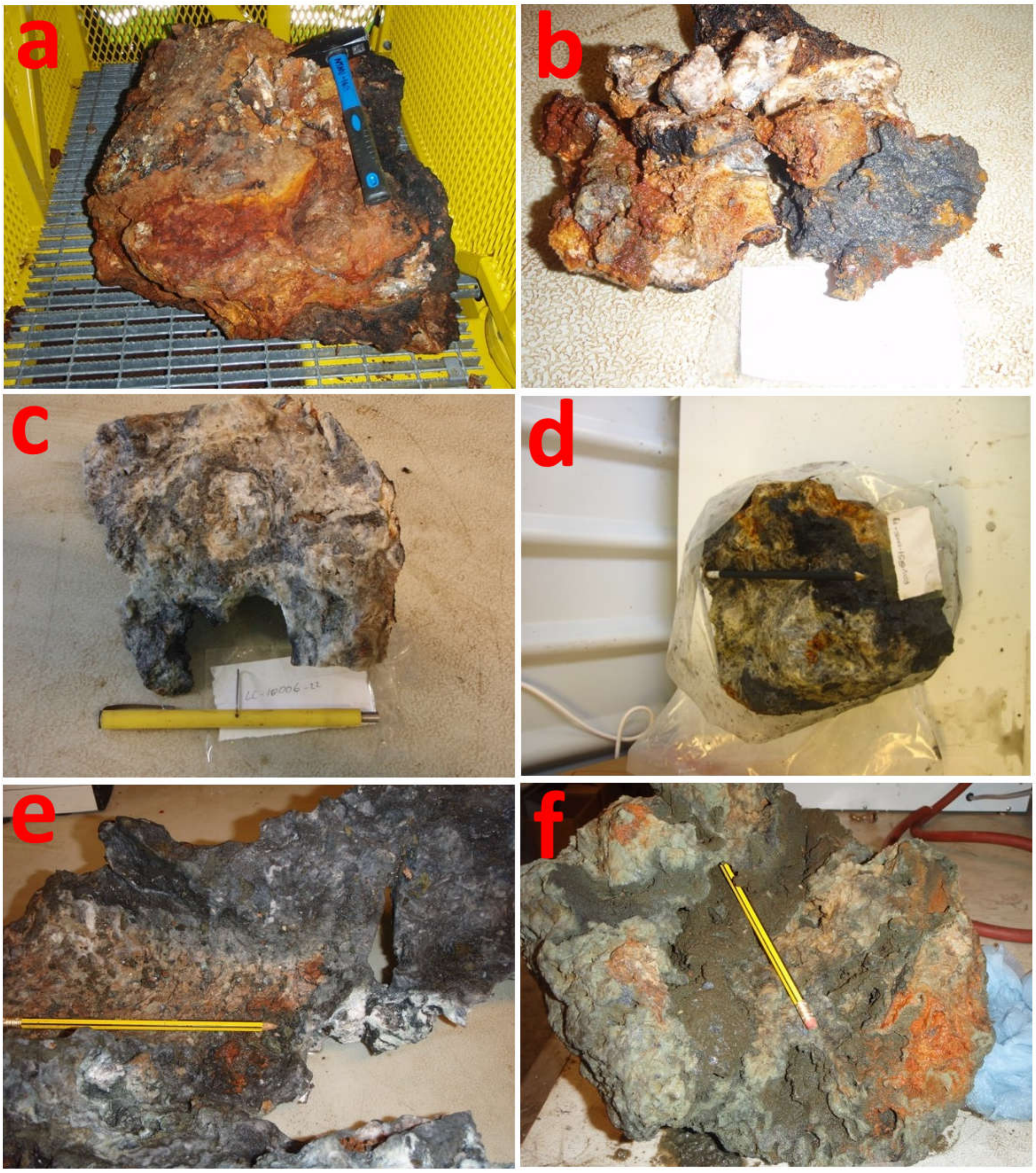


Figure 22: Examples of rock samples collected from Loki´s Castle. a) Large sample collected at the lower part of the eastern mound. b) Part of the crushed rock in a). c) Internal variation of the rock in a). d) Core of the big rock in a). e) Large fragment of white smoker from the western mound. f) Fragment of black smoker from western mound. Channels are visible with mineralized material. Photo: a), b) c), f) NTNU MarMine / Kurt Aasly; d) NTNU MarMine / Steinar Ellefmo

In addition to the rock, grab samples, 3 scoop samples were collected on the mounds, two from the western and one from the eastern mound side. The scoop samples (western) differ in consistency from the eastern ones, which are brownish relatively coarse-grained ones western are darker, less coarse grained and claylike. However, due to the relatively limited number of samples, this is merely an observation and no general description of the two mounds.

3.2.2 Mohn’s Treasure Area

The Mohn’s Treasure area is an axial relief created as a response to normal faulting during tectonic displacement. This marginal relief presents minor triangular-shaped structures that terminate into narrower lobes and pronounced hemi-circular landslide scars associated to lobe-shaped features that may define landslide deposits. Large landslides may have controlled mass-wasting events that must have formed after the fault had created a few hundred meters of relief. The resulting outcrops consist primarily of brecciated pillow lavas trending along the fault scarp while more flattened areas show well-defined unconsolidated sediment depositions and widespread centimetre to decimetre large remnants of brecciated basalts.

In total 13 ROV dives were carried out on the Mohn´s Treasure area, previously described as an extinct vent site by Pedersen et al. (2010). In order to confirm the Mohn´s Treasure area as extinct vent site, several ROV dives were carried out on the seafloor to survey the area. Presumed partly lithified sediments and basaltic substrates on the crest of a rifted portion of a ridge lying at the bottom of the east-facing ridge valley wall have been observed. The observed mineralized area covers a few meters along oxidized basalt outcrops comprising minor pyrites and distinctive features possibly formed by diffuse discharges. Around this area, extensive investigation along the vertical extent of the ridge wall did not present conclusive indication of other sulphide mineralizing. Given that this is an extinct vent field as described in Pedersen et al. (2010), mass-wasting events may have played a major role in displacing and burying the overall massive sulphide deposits and its associated extinct vent field.

Figure 23 shows the extent of the Mohn’s Treasure area investigated.

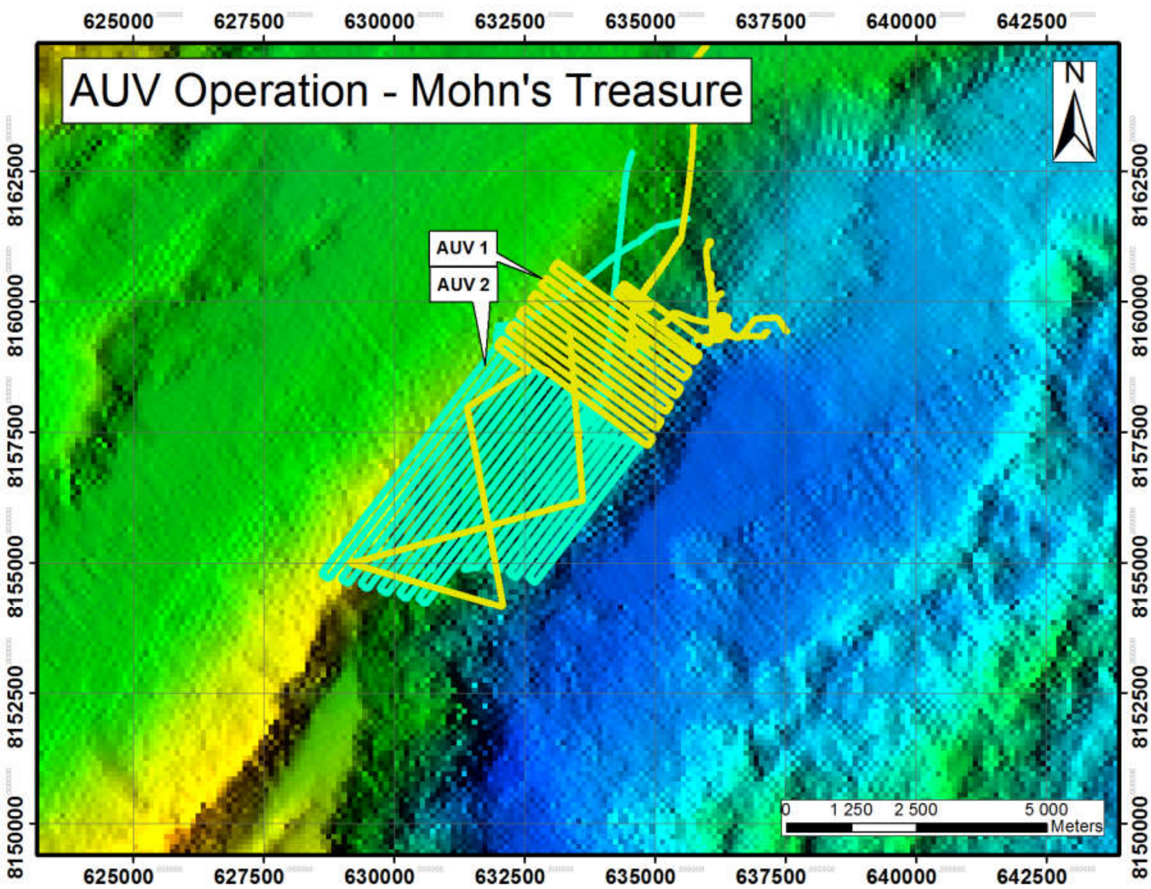


Figure 23 Extent of the Mohn's Treasure area situated at the western axial valley wall.

During bio-transects, geological features were logged for reference. Separate geological survey and sampling dives were also performed. Portions of the Mohn´s Treasure area, starting at ca 2750 m towards the highest point of the scarp at ca 1900 m, were surveyed. The area consists of ledges, semi-levelled, with mostly fine sediments mixed with fragments of basalt. Ridges and small mounds as well as the steep walls consist of pillow lavas. The sediments tend to change in appearance from time to time, with sharp boundaries between the zones. Sediment variations related to coarse/fine sediments, higher concentrates of foraminifera on the surface. Northeast of S11, along the ridge on top of the first scarp of transect S11-S12, a patch of sediments covered with dead shells were discovered. As described in the biology section these shells may resemble species that live on or near active vents. Samples were taken for species identifications in lab. On a later dive, an outcrop along the same small ridge was discovered which showed oxidized surfaces. When the manipulator on the ROV grabbed the rocks, they crumbled in the same way as the vent fragments at the Loki´s Castle mounds. One sample was collected from this site (Figure 24). At the surface, the rock sample taken from this location seems like silicified basalt with oxidized material on fracture surfaces rather than chimney fragment. Visible small channels through the rock. Not stock work like for chimneys, but small thin round channels.

Figure 24: Rock sample from the area N of S11 where some type of venting is suspected. a) staining on fractures b) py grains on the rim towards the fracture plane. Photo: NTNU MarMine / Kurt Aasly

Two drill tests were performed. Both successful in the sense of drilling. First drill hole was collared near S54 and the second near S55. The challenge was to find a smooth surface to set down the ROV steady with high down thrust in order to resist the upwards thrust from the drill rig. Drill event one produced ca 20 cm drill penetration and the second ca 85 cm drill penetration. However, the first core was lost during recovery. For the second core, approximately 73 % recovery was achieved and thus, ca 62 cm core were recovered on surface. The core was packed and frozen for storage.

Figure 25: a) Part of the drill core obtained from drilling in basalt near S55. Pure basalt fracture surface. b) ROV control screens during drilling. Lower left photo shows the collar of the drill hole underneath the rig. Photo: a) MarMine/Anna Lim b) MarMine/Kurt Aasly

The AUV dive 2 gave a T- and SCM anomaly over some indicative morphological structures in the southwestern part of the Mohn's Treasure area. This area was therefore target checked during ROV12. The area is situated on the edge of Mohn's Area scarp. Area was covered by sediment with relatively few outcrops. No obvious geological signs of active or inactive vent fields. Possible manmade tracks in the sediment cover identified. Cave-like features observed in the upper layers of the sediment cover. Scoop sample in oxidized sediment collected. To be analysed for traces of venting or seepage. A table of samples collected during the cruise can be found in Table 10.

3.3 Biology

The Loki's Castle vent field and Mohn's Treasure inactive site were surveyed with video and photographic transects (VT) for general description of the habitat and faunal communities. The benthic communities (microbes, meio, macro and megafauna) at Mohn's Treasure were sampled using the following equipment:

- Push-cores (PC) for environmental characterization of the sediment, metagenomics, microbial, meiofaunal and macro faunal analyses.
- A scoop with a lid was used to collect sediment from the first 10 cm to examine the macro fauna community. It was also used as a bio box.
- The ROV manipulator and a suction sampler were used to collect megafauna.

3.3.1 Video/Photo Transects

Video/photo transects were conducted with the XLR ROV. To conduct these transects, the ROV was flown at < 1 m above the seafloor at a constant speed of 0.4 knots (0.2 m/s). Because the video camera was not high resolution, photographs were taken at regular intervals (approx. 10 seconds apart), providing higher resolution images for further analysis. The field of view was calibrated with line lasers that were turned on for the first three photos and turned off for the reminder of the transect to avoid light interference with particles in the water.

Table 5: List of video/photo transects.

Video Transect	ROV dive	Start site	End site	Location
VT3	ROV4	S7	S8	Loki's Castle
VT4	ROV4	S9	S10	Loki's Castle
VT5	ROV8	S13	S15	Mohn's Treasure
VT6	ROV8	S11	S24	Mohn's Treasure
VT7	ROV8	S25	S26	Mohn's Treasure
VT8	ROV10	S46	S47	Mohn's Treasure
VT9	ROV5	S23	S27	Mohn's Treasure
VT10	ROV5	S28	S29	Mohn's Treasure
VT11	ROV9	S39	S40	Mohn's Treasure
VT12	ROV9	S41	S42	Mohn's Treasure

Loki's Castle

Two video transects were conducted on the eastern mound of Loki's Castle (Table 5 ,Figure 26). A short description of each transect is detailed below.

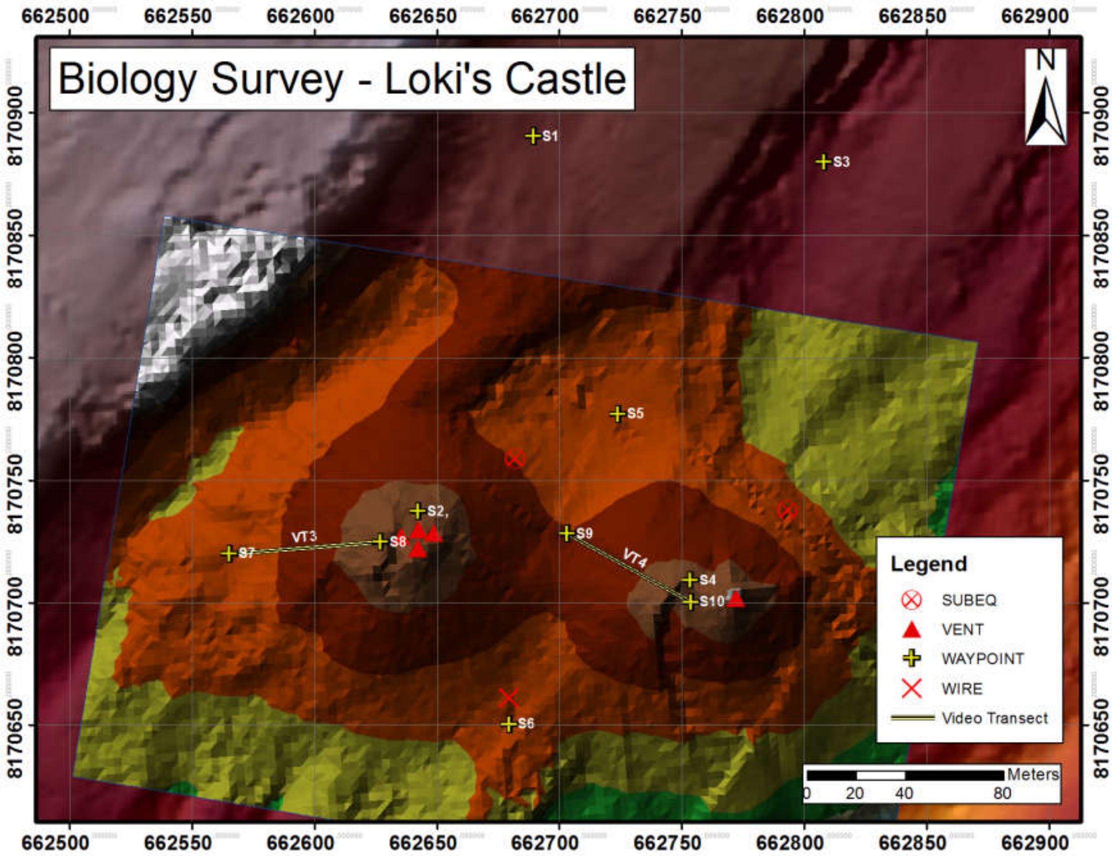


Figure 26: Map of Loki's Castle showing video/photo transects.

VT3 started at the base of the western mound (S7) and finished at the top (S8). There is a clear transition from the background fauna of sponge communities with crinoids to the vent ecosystem where these species are not observed (Figure 6). However, we did not observe the vent fauna described from this site in Pedersen et al., 2010.

VT4 started at the base between the two mounds (S9) and moved to the top of the eastern mound (S10). A similar habitat and fauna transition than in VT3 was observed (Figure 6).

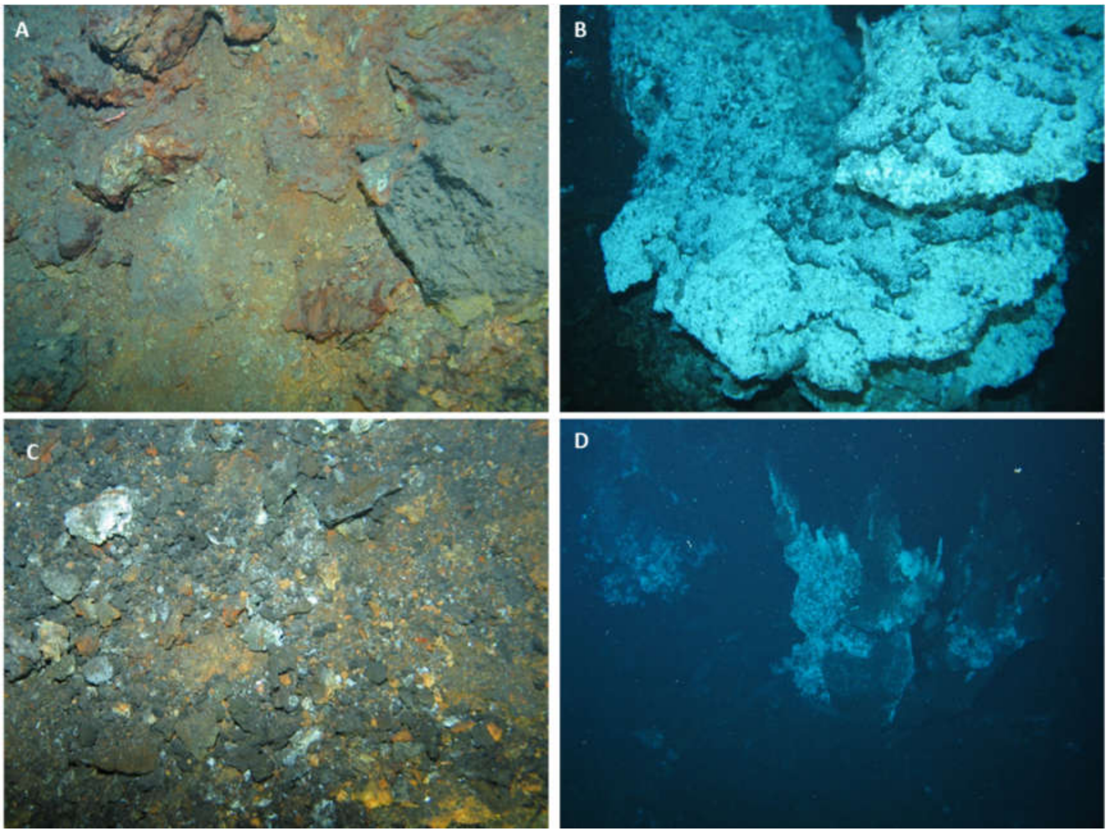


Figure 27: VT4 (A,B) and VT5 (C,D)

Mohn's Treasure

A total of 8 video transects were conducted at Mohn's Treasure (Table 5), at selected locations in what was assumed to be three different habitat types: the lower slope, the mid-plateau and the upper slope. One transect of 800 m was conducted perpendicular to the dredge track made by University of Bergen (UiB), 3 transects (replicates) of 200 m were conducted in the deepest area, 2 transects (replicates) of 200 m were conducted in the middle area and 2 transects (replicates) of 200 m in the shallowest area (Figure 28). A short description of each transect is detailed below.

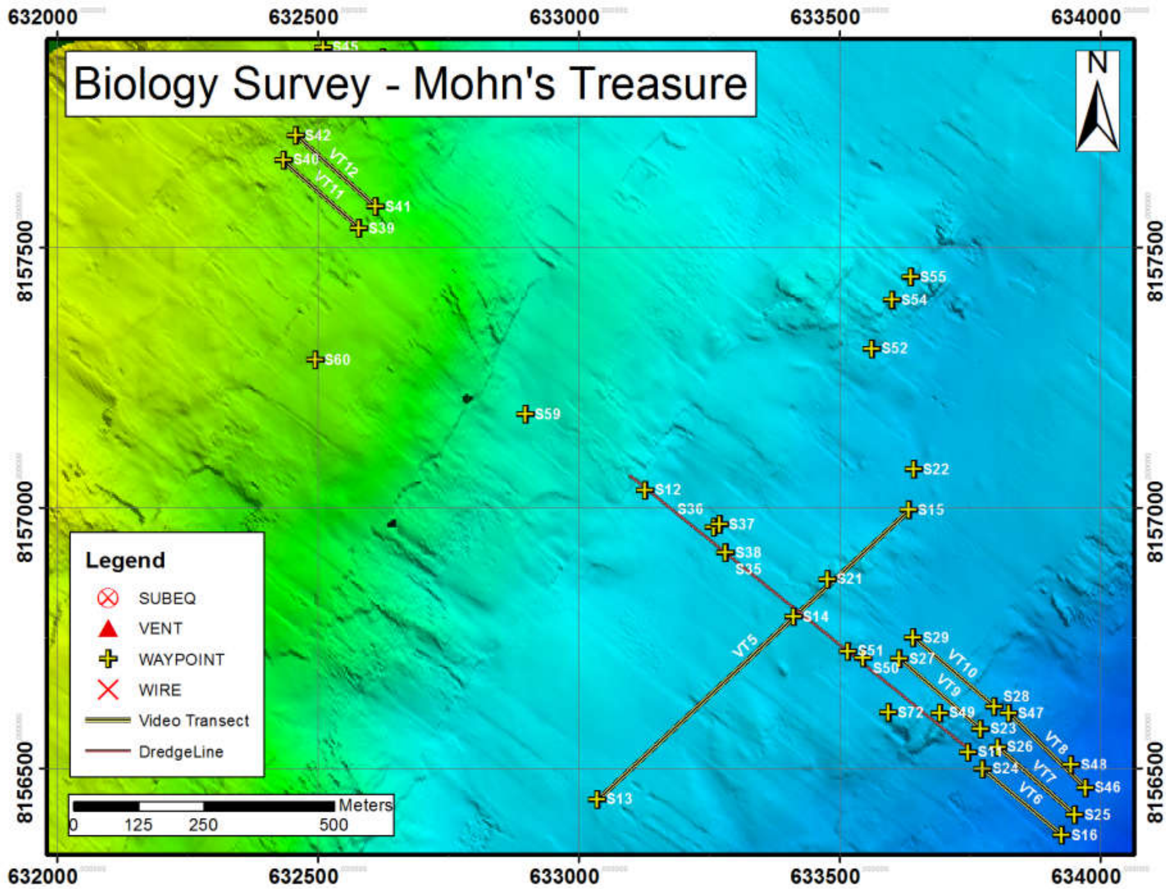


Figure 28. Map of Mohn's Treasure showing the video/photo transects.

VT5: this 840 m video/photo transect was perpendicular to the UiB dredge track. It started at S13 and ended at S15, taking a fix position at S14 when we went past the dredge track. Between S13 and S14, the seafloor is mainly fine sediment with some stalked crinoids and an area where large numbers of small holothurians were observed. Between S14 and S15, the transect went over a rocky area with rocks covered in large and small sponges of different morphologies and crinoids (S21). The slope then became steep and significant abundances of stalked crinoids were observed on the sediment.

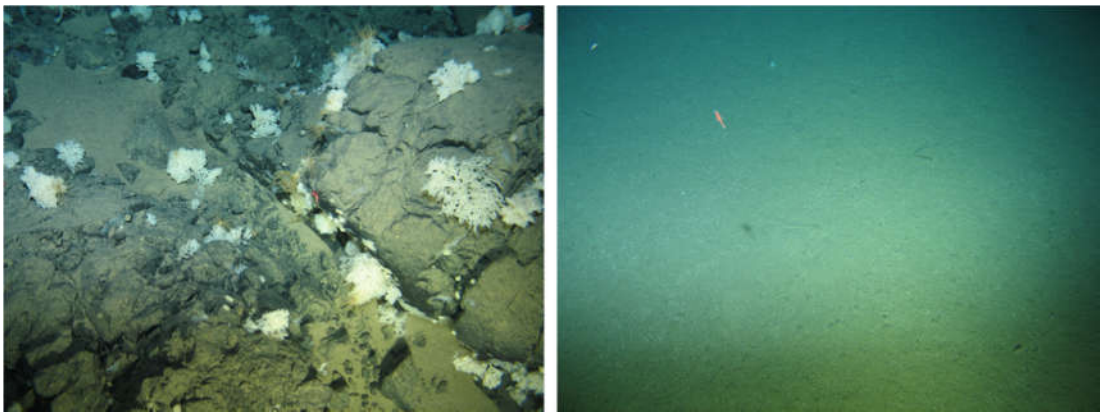


Figure 29. Rocky outcrop with sponges and soft sediment habitat observed during VT5.

VT6: this video/photo transect started at S16 and ran for 200 m, finishing in S24. Most of the transect went over a stalked crinoid field, with only some sparse asteroids, holothurians and fish observed. The transect crossed patches of rocks colonized by sponges and crinoids (Figure 30). Many lebesspuren were observed.

VT7: this video/photo transect started at S25 and ran for 200 m, finishing in S26. The habitat and communities were very similar to VT6, with stalked crinoid fields dominating and sparse rocks and boulders with sponges and crinoids (Figure 30).

VT8: this video/photo transect started at S46 and ran for 200 m, finishing in S47. The habitat and communities were very similar to VT6 and VT7, with stalked crinoid fields dominating and sparse rocks and boulders with sponges and crinoids.

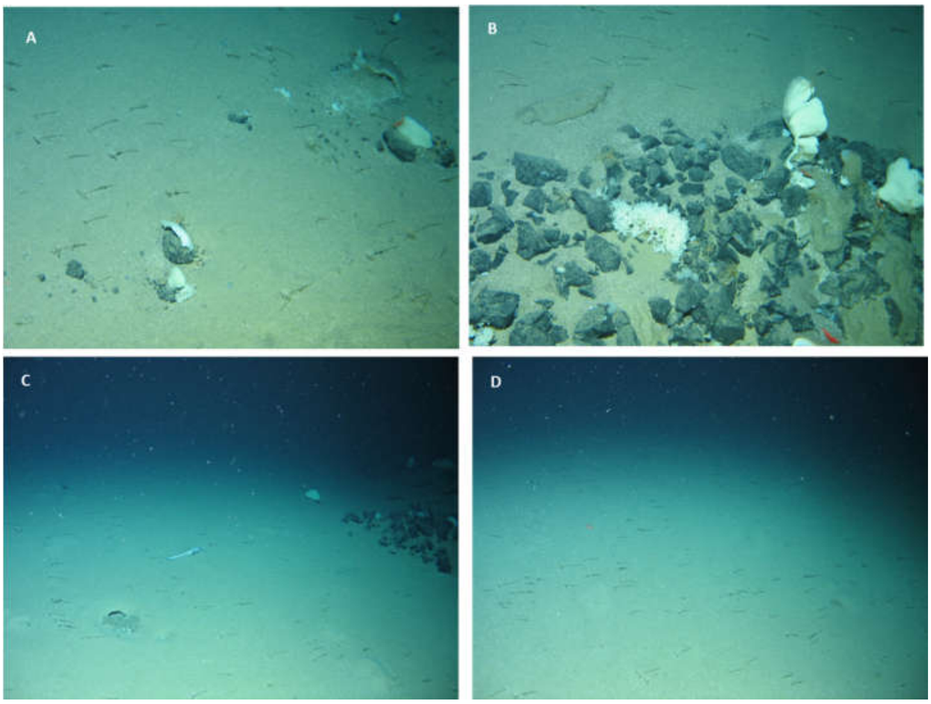


Figure 30. Close up of the crinoid field (A) and rocky outcrop (B) from VT6. Crinod fields from VT7 (C,D).

VT9: this video/photo transect started at S23 and ran for 200 m, finishing in S27. The transect started on a slope going up over rocky ridge colonized by sponges and crinoids. After the ridge, the seafloor sloped slightly down to a sediment habitat, but here no stalked crinoid fields are observed. Boulders with high accumulation of foraminifera tests at the base were observed (Figure 31).

VT10: this video/photo transect started S28 and ran for 200 m, finishing in S29. This transect started on the rocky ridge, followed by sediment with some stalked crinoids and sparse rocks with sponges and crinoids. On the slope, there were high accumulations of foraminifera tests (Figure 31).

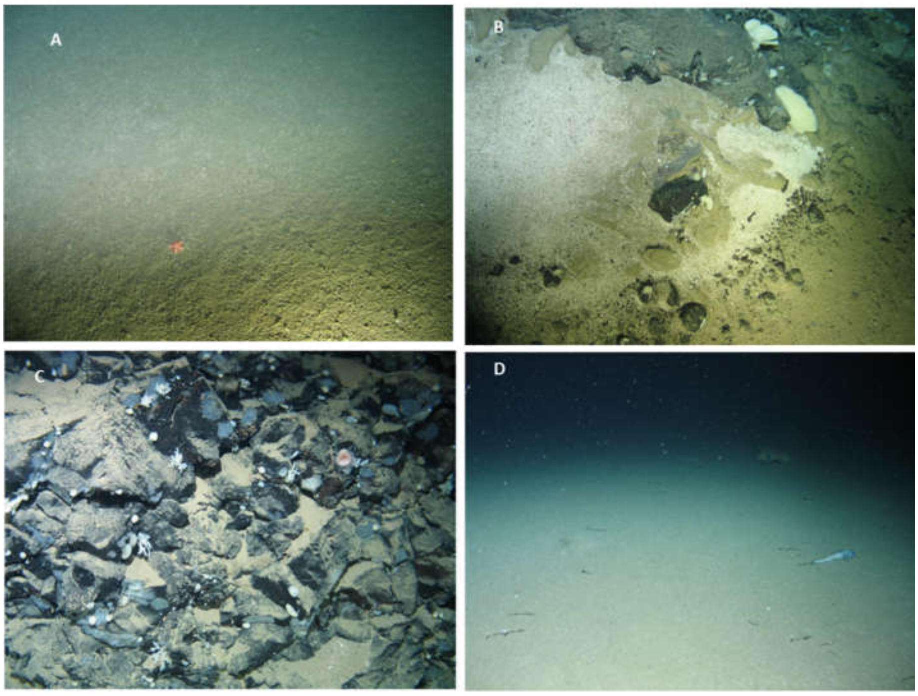


Figure 31. Sediment habitat with an asteroid (A) and foraminifera shell accumulation below a rock (B) from VT9. Rocky outcrop with sponges (C) and sediment with stalked crinoids and a fish (D) from VT10.

VT11: this video/photo transect started S39 and ran for 200 m, finishing in S40. The transect started over sediment with areas with rocks with sponges (Figure 32). These two habitats were crossed several times and towards the end the transect flu over a steep rocky environment with sponges and crinoids and finished on a sedimentary slope with stalked crinoids. The stills camera ran out of free space on the memory card half way through the transect. The photomosaic camera was used to finish the transect.

VT12: this video/photo transect started S41 and ran for 200 m, finishing in S42. This transect was similar to VT11.


Figure 32. Coarse sediment and small rock habitat from VT11.

3.3.2 Manipulator, scoops and suction sampler

All manipulator, scoop and suction samples for macrofauna and megafauna analyses were collected at Mohn's Treasure (Figure 33). Table 12 provides a detailed list of the samples obtained and their future analysis.

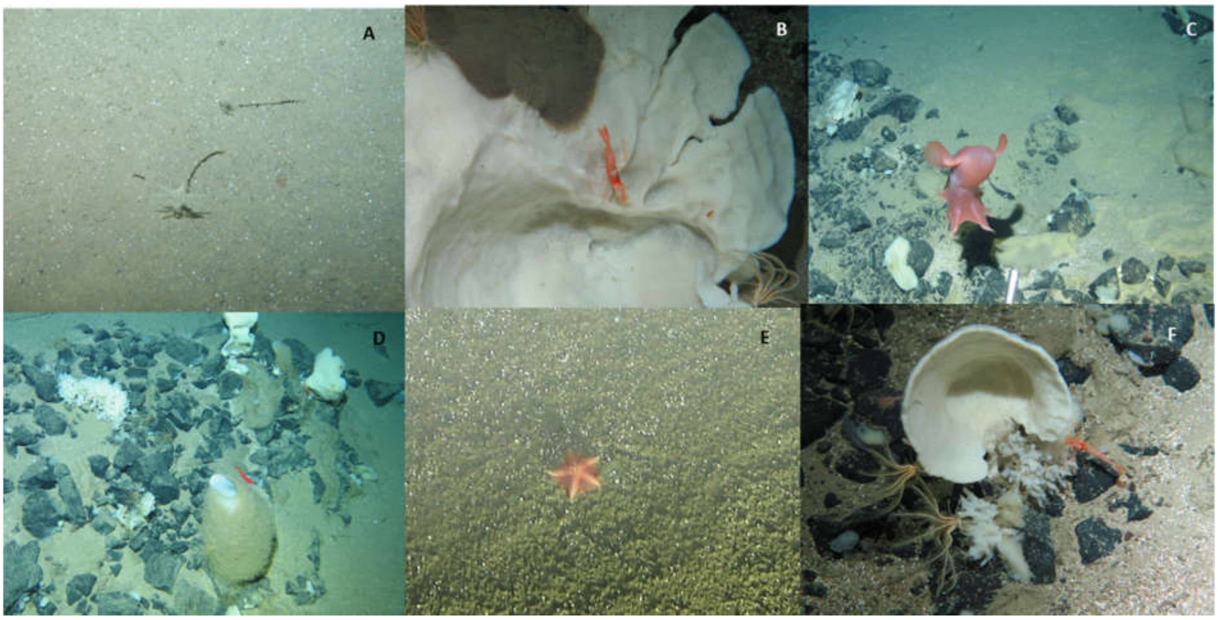


Figure 33. Benthic fauna from Mohn's Treasure. Stalked crinoids (A), sponge with crinoids and shrimp (B), Dumbo octopus (C), rocky outcrop with sponges and shrimp (D), asteroid (E), sponge showing crinoids and shrimp (F).

Holothurians: 24 individuals of a small elasipodid holothurian were collected from S13a using the suction sampler. Of these, six were frozen for stable isotope analyses, 9 were preserved in formalin and 9 in 96% ethanol.

Stalked crinoids: 13 individuals were collected from S48 using the manipulator of the ROV and the scoop as a bio box. Of these, five individuals were frozen for stable isotope analyses, 3 were preserved in formalin and 5 were preserved in 96% in ethanol. Several specimens of epibionts (hydrozoan, anemones and serpulid polychaetes) were collected from the stalks and preserved in 96% ethanol.

Sponges: different morphotypes of sponges were collected from rocks using the manipulator of the ROV. All samples were preserved in ethanol, excluding subsamples of two specimens that were dried and frozen to be used for UHI calibration.

Shell graveyard: a suction sample was taken on a bed of dead shells on S49. This sample contained dead shells of bivalves of the family Propeamussidae, dead gastropods, echinoid skeletons and small round sponges. The sample was preserved in 96% ethanol. This dead shell bed could indicate extinct seepage or past vent activity.

Macrofauna: 3 scoop samples were taken from S36, S37 and S48. The samples were sieved through 1000 µm, 500 µm and 250 µm and preserved in 96% ethanol.

3.3.3 Push-cores

In total, 55 push-cores (24 Ifremer cores and 31 Geomar cores) were used at Mohn's Treasure (Figure 34). Below is a short description of the cores deployed to the seafloor, the number of cores that were processed and observations on each deployment (Table 6).

Table 6. List of push-core deployments.

ROV#	Site	Deployed	Deployment method	Processed	Observations
8	22	8 GEOMAR	Basket	7	Core #10 did not work.
8	22	8 Ifremer	Basket	7	These cores were found horizontal in the basket. 3 were preserved whole for metagenomics (0-15 cm) and 4 for environmental analyses. One was discarded.
8	35	8 GEOMAR	Basket	8	
8	35	8 Ifremer	Basket	0	The rack arrived horizontal to the seafloor so they could not be used.
8	38	8 Ifremer	Basket	7	Core #3 did not come out of tube
10	48	8 GEOMAR	ROV frame	2	6 cores were jammed in the rack
14	48	7 GEOMAR	ROV frame	6	1 core was not deployed because the inner tube was deformed. Core #11 was very short and partly lost during ROV recovery and on board.

The cores were preserved following different protocols to be used for further analyses of microbial communities, metagenomics, meiofauna and macro fauna genetics and community analyses and analyses of environmental variables (Figure 34). Table 11 provides a detailed list of the push-cores samples obtained and their future analysis.

Figure 34. Push-cores in the sediment (A), the rack of push-cores after recovery in the front of the ROV (B) and a push-core in the lab ready to be processed (C).

3.4 Exploration and new methods

The first part of the explorative activities aimed at investigating known prospective areas (i.e. the Loki's Castle and Mohn's Treasure areas) based on the information of past investigations at the Mohn's Ridges (Pedersen et al., 2010). The second part consisted of defining and prospecting undiscovered areas (i.e. Exploration Area 1 and Exploration Area 2) suggested as favourable for the formation of SMS deposits at the Mohn's Ridge, based on diverse geological criteria.

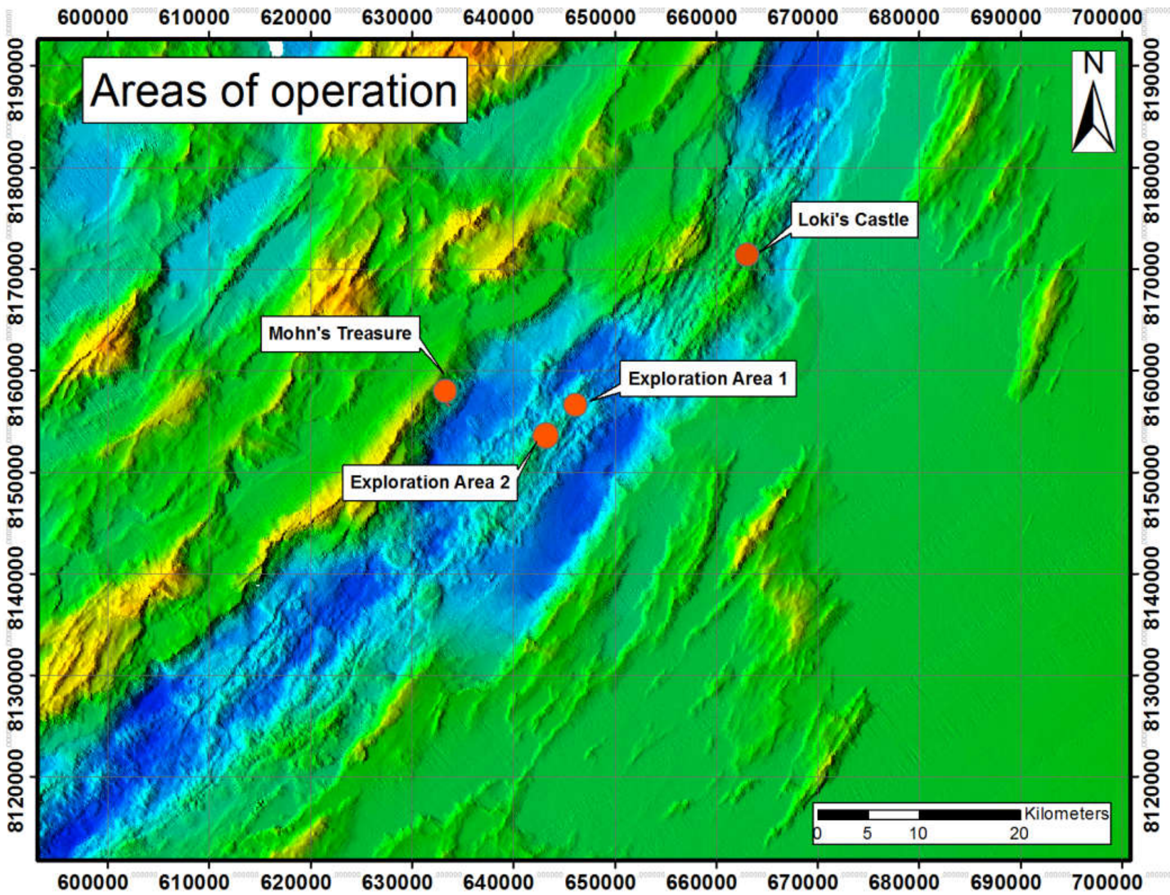


Figure 35 Explored areas at the Mohn's Ridge.

3.4.1 Exploration Area 1

The Exploration Area 1 delineates the northern part of the AVR at the East of the Mohn's Treasure area and close to the transition with the northern AVR comprising the Loki's Castle vent field. It can be subdivided into a large eastern valley and a western plateau. The area has been chosen based on critical assumptions made from the observation of previously discovered hydrothermal vent fields in similar settings at the Mid-Atlantic Ridge (e.g., Fouquet et al., 1993; Murton et al., 1994). Several target criteria for this system closely associated with axial neo-volcanic activity along the trending ridge, consisted of an observable axial graben with fissured areas focusing tectonic activities at the top of the ridge, volcanic edifices in the centre of the ridge segment and small depressions associated with fractures marked by aligned collapse pits. The assumed more prospective areas were areas on the flank of the intra-rift ridge that extends parallel to the crest or near volcanically and tectonically active areas controlled by fissures and cracks running both parallel and orthogonal to the general strike direction. Proposed target sites consisted of mound-shaped build-ups associated with fissured volcanic edifices lying close to major faults operating parallel to the ridge trend. See Figure 36 for an outline of the exploration area.

3.4.2 Exploration Area 2

The Exploration Area 2 has been first characterized by a rough massif in the topography, and interpreted as having a volcanic origin. It presents a large volcanic edifice delimited by a western valley and large east-west topographic dislocations defining large-scale structures trending near parallel to the spreading direction. The neo-volcanic zone itself is a large volcano faulted on its western side. The combination of faulted areas, cracks and fissuring, and an axial magmatism enhancement may play a key role in leading to hydrothermal fluid circulation to form vent fields as evidenced in similar settings (German et al., 2008).

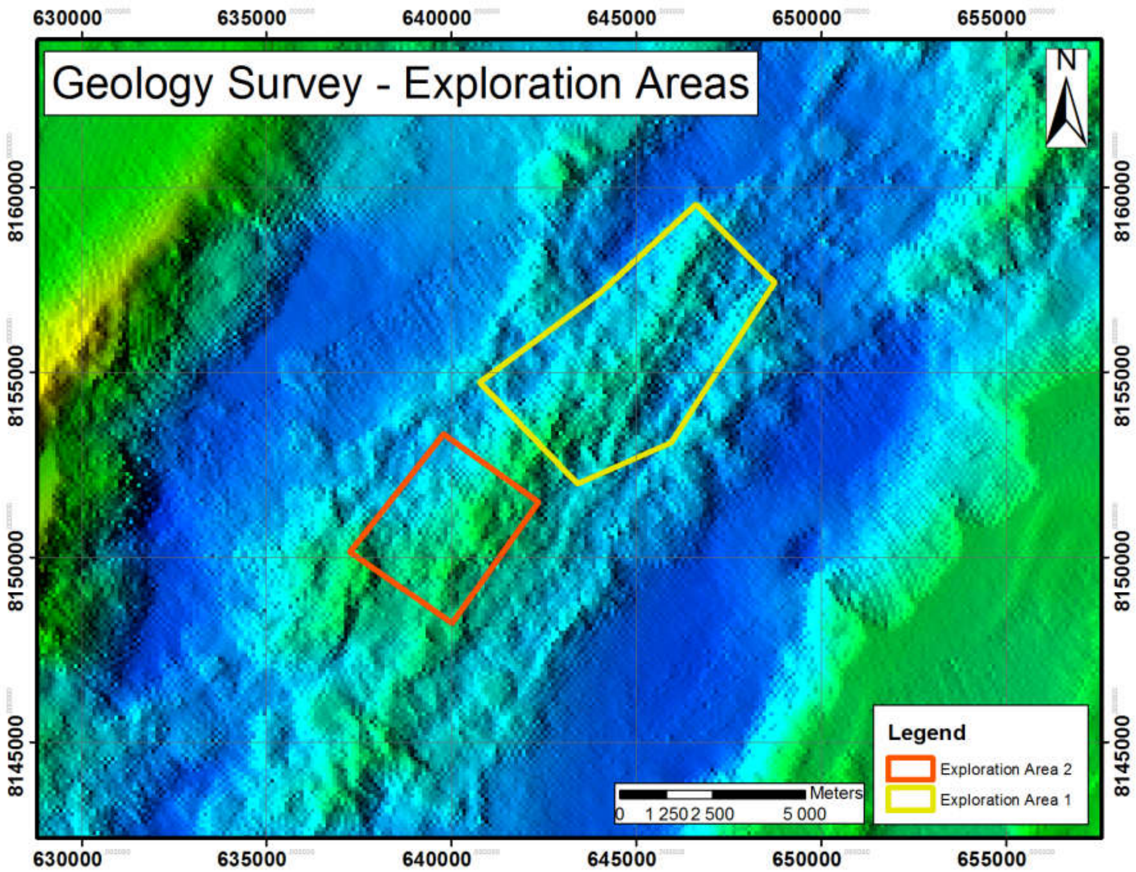


Figure 36 Extents of the Exploration Areas 1 and 2 situated on the AVR at the East of the Mohn's Treasure area.

3.4.3 Remotely Operated Core Sampler (ROCS)

Two initial test dives were made prior to any sample recovery missions. During these dives, the drill team was able to identify operational issues that needed to be corrected before drilling operations could be possible. These issues can be summarized as communications instability and low system pressure.

The communications instability was addressed through adjustments to the software. The low fluid pressure problem was solved by reconfiguring the hydraulic connection to the XLX system. These changes were made in time for the first sample recovery dive.

As no suitable hard rock ground was identified for coring near the area of interest, the ROCS was refitted to take push core samples. Two successive push core operations successfully retrieved seabed material. During the first dive 67% core recovery was achieved and 39% during the second.

Figure 37: Modified core lifter case for soft sample.

Following these initial dives, *ROCS* was reconfigured for hard rock drilling and an area of basalt was selected to test the hard rock drilling capabilities of the drill.

The initial dive to recover hard rock core was aborted shortly after the drill sight was reached. Upon commencement of drill operations, the system experienced several power blackouts. This was due to the soft fuse of the XLX 24VDC power supply defaulting to 2A prior to launch. A minimum of 7A is required for drilling operations thus the supply was tripped when hydraulic functions were activated. This problem was solved by resetting the ROV soft fuse to 10A. After this issue was resolved, a hydraulic leak was detected on the XLX independent of the ROCS system. As a result, the ROV had to be recovered to deck for repairs.

During the fourth dive (second dive to recover hard rock core), the drill tool disconnected from the drive spindle at the start of drilling. This issue occurred when the drill fluid pump was activated. The pressure created by this pump was greater than anticipated and was enough to pump the tool out of place.

Using the positioning capabilities of the ROV, the tool was successfully reset and drilling operation could proceed. After 20 cm of seabed penetration, there was an apparent core block and further drilling could not continue. The drill was recovered to deck. While there were signs of sediment in the core barrel, no sample was recovered. Following the fourth dive, modifications were made to the core lifter to assist in retaining core within the core barrel.

A fifth dive proceeded about twelve hours later. Prior to this dive, some adjustment to the linear position sensor had to be made and a recalibration was necessary. In addition, an adjustment was made to the drilling core barrel to prevent the drill tool disconnect, as experienced on the third dive. The fifth dive went smoothly from launch. The drill tool was able to penetrate 805 mm into the seabed. After a total duration of about 2.5 hours, the drill was recovered to deck with a hard rock core sample. In this case, 84% core recovery was achieved.

Figure 38: a) Modified hard rock core lifter; b) Core retained in core lifter case; c) 350C Series 14 thin kerf core bit; d) Core bit impregnated diamond cutting surface

This concluded ROCS drilling operations for the August/September MarMine cruise of 2016.

3.4.4 UHI

The UHI was used on four ROV dives and two AUV Dives. As outlined in the dive schedule, these dives were ROV1, ROV3, ROV19, ROV22, AUV2 and AUV8. The results presented here are preliminary, and does not represent the quality and interpretation possible given sufficient post-processing.

Table 7. List of UHI data sets

Dive	Location	Duration	Length	Comments
ROV1	S1–S2 (LC)	40min	130m	Poor lighting due to lamp angle
ROV3	S1–S2 (LC)	18min	130m	Lighting improved compared to ROV1
ROV19	S49 (MT)	5min	10m-20m	Calibration plate and short transect
ROV22	S11–S12 (MT)	1h 50m	800m	
AUV2	MT	40min	4900m	Low framerate
AUV8	LC	40min	3700m	Fixed framerate 20Hz

The UHI is a demanding sensor in terms of the required light conditions and navigation accuracy. If the vehicle is stable, the raw data can be easily interpretable. Any motion in roll, pitch, yaw or sway, or variations in surge-speed will cause distortions. In order to correct for these distortions in post-processing, accurate navigation data is needed. Unfortunately, the DVL-measurements of the ROV were not available for recording, which will make proper correction difficult.

Changes in altitude will result in changes in light intensity and swath width of the scans. Because of the complex terrain of the surveyed area, maintaining a fixed altitude is very challenging. Improvements in the software for automatic gain adjustment (light sensitivity) coupled with a well-designed lighting setup for the ROV will be essential in future cruises. High quality navigation data for the ROV, including DVL and IMU measurements will also need to be considered for geo-correction to be achievable.

ROV

Hyperspectral imaging was performed in the same location for ROV1 and ROV3. The reason for this was that the first transect had a suboptimal angle between the lamp and the seabed. This was improved on for the next dive by physically repositioning the lamp on the ROV. These dives were important as they were performed in a region of known hydrothermal activity, thus capturing the spectral signature of the sediments surrounding this phenomenon.

The necessity of navigation correction can easily be seen in Figure 39 and Figure 40, where the former is one performed with steady navigation and the latter is unstable navigation.

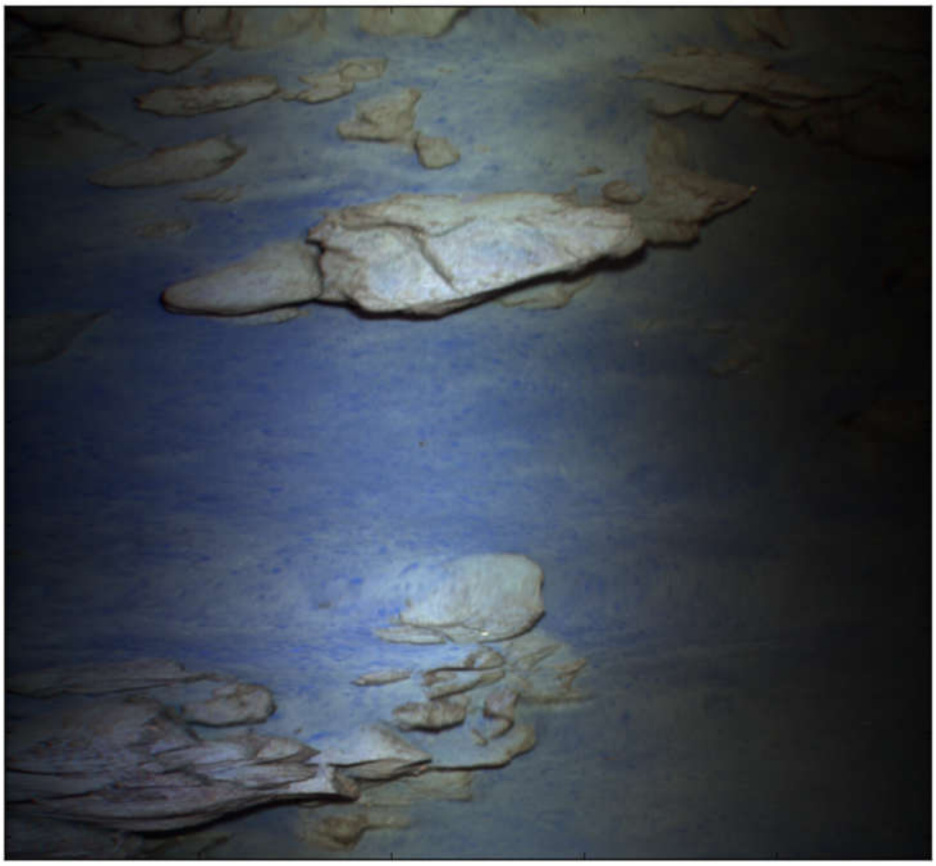


Figure 39: Example RGB projection of UHI footage from ROV3

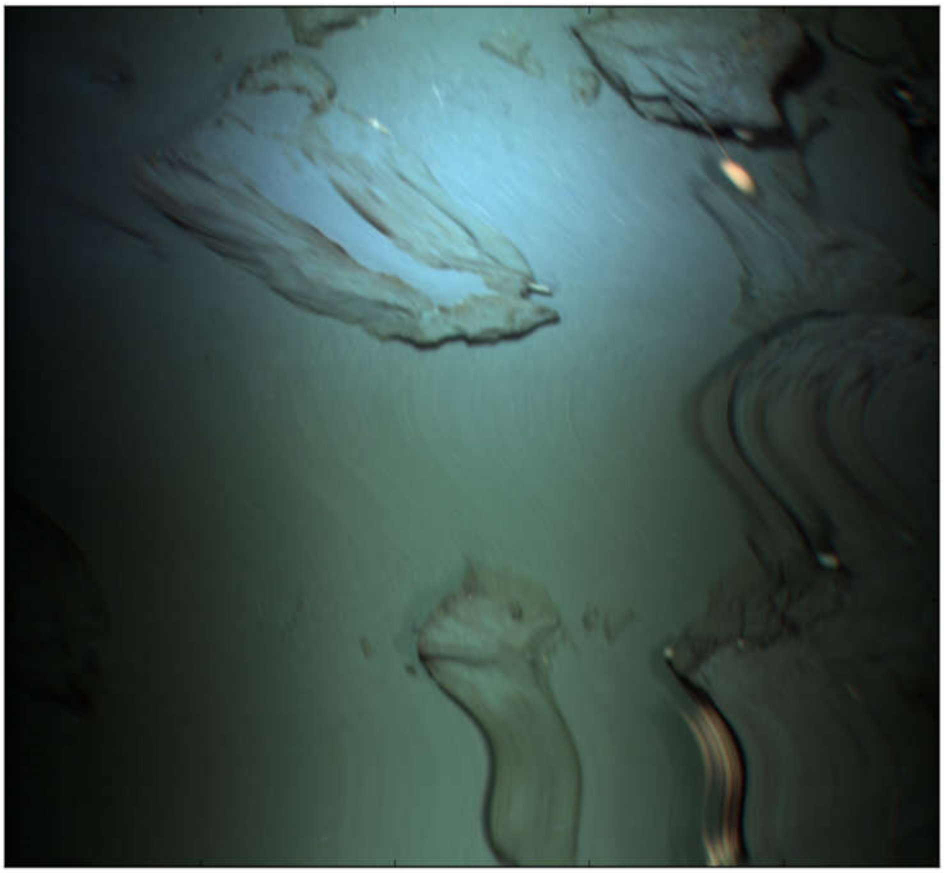


Figure 40: Example RGB projection from ROV3, where distortion occurs as a result of ROV movements

AUV

Figure 41 shows part of the scan from AUV10, and even with a speed of 3 knots, the terrain is clearly discernible in the raw data. For the AUV dives, the quality of the navigation data is very high, and the light source setup is specifically designed for the Hugin. Thus, even with the drawbacks of higher vehicle speed and altitude (resulting in lower spatial resolution and light intensity), the AUV data may prove easier to geo-correct and interpret than the ROV data.

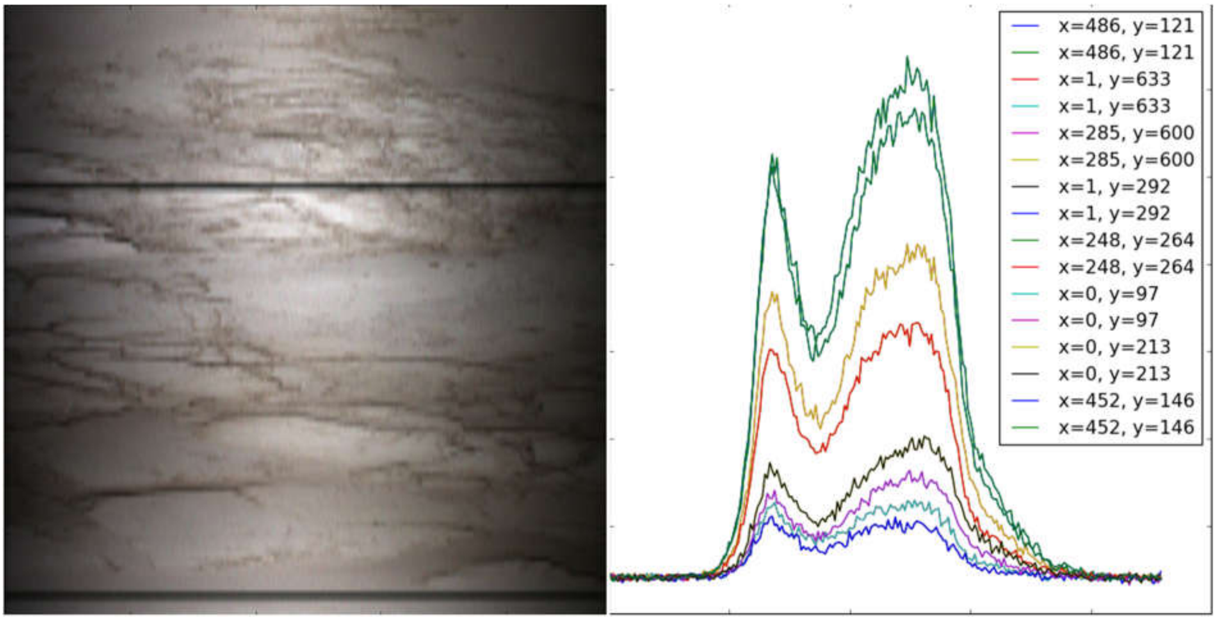


Figure 41: RGB projection of UHI data from AUV

3.4.5 Photogrammetry

The XLR ROV was equipped with an AVT 1380C camera for collecting still images for photogrammetry. Photogrammetry uses overlapping 2D still images to reconstruct a 3D model of the recorded scene. The AVT 1380C camera has a relatively low resolution (1360*1024 pixels), high light sensitivity and good depth of focus. It was set up to take one image every two seconds.

The still camera was used to record transects on the ROV9 and ROV16 dives. In addition, a photogrammetric survey was conducted on one of the vents of Loki's castle on the ROV20 dive. 354 images were collected over the course of 45 minutes and used to construct a 3D model of the vent. Images of one side of the 3d model can be seen in Figure 42 and Figure 43.

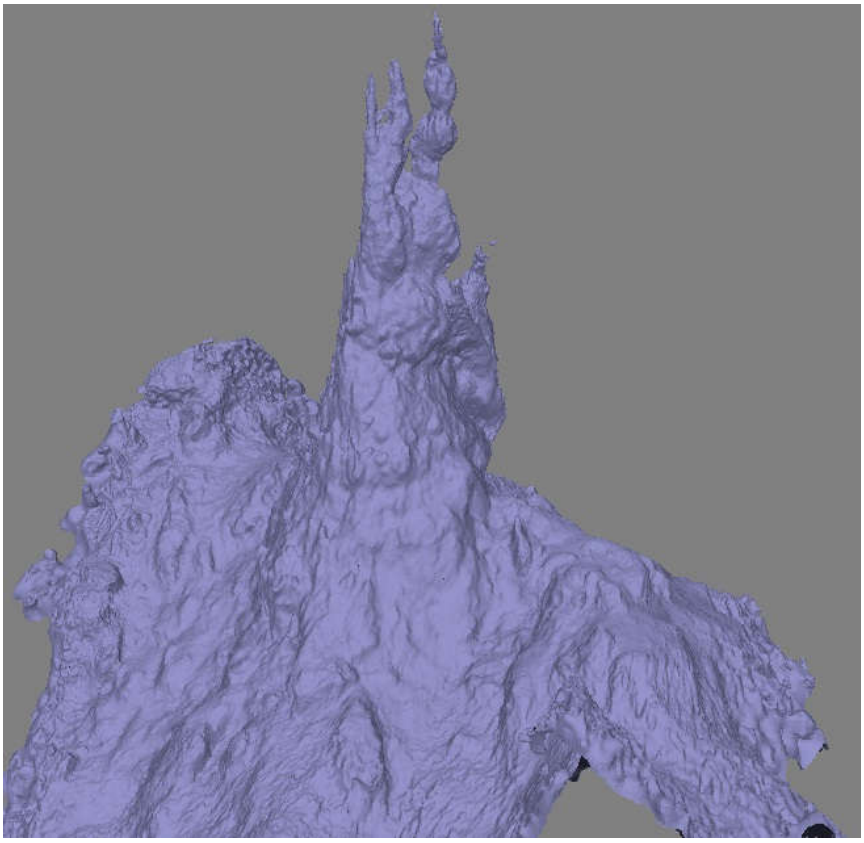


Figure 42: 3D model of one of the hydrothermal vents at Loki Castle (shaded)

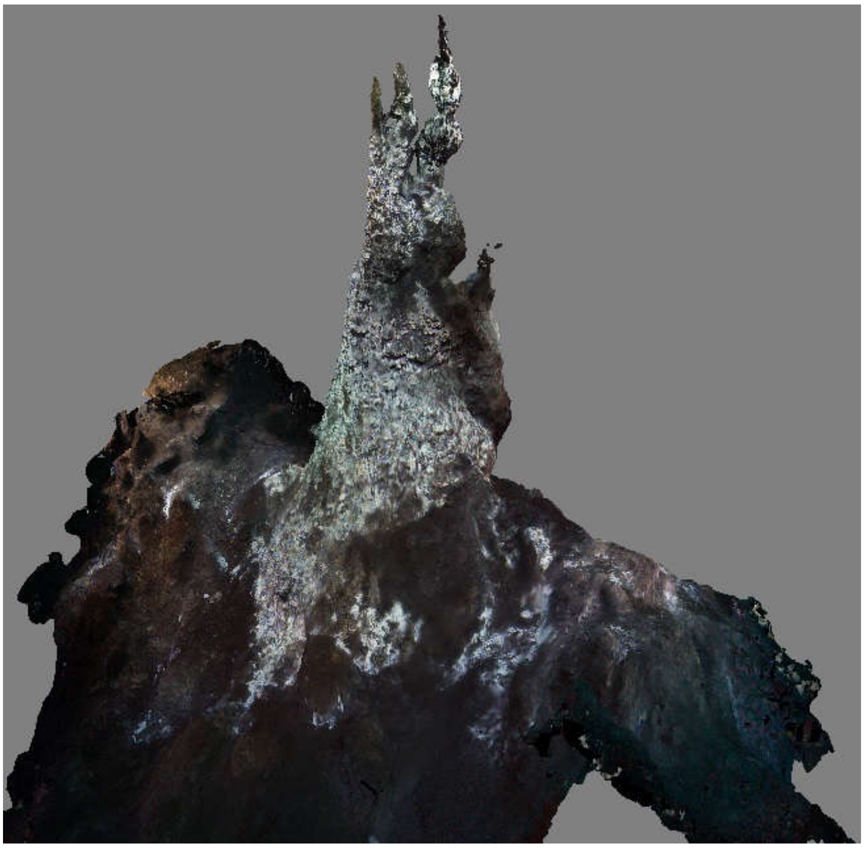


Figure 43: 3D model of one of the hydrothermal vents at Loki Castle, with projected texture

3.4.6 Magnetic Measurements

This is an example of magnetic measurements conducted with the use of AUV at Mohn's Treasure area. Overall, seven areas were mapped using the self-compensating magnetometer. The example shows only preliminary results with only compensation for vehicle-induced field. The rest of components not depending on the local varying field of interest will be removed and analysed in post-processing after the cruise.

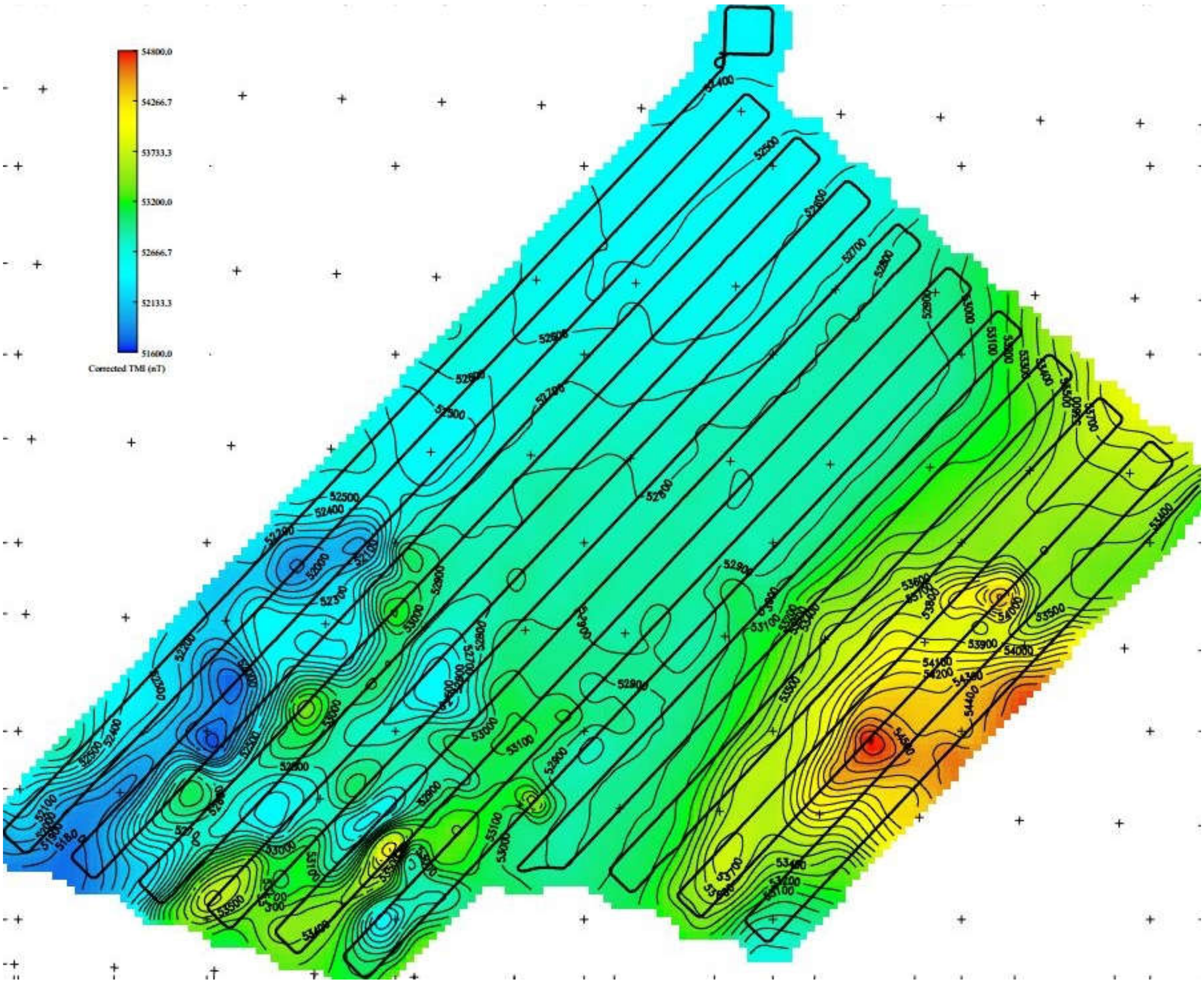


Figure 44: Magnetic field intensity measurements from the Mohn's Treasure area.

4 Further Work

4.1 Geology

The rock collection carried out during this cruise represents an invaluable potential source of data that should be carefully addressed. The success of potential mining on target sites will depend on parameters such as quality and quantity of minerals, but also the evaluation of industrial costs.
Mineral- and rock mechanical characterization described below will contribute with important information in the assessment of mineral processing and mining technologies.

4.1.1 Mineral characterization

In order to understand the geological and mineralogical properties of the areas investigated and the specific samples collected, a thorough mineralogical characterization will be performed. This mineralogical characterization will typically involve:

- Mineralogy
  - Mineral identification
  - Modal mineralogy
- Mineral chemistry
  - Mineral composition
  - Distribution of elements (zoning)
- Mineral texture
  - Grain and particle shapes
  - Grain and particle size
  - Mineral associations
- Mineral liberation

Initial characterization will typically be performed on slabs and polished thin sections of rock samples. However, in order to characterize mineralized samples and gangue for mineral processing tests, grain mounts will also be used for characterization. As part of the evaluation of mineral processing test work, mineral characterization of grain mounts from various product streams is also necessary.

Equipment and tools to be used in mineral characterization will include

- X-ray fluorescence (XRF)
- X-ray diffraction (XRD)
- Polarized light microscope (transmitted- and reflected light)
- Scanning Electron Microscope
  - Including automated mineralogy tools
- Electron Probe Micro Analysis (EPMA)
- ICP-MS

In order to achieve accredited analyses of element content, sample splits will be sent to an accredited lab for analyses.

As part of the characterization, a study on the effects of freezing on the formation of micro cracks will be carried out. This is motivated by the necessity of freezing samples for storage in none oxidizing environment. Freezing of wet samples will presumably induce micro cracks in the rocks, that again may influence the crushing and grinding strength of the rocks.

Deliverables:

1. Qualitative and quantitative mineral characterizations of sampled material
2. Qualitative and quantitative mineral characterizations of processed mineralized material
3. Publications in peer reviewed international journals
4. Provide input to MarMine WP2, WP3 and WP5 and to relevant MSc projects
5. Post doc projects on mineral characterization

4.1.2 Rock mechanical and geophysical characterization

The large volume of collected samples allows further investigations on the geophysical properties of the rock - the preferred tool for (sub-) surface survey exploration [*Falcon-Suarez et al.*, 2016].

Seismic wave velocities are commonly used to identify lithologies, but also to interpret physical parameters of the rock as density, porosity (and fractures) or degree of saturation. However, the use of S-wave is challenging in the sea because it doesn't propagate through water [*Minshull*, 2009]. Electrical resistivity is highly sensitive to lithologies and physical changes, which together with the seismic become a powerful tool of lithological identification and physical properties assessment. However, geophysics tools are, essentially, indirect methods to infer rock properties. Hence, calibration from real samples of well-known mineralogical and physical properties is needed.

According to this, the aim of the future work should be twofold: (i) a rock mechanical analyses to determine the stress envelope based on the Hoek-Brown model [*Hoek and Brown*, 1980], along with a characterization of the basic physical properties (at least density and porosity) prior to rock mechanical (destructive) testing; (ii) an assessment of the geophysical properties of the rocks -using analogues samples to those used during the rock mechanical-physical characterization, which include P- and S-wave velocities and their respective attenuation factors, and electrical resistivity tomography.

The geophysical measurements will be performed at the in situ salinity-pressure conditions of the target sites. Upon results and further objectives, more measuring points will be defined.

Deliverables:

1. Quantitative rock mechanical and petrophysical characterizations of sampled material
2. Publications in peer reviewed international journals
3. Provide input into MarMine WP3

4.2 Biology

Table 12 provides a detailed list of all biological samples collected during the MarMine cruise, indicating sample number, location, ROV dive number, site (S), collection method, content, preservation and notes related to the sample.

4.2.1 Video/photo transects

All relevant photos and videos for the transect analyses were saved on two external hard discs. The area covered by each photograph will be calculated using the area covered by the lasers. All photographs will be analysed and all megafauna observed identified to the lowest taxonomic level possible and counted. Abundance and density will be calculated for each faunal taxon identified and statistical tests undertaken amongst sites. MDS analyses will be conducted to compare the community structure in the three different sites on Mohn's Treasure. The results of the community composition and structure will be discussed in relation to our own observations and published data from the active Loki's Castle vent field (Pedersen et al., 2010). The video and photo transects will be further analysed by Eva Ramirez-Llodra (NIVA, Norway) and Ana Hilario (Uni. Aveiro, Portugal) to describe the Mohn's Treasure communities in the 3 different sites and compare them to known data from other inactive and active sites.

Deliverables:

1. MSc thesis on megabenthic community structure of the Mohn's Treasure
2. Scientific paper on megafauna community structure at Mohn's Treasure

4.2.2 Manipulator, Suction sampler and scoop

The macro fauna and megafauna samples were divided between NIVA and NTNU (Table 12). The frozen samples (NIVA) of holothurians and stalked crinoids will be analysed for stable isotopes to identify the trophic position of these key species in an inactive site. The samples preserved in 96% ethanol include sieved samples from the scoops for macro fauna, and holothurians, crinoids, asteroids, sponges, shells of bivalves and gastropods collected with the manipulator or with the suction sampler. These samples will be curated at the NTNU University Museum by Dr Torkild Bakken. The samples will be used for morphological species identification and barcoding. The holothurian and stalked crinoid samples preserved in formalin will be analysed in NIVA for morphological identification and, potentially, reproductive studies.

Deliverables

1. Barcodes of species.
2. Depending on the SIA results, a paper on the trophic position of key species of the inactive Mohn's Treasure will be prepared. If the results are not sufficient for

a single paper, this data will be integrated with the paper describing the benthic communities from the video transects.

3. Data on macro and megafauna species identification, to be used in the publication on community description from the video transect results.

4.2.3 Push-cores

The push-core samples were distributed amongst four different teams for further analyses (

Table 8).

Table 8. Use of push-cores samples per research team.

Analyses	Institute	Country	Contact	E-mail
Microbiology	Uni. Aveiro	Portugal	Ana Hilario	ahilario@ua.pt
Metagenomics	Ifremer	France	Sophie Arnaud	Sophie.Arnaud@ifremer.fr
Environmental	Uni. Gent	Belgium	Katja Guilini	Katja.guilini@ugent.be
Meiofauna	Uni. Gent	Belgium	Katja Guilini	Katja.guilini@ugent.be
Macro fauna	NIVA	Norway	Eva Ramirez-Llodra	eva.ramirez@niva.no

In the laboratory, the samples will be analysed for microbial community studies and functional traits (Uni. Aviero, Portugal), characterization of the sediment fauna diversity with metagenomics (Ifremer, ABYSS project), description of the meiofaunal communities in relation to sediment environmental variables and barcoding of key species (UGENT, Belgium) and description/barcoding of macro faunal species if present in the push-cores (NIVA and NTNU, Norway). The detailed information of the individual samples preservation method and distribution for each push-core is described in Table 11.

Deliverables

1. Publication on the characterization of the microbial communities at Mohn's Treasure
2. Publication on the metagenomics (Ifremer, in the framework of the ABYSS project)
3. Publication on the meiofaunal communities of Mohn's Treasure
4. Additional data on macro fauna species, to be used in the publication on community description from the video transect results.

All the above-mentioned publications may be integrated into a single comprehensive publication describing the Mohn's Treasure ecosystem.

4.3 Exploration

Further analyses of the collected multi beam data will be established to provide descriptions of the seafloor's spatial distribution of relief, terrain derivatives, and expression of geological features. The seafloor properties are important physical variables that govern the distribution of hydrothermal vent systems and their associated SMS deposits. It is thus fundamental to investigate the potential of multi beam sonar data to determine favourable zones where resource minerals may accumulate. Map products in association with videos and images (geological observation data) obtained from on-site explorations will be used in an attempt to depict seafloor features at the level of resolution of the sonar system. Quantitative measures for depth, topographic roughness and orientation, and backscatter strength will be derived and used as support materials for future explorative activities.

Deliverables:

1. MSc thesis on structural geology and tectonics
2. PhD on resource assessment
3. Publications in peer reviewed international journals
4. Updated permissive tract definition

5 Conclusion

The MarMine cruise studied three areas, the Loki Castle and Mohn's Treasure identified by University of Bergen and exploration areas defined by the previous analyses of the resource potential and identification of permissive tracts during the NTNU pre-project. The cruise was defined to provide samples, measurements and observations for the scientific work packages within (1) Sample identification and collection (2) Mineral processing options for submarine massive sulphide ores, (3) Conceptual studies of methods for extraction of marine minerals, (4) Characterization and (5) Implementation methods to assess environmental impacts and recovery potential.

Aboard the Polar King, two work-class ROVs and the Hugin AUV have been deployed to perform video survey, rock sampling, push core sampling, suction sampling, collection of megafauna, core drilling in hard rock, drilling in soft material, photogrammetry, multi-beam echo-sounder surveys, side scan surveys, hyperspectral surveys, optical seabed imaging, CTD, turbidity, magnetic and methane surveys. In total 22 ROV dives have been performed together with 10 AUV dives.

The observations, measurements and samples together with the experiences obtained with the techniques and methods provide invaluable insight and knowledge for MarMine to fulfil the original scientific goals.

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Appendix A Project Crew

Surname	Given name	Organisation	Role	Project	E-mail
Ludvigsen	Martin	NTNU	Cruise leader	MarMine	martin.ludvigsen@ntnu.no
Søreide	Fredrik	NTNU	Cruise co-leader	MarMine	fredrik.soreide@ntnu.no
Ellefemo	Steinar	NTNU	Lead WP3	MarMine	steinar.ellefmo@ntnu.no
Aasly	Kurt	NTNU	Lead WP4	MarMine	kurt.aasly@ntnu.no
Ramirez-Llodra	Eva	NIVA	Lead WP5	MarMine	eva.ramirez@niva.no
Sture	Øystein	NTNU	PhD WP1	MarMine	oystein.sture@ntnu.no
Malmquist	Christian	NTNU	Lead surveyor	AUR-Lab	christian.malmquist@ntnu.no
Nornes	Stein M.	NTNU	Data processor	AUR-Lab	stein.nornes@ntnu.no
Reimers	Hauke	NTNU	Data processor		hauke.reimers@gmail.com
Lorentzen	Ole Jacob	FFI	Lead AUV operator		ole.lorentzen@ffi.no
Jubskås	Helge	FFI	AUV operator		Helge.Jubskas@ffi.no
Pardey	Marshall	QD Tech	Driller		mpardey@qdtech.com
Schelereth	Max	Williamson	Drill tech.		MSchlereth@wassoc.com
Milsap	Rob	Williamson	Drill tech.		
Paulsen	Emil	NTNU	MSc student WP5		emilp@stud.ntnu.no
Kieswetter	Amanda	Uni. Gent, BE	MSc student WP5		kieswetter.a@gmail.com
Hilario	Ana	Uni. Aveiro	WP5	MarMine	ahilario@ua.pt
Lim	Anna	NTNU	Geomagnetics	DSM Pilot	anna.lim@ntnu.no
Juliani	Cyril	NTNU	Geology	DSM Pilot	cyril.juliani@ntnu.no
Egseth	Martin	NTNU	ROV-trainee	AUR-Lab	martegse@broadpark.no
McConnell	Daniel	Fugro	Observer		DMcConnell@fugro.com
Falcon-Suarez	Ismael	NOC	Geology		isfalc@noc.ac.uk
Holth Rustad	Even	NTNU	Medical		evenholth@gmail.com
Tumyr	Lars Ivar	Reach	Photographer		larsivartumyr@gmail.com
Parisi	Oriana	Statoil	Observer		OPAR@statoil.com

Antonsen	Tore	Nordic Subsea/NTNU	Shift supervisor		tore.anthonsen@nordicsubsea.no

Appendix A Dive Narratives

A.1 Geology - AUV

Dive #1 (HUGIN)

Date started: 22.08.16 @10:22

First dive at Mohn's Treasure to collect high-resolution MBES- and backscatter data for site description.

Dive completed with CTD-, CH4, magnetometer (SCM) and turbidity sensors activated.

Date ended: 22.08.16 @23:20

Dive #2 (HUGIN)

Date started: 23.08.16 @16:42

Second dive at Mohn's Treasure to collect high-resolution MBES- and backscatter data for site description.

Collected also SSS- and UHI-data at lower altitudes to be able to do multivariate analysis and to co-interpret these data types.

Dive completed with CTD-, CH4, magnetometer (SCM) and turbidity sensors activated.

Date ended: 24.08.16 @08:30

Dive #3 (HUGIN)

Date started: 26.08.16 @11:42

Dive at exploration area 1 to collect high-resolution MBES- and backscatter data for area description and identification of indicative morphological structures.

Collected also SSS-data.

Dive completed with CTD-, CH4, magnetometer (SCM) and turbidity sensors activated.

Date ended: 27.08.16 @02:32

Dive #4 (HUGIN)

Date started: 27.08.16 @18:37

Dive at the southward extension of exploration area 1 to collect high-resolution MBES- and backscatter data for area description and identification of indicative morphological structures.

Collected also SSS-data.

Dive completed with CTD-, CH4, magnetometer (SCM) and turbidity sensors activated.

Date ended: 27.08.16 @22:10

Dive #5 (HUGIN)

Date started: 28.08.16 @00:47

Dive to complete the southward extension of exploration area 1. Collected high-resolution MBES- and backscatter data for area description and identification of indicative morphological structures.

Dive completed with CTD-, CH4, magnetometer (SCM) and turbidity sensors activated.

Date ended: 28.08.16 @03:56

Dive #6 (HUGIN)

Date started: 29.08.16

On deck testing (HISAS).

Date ended: 30.08.16

Dive #7 (HUGIN)

Date started: 30.08.16 @07:15

Dive in the Loki's castle area at different altitudes (100, 50 and 30 meter) to get a complete suite of datasets over an active vent field.

Dive completed with CTD-, CH_4, magnetometer (SCM) and turbidity sensors activated.

Emergency ascent in first line on 30 meter altitude.

Date ended: 30.08.16 @12:17

Dive #8 (HUGIN)

Date started: 30.08.16 @13:30

Dive in the Loki's castle area at different altitudes (30 meter and ~5 meter) to complete data collected in dive 7.

Dive completed with CTD-, CH_4, magnetometer (SCM), turbidity sensors, tile cam and UHI activated.

Date ended: 30.08.16 @16:44

Dive #9 (HUGIN)

Date started: 31.08.16 @07:35

Dive at the further southward extension of exploration area 1 to collect high-resolution MBES- and backscatter data for area description and identification of indicative morphological structures.

Dive completed with CTD-, CH_4, magnetometer (SCM) and turbidity sensors activated.

Date ended: 31.08.16 @18:17

Dive #10 (HUGIN)

Date started: 01.09.16 @05:43

Dive at exploration area 2 to collect high-resolution MBES- and backscatter data for area description and identification of indicative morphological structures.

Dive completed with CTD-, CH4, magnetometer (SCM) and turbidity sensors activated.

Date ended: 01.09.16 @11:39

A.2 Geology - ROV

Dive #1 (XLR)

Date started: 20.08.16 @23:55

Dive no 1 was planned as a survey dive at Loki´s Castle. We arrived at site in the evening on the 20th august. The ROV left deck at 23:00. After some system checks, we were ready to start surveying at 02:00 at 2450 mbs. The first hours were used to follow VT1. The transect started in basalts north of the mound and continued into sediment cover. As the slop of the mound started, the sediments changed characteristics and elements of more porous rock fragments appear. Sampling using the manipulator arm showed that these fragments were more brittle/fragile than the basalt. Higher up on the mound, the sediment cover started to show elements of collapsed chimneys. Closing in on the top, the five chimneys appeared with their characteristic shape and when approaching these, the venting also became visible.

After transecting up and close to the top of the mound, the survey continued to predefined sites for potential core drilling. It became clear that the most suitable site was in the bottom of the valley between the two mounds, site S9.

Wire and gravity corer observed around S6.

VT3 and VT4 were completed the western and the eastern mounds respectively. During transects samples were collected from potential mineralized rocks.

Date ended: 21.08.16 @07:09

Dive #2 (XLR)

Date started: 21.08.16 @12:15

In order to fulfil one of the main goals for the cruise, dive2 focused on sampling. In the first part of the dive, one profile to each mound were prepared with potential sampling points for grab. Both profiles originated from S9 with heading towards mound peaks. A minigrab of 180 liters were deployed to the sea floor for the sampling. A problem with the hotstab system prohibited sampling. One scoop sample was collected.

Date ended: 21.08.16 @15:59

Dive #3 (XLR)

Date started: 21.08.16 @16:14

After realizing that the mini-grab did not work, sampling was initiated based on grabbing with manipulator arms and ROV basket. In addition, the basket was fitted with two Zarges boxes for storage of samples. Additionally, two scoops and a water sampler were brought down in the basket. The water sampler was attempted released before the basket was emplaced on the bottom. Unfortunately, the release mechanism broke before releasing. Following the sampling profiles set out by Dive2, samples were collected along the eastern mound and later the western mound. The first sample, GS1 from the eastern mound was a large boulder and fitted only in the open half of the basket. The remaining samples from the eastern mound were collected and stored in a designated Zarges box (left side facing the boxes). Samples from the western mound were collected in the other Zarges box (right side).

Date ended: 22.08.16 @02:18

Dive #4 (XLR)

Date started: 23.08.16 @02:50

Dive4 had the objective to sample the vent fluid, document and observe the XLX in drilling operation and to do biological transects and sampling.

Upon landing the XLR moved to the predefined drilling area mid-way up the western mound from station S9 to identify a drilling location for the XLX and helped the XLX navigate to the location. During coring the drilling operation was documented with photos and video. After successful first coring, the XLR waited for the XLX on the seafloor while performing other tasks (vent fluids sampling, biological sampling).

Date end: 23.08.16 @11:38

Dive #5 (XLX)

Date started: 23.08.16 @02:50

Dive 5 had the objective to drill the first hole. Because of the state of the sea floor at Loki´s Castle area, the drill rig had been modified into a push corer (one core capacity).

The XLR assisted in positioning the XLX and prepare for drilling at site.

Approximate drill position is 662675, 8170718 (UTM31N, WGS84). Heading 281; Pitch 17 °U; Roll 5 °P. This gives a borehole dip and dip direction of 72° and N264°E.

Drill time: 35 minutes.

The core length was ca 17 cm and consisted mainly of semi-fine fragments and mud.
Date end: 23.08.16 @05:33

Dive #6 (XLX)

Date started : 23.08.16 @09:37

Dive #6 was carried out in order to produce the second drill (push) core. A successful drilling took place at 10:07.

The XLR navigated to a suitable location for drilling mid-way up the eastern mound from station S9. The XLR helped to position the XLX and prepare for drilling at site. Approximate drill position was 662717, 8170715 (UTM31N, WGS84). Heading 14 (on the GUI), 9.5 (on the video); Pitch 1 °D; Roll 20°P. Using the heading on the video, this gives a borehole dip and dip direction of 70° and N277°E.

Drill time: ca 10 mins.

The second core length was ca 40 cm and consisted mainly of semi-fine fragments and mud.
Date end: 23.08.16 @11:38

Dive #7 (XLR)

Date started : 24.08.16 @10:00

Dive for bio transect and sampling.

Dive aborted due to possible hydraulic failure

Dive end: 24.08.16 @12:00

Dive #8 (XLR)

Date started: 24.08.16 @12:30

Biological transects and sampling along VT 5-VT10 (not VT8).

Geologists annotated sediment variations and outcrops.

Date ended: 25.08.16 @15:30

Dive #9 (XLR)

Date started: 25.08.16 @16:00

Biological transects and sampling along VT11-VT12.

Geologists annotated sediment variations and outcrops.

Date ended: 26.08.16 @00.55

Dive #10 (XLR)

Date started: 26.08.16 @01:20

Biological transects and sampling along VT8.

Geologists annotated sediment variations and outcrops.

Date ended: 26.08.16 @ 10:30

Dive #11 (XLR)

Date started: 27.08.16 @04:14

Start at S11. North-west toward S12. Geological sampling and –mapping. Taking off towards S52 to check for potential drilling sites.

Date ended: 27.08.16 @13:08

Dive #12 (XLR)

Date started: 27.08.16 @13:14

Inspect geophysical anomaly on the scarp edge at Mohn´s Treasure area. Rock samples and scoop samples (sediments) collected.

Date ended: 27.08.16 @17:10

Dive #13 (XLX)

Date started: 28.08.16 @05:50

XLX dive to drill. Drilling cancelled due to technical issues.

Date ended: 28.08.16 @10:10

Dive #14 (XLR)

Date started: 28.08.16 @10:49

Pushcoring at S16. Biology.

Date ended: 28.08.16 @16:41

Dive #15 (XLX)

Date started: 28.08.16 @21:00

Drilling close to S54. Stable ROV. Drilling commenced at heading: 071°; Pitch: 1°D; Roll 0°P. This gives a borehole dip and dip direction of 89° and N251°E.

Drilling time: 27 minutes (according to event log)

Drilling to ca 20 cm depth. Drill operator chose to cancel because of locked barrel. Core lost during accent or left in hole.

Date ended: 29.08.16 @ 00:48

Dive #16 (XLR)

Date started: 29.08.16 @03:48

Target check exploration area 1 to investigate promising targets.

Date ended: 29.08.16 @07:22

Dive #17 (XLR)

Date started: 29.08.16 @11:17

Survey Mohn´s Treasure. VT14, VT15. Transect up the scarp to assess the sediment variations from the bottom and up the scarp.

Date ended: 29.08.16 @16:56

Dive #18 (XLX)

Date started: 29.08.16 @18:02

Drilling near S55. Stable ROV. Drilling commenced at heading 034N; Pitch: 0 °; Roll 1 °P. This gives a borehole dip and dip direction of 89° and N124°E.

Drilling time: 80 minutes.

Drilling to ca 85 cm depth. Driller chose to cancel due to lower penetration rate. ROV had issues with the hydraulics.

A 62 cm long core of basalt retrieved from the core barrel. 73 % recovery.

Date ended: 29.08.16 @22:06

Dive #19 (XLR)

Date started: 29.08.16 @23:00

Dive to check assumption that the Mohn's Treasure is an extinct went. Survey for remnants of the extinct vent at and around S11. This dive focus on the ridge just N of S11 where a sediment variation with shell fragments were identified in Dive11. Push coring and scoop sampling was planned as the main sampling methods on the dive. Push coring performed on sediment variations. PC1: SE of S11 – sediment with coarser texture on the top; PC2 N of S11 – over ridge, more coarse sed. PC3 N of S11 along S11-S12 transect. A small ridge with very clear SW-NE dredge mark was observed. Limited extension. Coarse fragmented sediments; PC4 NE of the S11-S12 transect, along small ridge. Rusty patch with fragile rocks. Rock sample from same point; PC5 – patchy sedimented in same area as PC4.

UHI across the outcrop from SW – NE. Dive ended with calibration plate for UHI.

Date ended: 30.08.16 @04:09.

Dive #20 (XLR)

Date started: 30.08.16 @18:16

Short dive for photogrammetry at Loki´s Castle.

Produced photogrammetry of tall vent on east mound. Success. ROV cancelled due to water alarm in electric system.

Date ended: 30.08.16 @20:49

Dive #21 (XLR)

Date started: 30.08.16 @23:55

Geology dive for target inspection at exploration area 1 target area 2.

Reached sea floor at 2930 m depth NW of S61. Transected S61 to S67, but missed S63 due to inaccurate navigation. No vents detected. Mainly sea mounts with pillow lavas. Typical pillow textures on and around the top of the mount. Sediment layer on all outcrops. Very few sponges.

TMS move from S67 to S68. Same type of geology no interesting features.

TMS move from S68 to S69. Transect to mound at S71. Interesting textures of the slope NW of S71 on opposite side of fault. Sample collected.

Date ended: 31.08.16 @06:26

Dive #22 (XLR)

Date started: 01.09.16 @19:50

Dive to drop the gravity corer at the Mohn's Treasure, just NW of S11 and performing a UHI transect towards S12. During the UHI-transect push-core samples were collected to characterize the seabed at sampling locations.

Date ended: 01.09.16 @03:18

A.3 Biology - ROV

6.1.1 DIVE #1 – XLR. Loki's Castle. Geo and Bio

Started on 20/08 at 23:02

Finished on 21/08 at 07:10

For biology:

At 03:34 to 03:44 we conducted a video transect from S7 to S8. This transect did not get to the top of the mound because of the smokers. At 04:06 to 04:15 we conducted a second video transect from S9 to S10.

At 04:20 some fauna was sampled with the suction sampler on the seafloor away from the mound.

6.1.2 DIVE #2 – XLR. Loki's Castle. Geo

Grabbing dive – Geo

Biologists as observers

DIVE #3 – XLR. Loki's Castle. Geo and Bio

Started on 21/08 at 16:14

Finished on 22/08 at 02:00

For biology:

From 18:30 to 19:30 video surveys and detailed photography were conducted on the mounds. At 20:42, the suction sampler was used to collect sponges for calibrating the UHI camera.

6.1.3 DIVE #4 – XLR. Loki's Castle. Geo and Bio

Started on 23/08 at 02:50

Finished on 23/08 at 11:38

For biology:

Between 06:22 and 06:38 we collected sponges of different morphotypes for UHI calibration.

At 06:59 we started video transect VT3 in S7 and finished at 07:09 in S8. At 07:22 we started video transect VT4 in S9 and finished at 07:41 in S8. Following the two video transects we conducted a video survey at S9 between the two mounds.

At 08:16 we started looking for a drill site between S9 and S10.

6.1.3.1 DIVE #5 – XLX. Loki's Castle. Drill

No biological sampling or observations made

6.1.3.2 DIVE #6 – XLX. Loki's Castle. Drill

No biological sampling or observations made

6.1.3.3 DIVE #7 – XLR. Mohn's Treasure. Bio

Started on 24/08 at 10:03

Finished on 24/08 at 12:03

The ROV was on the seafloor at 11:19. However, there was an issue with the TMS and the dive was aborted. The ROV was back on board at 12:03 and the issue sorted.

6.1.3.4 DIVE #8 – XLR. Mohn's Treasure. Bio

Started on 24/08 at 12:28

Finished on 25/08 at 14:00

24 August

The dive started at S13, with a video transect from S13 to S15 (VT5) that lasted 2h. At the end of the transect, the basket carrying the Ifremer and GEOMAR push-cores was deployed with the crane. While we waited for the basket, we took close up photographs of stalked crinoids.

At 17:15 the basket was on the seafloor and the push-cores deployed (S22). At 20:47 the basket was recovered with the two racks of push-cores. However, the Ifremer rack was horizontal when the basket was recovered on deck.

At 21:04 the ROV was docked in the TMS and headed to S16.

24/25 August

At 22:17 we started VT6 in S16 and ran for 200 m, finishing in S24 at 22:55. At 23:22 we started VT7 in S25 and ran for 200 m, finishing at S26 at 00:11 (25/08/2016). At 00:27 we started VT9 in S23 and ran for 200 m, finishing in S27 at 01:00. At 01:29 we started VT10 in S28 and ran for 200 m, finishing in S29 at 02:14.

After finishing V10, we moved to S12 where the basket with the push-cores was deployed. The 8 GEOMAR and 8 Ifremer cores were descended with the basket. However, only the GEOMAR cores could be deployed because the Ifremer rack was horizontal in the basket. At 07:00 the ROV started rigging the basket, but this was not accomplished until 07:50. The basket was re-deployed straight away with the Ifremer cores and arrived on the seafloor at 10:00. The 8 cores were deployed and taken back to the basket at 11:50. The basket could not be rigged to the crane until 13:15.

AT 14:00 then the basket and the ROV are back on deck.

6.1.3.5 DIVE #9 – XLR. Mohn's Treasure. Bio

Started on 25/08 at 15:00

Finished on 25/08 at 23:00

At 16:42 the ROV was on the seafloor at S39.

At 16:52 we started VT11, from S39 for 200 m, ending at 17:37 at S40. The stills camera memory card was full after 24 minutes, so the transect was finished with the photomosaic camera. We then repositioned to S41 and started VT12 at 18:15 in S41 and finished at 18:57 in S42.

At 19:12 we started a survey towards the upper part of the wall, from S42 to S43. When we reached the top of the ridge, we stopped to sample epibionts on sponges with the suction sampler at 19:49, 20:16, 20:34 and 21:23. At 21:58 we took a scoop sample on a rocky community.

At 22:19 the ROV went back to the TMS for recovery.

6.1.3.6 DIVE #10 – XLR. Mohn's Treasure. Bio

Started on 26/08 at 01:20

Finished on 26/08 at 10:00

At 01:20 ROV10 started. At 01:54 the ROV was on the seafloor at S16.

At 02:18 we started collecting stalked crinoids with the manipulator, which were then put in the scoop used as a biobox.

At 03:24 the basket was deployed with the GEOMAR push-cores. While we waited for the basket we conducted VT8, starting in S46 at 03:30 and ending in S47 at 04:08.

At 04:44 the basket was on the seafloor and at 04:57 the rack of push-cores was out of the basket. We started deploying the push-cores at 05:07, but the tubes had not been filled in with water before deployment and had made the vacuum during descent so they did not come loose out of the outer tube (the tops were coming out). Only 2 cores could be taken.

A scoop of the top 10 cm was taken at 05:55 and put in the basket. The scoop with the crinoids was carried by the ROV in its manipulator.

At 06:32 the ROV moved to TMS and moved to S13a where we had observed many holothurians at the start of ROV8. At 08:14 we started collecting holothurians with the suction sampler. 10 holothurians were seen go in but one fell. However, upon recovery only 5 holothurians were in the suction sampler bucket. The suction sampler has not enough power.

At 09:09 the ROV started recovery to the vessel. Unfortunately, upon ascent the scoop with all the stalked crinoids fell from the manipulator when the ROV was 70 m from the surface and both the scoop and sample were lost!

6.1.3.7 DIVE #11 – XLR. Mohn's Treasure. Geo

Started on 27/08 at 04:14

Finished on 27/08 at 13:08

ROV11 started on the seafloor at 05:07 in S11 for survey of the Mohn's Treasure along VT5 towards the dredge track. At 05:56 we saw a Dumbo octopus! Good video and photos. At 08:56 we found the dredge track at S14 and we followed it up. At 09:25 the ROV was docked in the TMS and we moved to S52. At 10:13 the ROV was on the seafloor at S52, in a new area that we have not explored yet. The area was surveyed and we looked for potential locations for drilling.

At 11:17 the ROV was docked in the TMS and we moved to S53.

The dive ended at 13:08.

6.1.3.8 DIVE #12 – XLR. Mohn's Treasure. Geo

Started on 27/08 at 13:14

Finished on 27/08 at 17:10

Geological survey dive. The biology team was observer in the dive.

6.1.3.9 DIVE #13 – XLX. Mohn's Treasure. Drill

Started on 28/08 at 05:50

Finished on 28/08 at 10:10

Drill dive but drill cancelled because of technical issues.

6.1.3.10 DIVE #14 – XLR. Mohn's Treasure. Bio

Started on 28/08 at 10:51

Finished on 28/08 at 16:41

ROV14 started in S48 and the ROV was on the seafloor at 12:02 with the GEOMAR push-cores attached to the front of the ROV.

At 12:08 we started deploying cores. At 12:44 all push-cores were recovered in the rack.

At 13:39 we started picking stalked crinoids with the manipulator and stored them in the scoop used as a biobox. Approximately 20 crinoids were collected.

At 15:18 the ROV was back in the TMS and recovered.

6.1.3.11 DIVE #15 – XLX. Drill

No biology

6.1.3.12 DIVE #16 – XLR. Exploration

No biological activities. Biology team as observers.

6.1.3.13 DIVE #17 – XLR. Mohn's Treasure. Geo

Geological survey. Biology team as observers.

6.1.3.14 DIVE #18 – XLX. Drill

No biology

6.1.3.15 DIVE #19 – XLR. Mohn's Treasure. Geo

Geological survey. Biology team as observers.

6.1.3.16 DIVE #20 – XLR. Loki's Castle. Imagery

Biology team as observers

6.1.3.17 DIVE #21 – XLR. Exploration area. Geo

Biology team as observers

6.1.3.18 DIVE #22 – XLR. Mohn's Treasure. Geo and Bio

Started on 31/08 at 19:50

Finished on 01/08 at 03:30

The dive started with the gravity core footage. Biology team as observers. The gravity core was released at 21:30 and recovered to the surface.

At 21:41 the UHI testing and calibration started. A UHI transect was conducted, starting at S11 towards S12. Several push-cores were taken along the line.

At 01:40 we started collecting holothurians at S13a with the suction sampler. 40 holothurians were suctioned, but only half made it to the surface. At 02:06 the sampling stopped. For about 20 min we looked for the lost scoop but it could not be found.

At 02:23 the ROV started its ascent.

A.4 MBES Acquisition Parameters

Acquisition parameters for the EM2040 used by Hugin are available in the file EMconfig.ini, available in the folder “pp” found in the mission folder. In short the runtime parameters used are:

Angular Coverage = Auto.

If Angular Coverage is set to ‘Auto’, the maximum coverage (in meters) and the maximum angles will set the swathwidth limit. The most limiting of the two criteria will be used. If the system is not able to fulfil the above, it will reduce the swath width further and as a consequence nearly all the beams will be valid. You may observe this in the Numerical display of the SIs software, as the numbers of beams accepted should almost equal to the number of beams available. (1)

Beam Spacing = High Density Equidistant

In this mode there are several soundings per beam. Beam angles are adjusted to give equal meter distance between all soundings. (1)

Pitch Stabilizing is used and the the sonar beamformer will in realtime correct for vehicle pitch up to 10 degrees.

The EM2040 ping frequency was set to 400kHz

Table 9 MBES Line Planning

Date	Dive	Area	Vertical Guidance	Line-spacing	Comments
20160823	AUV 1	Mohns Treasure North	Fix Altitude = 100m	150m	Erroneous sonar mounting angle (Sonar Head 1: heading offset in deg.) Lines running up/down slope
20160824	AUV 2	Mohns Treasure South	Fix Altitude = 80m	150m	Erroneous sonar mounting angle (Sonar Head 1: heading offset in deg.) Lines running along slope
20160827	AUV 3	Exploration Area	Fix Depth per line, see mission.mp for values	150m	Erroneous sonar mounting angle (Sonar Head 1: heading offset in deg.) Lines running along slope
20160830	AUV 7	Lokis Castle	Altitude = 100 / 50 / 30m	150m	
20160830	AUV 8	Lokis Castle - UHI	Altitude = 14m	One Line	
20160831	AUV 9	Exploration Area 1	Fix Depth per line, see mission.mp for values	250m	
20160830	AUV 8	Lokis Castle - UHI	Altitude = 14m	One Line	
20160831	AUV 9	Exploration Area 1	Fix Depth per line, see mission.mp for values	250m	
20160901	AUV 10	Exploration Area 2	Fix Depth per line, see mission.mp for values	250m	

(1) EM Technical Note: “Sector coverage and beam spacing modes for multibeam echosounders”, Desember 2013

A.5 ROCS Drill Log

DIVE I			**23.08.2016**
			Tool configuration: modified corebarrel using hard rock
			innertube and modified core lifter case as "push" shoe
	02:21		Deck check complete
	02:24		ROV in water
	03:21		Positioning ship
	04:21		Touch down at site
	04:24		Start of run
			Difficulty with feed penetration
			Pulled back off site to review drill controls
	04:38		Moving to new site
	04:46		Landed at second site
	04:52		Start of run
	05:00		Started penetration, drill head position 1120 mm
			Penetrating with occasional rotation
	05:20		End of run, drill head position 494 mm
			Total drilled depth 626 mm
	05:28		Drill tool stowed
			Return to surface
			420 mm sediment core recovered 67%
DIVE II			23.08.2016
			Tool configuration: modified corebarrel using hard rock
			innertube and modified core lifter case as "push" shoe
	08:50		Deck check complete
	08:52		ROV in water
	09:56		Touch down at site
	10:05		Started penetration, drill head position 1120 mm
			Penetrating with occasional rotation
	10:08		End of run, drill head position 380 mm
			Total drilled depth 740 mm

	10:16		Drill tool stowed
			Return to surface
			290 mm sediment core recovered 39%
DIVE III			28.08.2016
			Tool configuration: #20256 ROCS hard rock corebarrel
			series 14 impregnated core bit
	08:34		Touch down at site
	08:35		Preparations to start drilling
	08:36		Lost power to drill, reset ROV soft fuse
			rebooted ROCS system
	08:39		Lost power to drill, reset ROV soft fuse
			rebooted ROCS system
	08:40		Troubleshooting ROV power issue
	09:15		Return to surface, due to ROV hydraulic leak.
			On deck, discovered ROV soft fuse default low setting
			reconfigured to 10amp
DIVE IV			28.08.2016
			Tool configuration: #20256 ROCS hard rock corebarrel
			series 14 impregnated core bit
	19:52		ROV in water
	19:57		Rotating drill head to warm manifold during dive
	21:19		Touch down at site
	21:33		Tool disconnected from drive spindle
			Positioned ROV to reconnect tool with drill spindle
	23:05		Start of run
	23:10		Started penetration, drill head position 1010 mm
			coring aprox. 300 rpm, drill fluid pump flow aprox 1.25 gpm
			penetration rate at 1 cm per minute in hard rock
	23:21		Penetration stop, drill head position 820 mm
			apparent core block, attempted remedy to break block
	23:30		Rapid advancement to drill head position of 800 mm

			no advancement deeper than 800 mm
	23:40		Set tool for core break and pulled back to stowed position
			return to surface
	01:12		No core recovered, possible slipped core through core lifter
DIVE V			29.08.2016
			Tool configuration: #20256 ROCS hard rock corebarrel
			series 14 impregnated core bit
	17:58		Deck check complete
	18:04		ROV in water
	19:21		Rotating drill head to warm hydraulic manifold
	20:19		ROV at depth, searching for landing site
	20:24		Touch down at site
	20:30		Drill head position 1005 mm, drill tool contact
	20:42		Drill head position 930 mm
	20:44		Drill head position 890 mm
	20:46		Drill head position 870 mm
	20:48		Drill head position 850 mm
	20:51		Drill head position 837 mm
	20:54		Drill head position 820 mm
	20:56		Drill head position 780 mm
	20:59		Drill head position 750 mm (drill fluid set point 500)
	21:02		Drill head position 728 mm
	21:04		Drill head position 710 mm
	21:06		Drill head position 684 mm
	21:08		Drill head position 648 mm
	21:10		Drill head position 620 mm
	21:16		522 mm
	21:18		500 mm
	21:22		429 mm
	21:29		347 mm
	21:33		310 mm
	21:38		280 mm
	21:44		248 mm

	21:48		200 mm end of run
	22:02:00 AM		
			Return to Surface
			Core Removed from core barrel
			670 mm Basalt 84% Core Recovery

Appendix B Samples and Sample Distribution

6.1.4 Geology

It should be noted that for Table 10 and the report sampling method grab does include sampled collected using the ROV manipulator and subsea basket and not the that hydraulic grab failed due to leaks.

Table 10: Summary of geological samples collected during the cruise. "Geochem ind of mineralization" is only based on point analysis with the HHXRF. Analysis using HHXRF cannot be regarded as representative for a larger volume.

Dive#	LogType Abr	Event_ID	Tag	ID	Sub-ID	Sampling site	Sampling method	XRF_ID	Geochem ind of mineralisation	Comment
1	GS	ROV#1GS1	LC-GS-10000-1	10000	1	LC	Grab	44		
1	GS	ROV#1GS2	LC-GS-10001-1	10001	1	LC	Grab	45	x	
1	GS	ROV#1GS3	LC-GS-10002-1	10002	1	LC	Grab	46-47	x	
1	GS	ROV#1GS4	LC-GS-10003-1	10003	1	LC	Grab	48-49		
1	GS	ROV#1GS5	LC-GS-10004-1	10004	1	LC	Grab	51-54	x	
2	SS	ROV#2SS1	LC-SS-10005-1	10005	1	LC	Scoop	57-59	x	

3	GS	ROV#3GS1	LC-GS-10006-0	10006	0	LC	Grab	65		1 large boulder parted in 29 pcs (LC-GS-10006-xx)
3	SS	ROV#3SS1	LC-SS-10007-1	10007	1	LC	Scoop			Brownish some dark matter. Many coars half consolidated. Filtered.
3	SS	ROV#3SS2	LC-SS-10008-1	10008	1	LC	Scoop			Dark (blackish). Coarse. More wet. Filtered. More clay
3	GS	ROV#3GS1	LC-GS-10006-1-10	10006	1-10	LC	Grab	66-88	x	Sub 1-10 is covered by this line
3	GS	ROV#3GS1	LC-GS-10006-11	10006	11	LC	Grab	89-91	x	
3	GS	ROV#3GS1	LC-GS-10006-12	10006	12	LC	Grab	92		
3	GS	ROV#3GS1	LC-GS-10006-13	10006	13	LC	Grab	93-95	x	
3	GS	ROV#3GS1	LC-GS-10006-14	10006	14	LC	Grab	96-97	x	
3	GS	ROV#3GS1	LC-GS-10006-15	10006	15	LC	Grab	98-100	x	
3	GS	ROV#3GS1	LC-GS-10006-16	10006	16	LC	Grab	101-102	x	
3	GS	ROV#3GS1	LC-GS-10006-17	10006	17	LC	Grab	103-104	x	
3	GS	ROV#3GS1	LC-GS-10006-18	10006	18	LC	Grab	105-113		

3	GS	ROV#3GS1	LC-GS-10006-19	10006	19	LC	Grab	114-115		CORE!
3	GS	ROV#3GS1	LC-GS-10006-20	10006	20	LC	Grab	116-120	x	
3	GS	ROV#3GS1	LC-GS-10006-21	10006	21	LC	Grab	121-122	x	
3	GS	ROV#3GS1	LC-GS-10006-22	10006	22	LC	Grab	123		
3	GS	ROV#3GS1	LC-GS-10006-23	10006	23	LC	Grab	124		
3	GS	ROV#3GS1	LC-GS-10006-24	10006	24	LC	Grab	125		
3	GS	ROV#3GS1	LC-GS-10006-25	10006	25	LC	Grab	126-130	x	
3	GS	ROV#3GS1	LC-GS-10006-26	10006	26	LC	Grab	131		
3	GS	ROV#3GS1	LC-GS-10006-27	10006	27	LC	Grab			
3	GS	ROV#3GS1	LC-GS-10006-28	10006	28	LC	Grab	132		
3	SAMLE	ROV#3SAMLENA	LC-SAMLE-10007-1	10007	1	LC	SAMLE			Collected from tank. Contains matter from all samples up to ROV#3Scoop2. Brownish sand

3	SAMLE	ROV#3SAMLENA	LC-SAMLE-10008-1	10008	1	LC	SAMLE			Collected from tank. Contains matter from all samples up to ROV#3Scoop2. Blackish sand
3	GS	ROV#3GS1	LC-GS-10009-1	10009	1	LC	Grab			Oxidized (not in freezer) mix from basket
3	GS	ROV#3GS1	LC-GS-10010-1	10010	1	LC	Grab			Oxidized (not in freezer) white from basket (Au)
3	GS	ROV#3GS1	LC-GS-10011-1	10011	1	LC	Grab			Oxidized (not in freezer) black from basket (Cu, Zn)
5	DC	ROV#5DC1	LC-DC-10012-1	10012	1	LC	Drillcore			
5	DC	ROV#5DC1	LC-DC-10013-1	10013	1	LC	Drillcore			
3	GS	ROV#3GS	LC-GS-10014-1	10014	1	LC	Grab	136		
3	GS	ROV#3GS	LC-GS-10014-2	10014	2	LC	Grab	138		
3	GS	ROV#3GS	LC-GS-10014-3	10014	3	LC	Grab	139-140	x	No photo, "rusty crust". Small pieces
3	GS	ROV#3GS	LC-GS-10014-4	10014	4	LC	Grab	141		Basalt brecchia, 10 cm thick oxidised crust
3	GS	ROV#3GS	LC-GS-10014-5	10014	5	LC	Grab	142		
3	GS	ROV#3GS	LC-GS-10014-6	10014	6	LC	Grab	143-144		

3	GS	ROV#3GS	LC-GS-10014-7	10014	7	LC	Grab	145	x	
3	GS	ROV#3GS	LC-GS-10014-8	10014	8	LC	Grab	146		
3	GS	ROV#3GS	LC-GS-10014-8	10014	8	LC	Grab	147		
3	GS	ROV#3GS	LC-GS-10014-9	10014	9	LC	Grab	148-150		XRF 148+149 in unoxidised brecchia, 150 in oxidised brecchia
3	GS	ROV#3GS	LC-GS-10014-10	10014	10	LC	Grab	151		
3	GS	ROV#3GS	LC-GS-10014-11	10014	11	LC	Grab	152-153		
3	GS	ROV#3GS	LC-GS-10014-12	10014	12	LC	Grab	154-155		
3	GS	ROV#3GS	LC-GS-10014-13	10014	13	LC	Grab	157-158		
6	DC	ROV#6DC1	LC-DC-10015-1	10015	1	LC	Drillcore			
6	DC	ROV#6DC1	LC-DC-10015-2	10015	2	LC	Drillcore			
3	GS	ROV#3GS	LC-GS-10014-14	10014	14	LC	Grab	161	x	
3	GS	ROV#3GS	LC-GS-10014-15	10014	15	LC	Grab	162-163		

3	GS	ROV#3GS	LC-GS-10014-16	10014	16	LC	Grab	164-165	x	Very dark, muddy, pyrite
3	GS	ROV#3GS	LC-GS-10014-16b	10014	16b	LC	Grab	214		Very dark, muddy, pyrite, no XRF
3	GS	ROV#3GS	LC-GS-10014-17	10014	17	LC	Grab	166	x	
3	GS	ROV#3GS	LC-GS-10014-18	10014	18	LC	Grab	167	x	
3	GS	ROV#3GS	LC-GS-10014-19	10014	19	LC	Grab	168-170		Black indecive (ubestemmelig) coat, course grained, quartz, oxidised
3	GS	ROV#3GS	LC-GS-10014-20	10014	20	LC	Grab	171-172		
3	GS	ROV#3GS	LC-GS-10014-21	10014	21	LC	Grab	173-175	x	
3	GS	ROV#3GS	LC-GS-10014-22	10014	22	LC	Grab	176-177		
3	GS	ROV#3GS	LC-GS-10015-1	10015	1	LC	Grab	180-183		White smoker W Mound. Ca+S in black matter. Scarce Cu, Zn, Au, Ag
3	GS	ROV#3GS	LC-GS-10015-2	10015	2	LC	Grab	184-187		White smoker W Mound. Ca+S in black matter. Scarce Cu, Zn, Au, Ag
3	GS	ROV#3GS	LC-GS-10015-3	10015	3	LC	Grab	188-191		White smoker W Mound. Ca+S in black matter. Scarce Cu, Zn, Au, Ag

3	GS	ROV#3GS	LC-GS-10015-4	10015	4	LC	Grab			White smoker W Mound. Ca+S in black matter. Scarce Cu, Zn, Au, Ag
3	GS	ROV#3GS	LC-GS-10016-1	10016	1	LC	Grab	192-193	x	
3	GS	ROV#3GS	LC-GS-10017-1	10017	1	LC	Grab	204(205)		Part of Black Smoker? Sponge like. Soaked with water greenish soft main matrix. Lots of stockworks covered in black matter. Oxidized red areas. Packed carefully and labelled "fragile". Two bags.
3	GS	ROV#3GS	LC-GS-10018-1	10018	1	LC	Grab	211	x	
3	GS	ROV#3GS	LC-GS-10019-1	10019	1	LC	Grab			
11	GS	ROV#11GS	MT-GS-10020-1	10020	1	MT	Grab	219		
11	GS	ROV#11GS	MT-GS-10021-1	10021	1	MT	Grab	223		
11	GS	ROV#11GS	MT-GS-10022-1	10022	1	MT	Grab	222		
12	SS	ROV#12SS	MT-SS-10023-1	10023	1	MT	Scoop			
12	SS	ROV#12SS	MT-SS-10023-2	10023	2	MT	Scoop			

12	GS	ROV#12GS	MT-GS-10024-1	10024	1	MT	Grab			
12	GS	ROV#12GS	MT-GS-10025-1	10025	1	MT	Grab			
14	GS	ROV#14GS	MT-GS-10026-1	10026	1	MT	Grab			
14	PC	ROV#14PC	MT-PC-10027-1	10027	1	MT	Push-core			
17	PC	ROV#17PC	MT-PC-10028-1	10028	1	MT	Push-core			PC10
17	PC	ROV#17PC	MT-PC-10029-1	10029	1	MT	Push-core			PC12
17	PC	ROV#17PC	MT-PC-10030-1	10030	1	MT	Push-core			PC9
17	PC	ROV#17PC	MT-PC-10031-1	10031	1	MT	Push-core			PC11
18	DC	ROV#18DC	MT-DC-10032-1	10032	1	MT	Drillcore			PL
19	PC	ROV#19PC	MT-PC-10033-1	10033	1	MT	Push-core			PC12
19	PC	ROV#19PC	MT-PC-10034-1	10034	1	MT	Push-core			PC4
19	PC	ROV#19PC	MT-PC-10035-1	10035	1	MT	Push-core			PC10

19	PC	ROV#19PC	MT-PC-10036-1	10036	1	MT	Push-core			PC15
19	PC	ROV#19PC	MT-PC-10037-1	10037	1	MT	Push-core			PC11
19	GS	ROV#19GS	MT-GS-10038-1	10038	1	MT	Grab	229-231		Possible diffuse seepage, rusty layer on altered basalt with py
21	GS	ROV#21GS	MT-GS-10039-1	10039	1	MT	Grab	234-237		
22	GC	ROV#22GC	MT-GC-10040-1	10040	1	MT	Gravity corer			

6.1.5 Biology

Table 11. Detailed list of push-core sample processing.

MarMine PUSH-CORE samples							
ROV	STATION	CORE	SAMPLE	SUBSAMPLES	LATITUDE	LONGITUDE	DEPTH
8	22	1	EXTRA SAMPLE: DID NOT USE	-	8157089,5	633621,3	2721,98
8	22	2	METAGENOMICS	-	8157077,9	633639,6	2721,93
8	22	3		-	8157069,9	633649,7	2721,94
8	22	4	METAGENOMICS	-	8157075,6	633637,7	2721,94
8	22	5	METAGENOMICS	ENV. (B3, C3, D3: All Layers)	8157082	633642,5	2721,99
8	22	6	ENV. (A3: All Layers)	-	8157075,1	633642,4	2721,95
8	22	7	ENV. (A2: All Layers)	-	8157071,7	633643,7	2721,99
8	22	8	ENV. (B2, C2, D2: All Layers)	-	8157088,9	633631,6	2721,94
8	22	9	MEIO (FORMALIN)	-	8157072,7	633642,2	2721,84
8	22	10	PUSH-CORE MALFUNCTION AT DEPTH	-	8157076,7	633640	2721,86
8	22	11	ENV. (A1, B1, C1, D1: All Layers)	-	8157074,2	633640,4	2721,84
8	22	12	MEIO (DESS)	-	8157071,9	633642,6	20:38:24
8	22	13	MEIO (DESS)	-	8157072,1	633641	2721,86
8	22	14	MEIO (DESS)	-	8157075,9	633641,3	19:40:48
8	22	15	MEIO (FORMALIN)	-	8157077	633641,7	20:09:36
8	22	16	MEIO (FORMALIN)	-	8157090,2	633631,1	2721,88

ROV	STATION	CORE	SAMPLE	SUBSAMPLES	LATITUDE	LONGITUDE	DEPTH
8	35	1	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	2	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	3	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	4	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	5	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	6	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	7	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	8	PUSH-CORES TIPPED OVER	-	-	-	-
8	35	9	MEIO (FORMALIN)	ENV. (A3, B3: All Layers)	8156960,6	633248,2	2682,66
8	35	10	METAGENOMICS	-	8156960,6	633248,2	2682,55
8	35	11	MEIO (FORMALIN)	ENV. (B1, C1, D1: All Layers)	8156960,6	633248,2	2682,65
8	35	12	METAGENOMICS	-	8156960,6	633248,2	2682,64
8	35	13	MEIO (FORMALIN)	ENV. (A2, B2: All Layers)	8156960,6	633248,2	2682,64
8	35	14	MEIO (DESS)	-	8156960,6	633248,2	2682,65
8	35	15	MEIO (DESS)	ENV. (A1: All Layers)	8156960,6	633248,2	2682,66
8	35	16	METAGENOMICS	-	?	?	?
ROV	STATION	CORE	SAMPLE	SUBSAMPLES	LATITUDE	LONGITUDE	DEPTH
8	38	1	MEIO (DESS)	ENV. (A1, B1: All Layers)	8156915,8	633286,5	2683,32
8	38	2	MEIO (DESS)	-	8156911	633277,2	2683,35
8	38	3	NOT DEPLOYED IN SEDIMENT	-	-	-	-
8	38	4	METAGENOMICS	-	8156913,6	633277,5	2683,47

8	38	5	MEIO (FORMALIN)	ENV. (A2, B2: All Layers)	8156916,9	633286,3	2683,29
8	38	6	MEIO (FORMALIN)	ENV. (A3, B3: All Layers)	8156913,6	633277,5	2683,37
8	38	7	METAGENOMICS	-	8156913,6	633277,5	2683,32
8	38	8	METAGENOMICS	-	8156915	633283,1	2683,32
ROV	STATION	CORE	SAMPLE	SUBSAMPLES	LATITUDE	LONGITUDE	DEPTH
10	48	9	PUSH-CORE MALFUNCTION AT DEPTH	-	-	-	-
10	48	10	PUSH-CORE MALFUNCTION AT DEPTH	-	-	-	-
10	48	11	MEIO (FORMALIN)	ENV. (A1, B1: All Layers)	8156506,3	633945,2	2827,69
10	48	12	PUSH-CORE MALFUNCTION AT DEPTH	-	-	-	-
10	48	13	PUSH-CORE MALFUNCTION AT DEPTH	-	-	-	-
10	48	14	MEIO (FORMALIN)	ENV. (A2, B2: All Layers)	8156506,3	633945,2	2827,8
10	48	15	PUSH-CORE MALFUNCTION AT DEPTH	-	-	-	-
10	48	16	PUSH-CORE MALFUNCTION AT DEPTH	-	-	-	-
14	48	9	METAGENOMICS	-	8156505	633945	2826
14	48	10	MEIO (DESS)	-	8156505	633945	2826
14	48	11	SAMPLE FELL OUT OF TUBE ON BOARD	-	8156505	633945	2826
14	48	12	MEIO (FORMALIN)	ENV. (A3, B3: All Layers)	8156505	633945	2826
14	48	13	NOT DEPLOYED (LEFT ON BOARD)	-	8156505	633945	2826
14	48	14	MEIO (DESS)	ENV. (C1, D1: All Layers)	8156505	633945	2826
14	48	15	METAGENOMICS	-	8156505	633945	2826
14	48	16	METAGENOMICS	-	8156505	633945	2826

Table 12. List of biological samples.

MarMine BIO samples							
Sample #	Location	ROV Dive	Site	Method	Content	Preservation	Notes
0	Loki's Castle	1		Suction sampler	sponge and shrimp	96% Ethanol	
1	Loki's Castle	3	1	Suction Sampler 1	coral like Sponge	96% Ethanol	Shared with UHI crew
2	Loki's Castle	3	1	Suction Sampler 1	Sponge	96% Ethanol	Shared with UHI crew
3	Loki's Castle	3	1	Suction Sampler 1	Sponge	96% Ethanol	Shared with UHI crew, very slimey
4	Loki's Castle	3	1	Suction Sampler 1	Sponge	96% Ethanol	Shared with UHI crew
5	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
6	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
7	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
8	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
9	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
10	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
11	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
12	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
13	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
14	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	

15	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
16	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
17	Loki's Castle	3		Rock_Scraping_on_deck	Sponge	96% Ethanol	
18	Loki's Castle	3		Rock_Scraping_on_deck	Bryozoan?	96% Ethanol	Soft, found on sulphide rock
19	Loki's Castle	3	1	Suction Sampler 1	Amphipod	96% Ethanol	Large amphipod
20	Loki's Castle	3	1	Suction Sampler 1	Amphipod	96% Ethanol	
21	Loki's Castle	3	1	Suction Sampler 1	Copepod	96% Ethanol	
22	Loki's Castle	3	1	Suction Sampler 1	Larva ?	96% Ethanol	
23	Loki's Castle	4		Suction Sampler 2	Isopod	96% Ethanol	
24	Loki's Castle	4		Suction Sampler 2	Shrimp larva	96% Ethanol	
25	Loki's Castle	4		Suction Sampler 2	Larva?	96% Ethanol	
26	Loki's Castle	4			Coral like sponge / Dry	96%Ethanol/ Dry	
27	Loki's Castle	4			2 x Round sponge	-20ºC	
28	Loki's Castle	4			3 x Round sponge	?	
29	Loki's Castle	4			1 sponge	dry	
30	Loki's Castle	4			1 sponge	?	
31	Mohn's Treasure	8		Manipulator - Rock 1	Mega	96% Ethanol	Mega
32	Mohn's Treasure	8		Manipulator - Rock 2	Mega	96% Ethanol	Mega
33	Mohn's Treasure	8		Manipulator - Rock 1	Mega	96% Ethanol	Mega
34	Mohn's Treasure	8	36	Scoop	250 µm	96% Ethanol	Macro
35	Mohn's Treasure	8	36	Scoop	500 µm	96% Ethanol	Macro

36	Mohn's Treasure	8	36	Scoop	1 mm	96% Ethanol	Macro
37	Mohn's Treasure	8	37	Scoop	250 µm	96% Ethanol	Macro
38	Mohn's Treasure	8	37	Scoop	500 µm	96% Ethanol	Macro
39	Mohn's Treasure	8	37	Scoop	1 mm	96% Ethanol	Macro
40	Mohn's Treasure	8	22	PC 13	0-2cm	Dess	Meio
41	Mohn's Treasure	8	22	PC 13	2-5 cm	Dess	Meio
42	Mohn's Treasure	8	22	PC 12	0-2cm	Dess	Meio
43	Mohn's Treasure	8	22	PC 12	2-5 cm	Dess	Meio
44	Mohn's Treasure	8	22	PC 14	0-2cm	Dess	Meio
45	Mohn's Treasure	8	22	PC 14	1-5cm	Dess	Meio
46	Mohn's Treasure	8	22	PC 09	0-1 cm	Formalin	Meio
47	Mohn's Treasure	8	22	PC 09	1-2 cm	Formalin	Meio
48	Mohn's Treasure	8	22	PC 09	2-5 cm	Formalin	Meio
49	Mohn's Treasure	8	22	PC16	0-1 cm	Formalin	Meio
50	Mohn's Treasure	8	22	PC16	1-2 cm	Formalin	Meio
51	Mohn's Treasure	8	22	PC16	2-5 cm	Formalin	Meio
52	Mohn's Treasure	8	22	PC15	0-1 cm	Formalin	Meio
53	Mohn's Treasure	8	22	PC15	1-2 cm	Formalin	Meio
54	Mohn's Treasure	8	22	PC15	2-5 cm	Formalin	Meio
55	Mohn's Treasure	8	35	PC15	0-2cm	Dess	Meio
56	Mohn's Treasure	8	35	PC15	2-5 cm	Dess	Meio
57	Mohn's Treasure	8	35	PC14	0-2cm	Dess	Meio
58	Mohn's Treasure	8	35	PC14	2-5 cm	Dess	Meio

59	Mohn's Treasure	8	35	PC11	0-1 cm	Formalin	Meio
60	Mohn's Treasure	8	35	PC11	1-2 cm	Formalin	Meio
61	Mohn's Treasure	8	35	PC11	2-5 cm	Formalin	Meio
62	Mohn's Treasure	8	35	PC13	0-1 cm	Formalin	Meio
63	Mohn's Treasure	8	35	PC13	1-2 cm	Formalin	Meio
64	Mohn's Treasure	8	35	PC13	2-5 cm	Formalin	Meio
65	Mohn's Treasure	8	35	PC09	0-1 cm	Formalin	Meio
66	Mohn's Treasure	8	35	PC09	1-2 cm	Formalin	Meio
67	Mohn's Treasure	8	35	PC09	2-5 cm	Formalin	Meio
68	Mohn's Treasure	8	38	PC02	0-2cm	Dess	Meio
69	Mohn's Treasure	8	38	PC02	2-5 cm	Dess	Meio
70	Mohn's Treasure	8	38	PC01	0-2cm	Dess	Meio
71	Mohn's Treasure	8	38	PC01	2-5 cm	Dess	Meio
72	Mohn's Treasure	8	38	PC05	0-1 cm	Formalin	Meio
73	Mohn's Treasure	8	38	PC05	1-2 cm	Formalin	Meio
74	Mohn's Treasure	8	38	PC05	2-5 cm	Formalin	Meio
75	Mohn's Treasure	8	38	PC06	0-1 cm	Formalin	Meio
76	Mohn's Treasure	8	38	PC06	1-2 cm	Formalin	Meio
77	Mohn's Treasure	8	38	PC06	2-5 cm	Formalin	Meio
78	Mohn's Treasure	8	35	PC10	1-3 cm	LifeGuard	Micro
79	Mohn's Treasure	8	35	PC12	1-3 cm	LifeGuard	Micro
80	Mohn's Treasure	8	35	PC16	1-3 cm	LifeGuard	Micro
81	Mohn's Treasure	8	38	PC ?	1-3 cm	LifeGuard	Micro

82	Mohn's Treasure	8	38	PC ?	10-15 cm	LifeGuard	Micro
83	Mohn's Treasure	8	22	PC05	0-15 cm	-20ºC	Meta
84	Mohn's Treasure	8	22	PC02	0-15 cm	-20ºC	Meta
85	Mohn's Treasure	8	22	PC04	0-15 cm	-20ºC	Meta
86	Mohn's Treasure	8	35	PC10	5 layers	-20ºC	Meta
87	Mohn's Treasure	8	35	PC16	5 layers	-20ºC	Meta
88	Mohn's Treasure	8	35	PC12	5 layers	-20ºC	Meta
89	Mohn's Treasure	8	38	PC07	5 layers	-20ºC	Meta
90	Mohn's Treasure	8	38	PC04	5 layers	-20ºC	Meta
91	Mohn's Treasure	8	38	PC08	5 layers	-20ºC	Meta
92	Mohn's Treasure	10	48	PC11	bottom 2 layers	-20ºC	Meta
93	Mohn's Treasure	10	48	PC14	bottom 2 layers	-20ºC	Meta
94	Mohn's Treasure	8	35	PC10	5 layers	-20ºC	Micro
95	Mohn's Treasure	8	35	PC16	5 layers	-20ºC	Micro
96	Mohn's Treasure	8	35	PC12	5 layers	-20ºC	Micro
97	Mohn's Treasure	8	38	PC04	5 layers	-20ºC	Micro
98	Mohn's Treasure	8	38	PC08	5 layers	-20ºC	Micro
99	Mohn's Treasure	8	38	PC07	5 layers	-20ºC	Micro
100	Mohn's Treasure	10	48	PC11	bottom 2 layers	-20ºC	Micro
101	Mohn's Treasure	10	48	PC14	bottom 2 layers	-20ºC	Micro
102	Mohn's Treasure	10	48	PC11	10-15 cm	LifeGuard	Micro
103	Mohn's Treasure	8	22	PC11		-20ºC	Env
104	Mohn's Treasure	8	22	PC07		-20ºC	Env

105	Mohn's Treasure	8	22	PC08		-20ºC	Env
106	Mohn's Treasure	8	22	PC05		-20ºC	Env
107	Mohn's Treasure	8	22	PC06		-20ºC	Env
108	Mohn's Treasure	8	35	PC15		-20ºC	Env
109	Mohn's Treasure	8	35	PC11		-20ºC	Env
110	Mohn's Treasure	8	35	PC13		-20ºC	Env
111	Mohn's Treasure	8	35	PC09		-20ºC	Env
112	Mohn's Treasure	8	38	PC05		-20ºC	Env
113	Mohn's Treasure	8	38	PC06		-20ºC	Env
114	Mohn's Treasure	8	38	PC01		-20ºC	Env
115	Mohn's Treasure	10	48	PC11		-20ºC	Env
116	Mohn's Treasure	10	48	PC14		-20ºC	Env
117	Mohn's Treasure	10	48	PC14	0-1 cm	formalin	Meio
118	Mohn's Treasure	10	48	PC14	1-2 cm	Formalin	Meio
119	Mohn's Treasure	10	48	PC14	2-5 cm	Formalin	Meio
120	Mohn's Treasure	10	48	PC11	0-1 cm	Formalin	Meio
121	Mohn's Treasure	10	48	PC11	1-2 cm	Formalin	Meio
122	Mohn's Treasure	10	48	PC11	2-5 cm	Formalin	Meio
123	Mohn's Treasure	9		Suction sampler		96% Ethanol	Mega
124	Mohn's Treasure	9		Suction sampler		96% Ethanol	Mega
125	Mohn's Treasure	9		Suction sampler		96% Ethanol	Mega
126	Mohn's Treasure	9		Scoop		96% Ethanol	Mega
127	Mohn's Treasure	9		Rock - manipulator		96% Ethanol	Mega

128	Mohn's Treasure	10	48	Scoop	250 µm	96% Ethanol	Macro
129	Mohn's Treasure	10	48	Scoop	500 µm	96% Ethanol	Macro
130	Mohn's Treasure	10	48	Scoop	1 mm	96% Ethanol	Macro
131	Mohn's Treasure	12		Manipulator - Rock		96% Ethanol	Mega
132	Mohn's Treasure	8		Manipulator - Rock 2		96% Ethanol	Mega
133	Mohn's Treasure	10		Suction sampler		96% Ethanol	Holothurians
134	Mohn's Treasure	11		Suction sampler		96% Ethanol	Sponges
135	Mohn's Treasure	11		Suction sampler		96% Ethanol	Mix mega/macro
136	Mohn's Treasure	14	48	PC16	0-1 cm	LifeGuard	Micro
137	Mohn's Treasure	14	48	PC16	5 layers	-20ºC	Meta
138	Mohn's Treasure	14	48	PC16	5 layers	-20ºC	Micro
139	Mohn's Treasure	14	48	PC16	10-15 cm	LifeGuard	Micro
140	Mohn's Treasure	14	48	PC09	5 layers	-20ºC	Meta
141	Mohn's Treasure	14	48	PC09	5 layers	-20ºC	Micro
142	Mohn's Treasure	14	48	Manipulator	Crinoids	-20ºC	SIA
143	Mohn's Treasure	14	48	PC15	5 layers	-20ºC	Meta
144	Mohn's Treasure	14	48	PC15	5 layers	-20ºC	Micro
145	Mohn's Treasure	14	48	PC12		-20ºC	Env
146	Mohn's Treasure	14	48	PC14		-20ºC	Env
147	Mohn's Treasure	14	48	Manipulator	Crinoids	Formalin	Mega
148	Mohn's Treasure	14	48	PC10	0-2 cm	Dess	Meio
149	Mohn's Treasure	14	48	PC10	2-5 cm	Dess	Meio
150	Mohn's Treasure	14	48	PC14	0-2 cm	Dess	Meio

151	Mohn's Treasure	14	48	PC14	2-5 cm	Dess	Meio
152	Mohn's Treasure	14	48	PC12	0-1 cm	Formalin	Meio
153	Mohn's Treasure	14	48	PC12	1-2 cm	Formalin	Meio
154	Mohn's Treasure	14	48	PC12	2-5 cm	Formalin	Meio
155	Mohn's Treasure	14	48	Rock	Sponge	96% Ethanol	Mega, from rock
156	Mohn's Treasure	14	48	Manipulator	Polychaete	96% Ethanol molecular grade	Mega
157	Mohn's Treasure	14	48	Manipulator	Crinoid	96% Ethanol molecular grade	Mega
158	Mohn's Treasure	14	48	Manipulator	Crinoid	96% Ethanol molecular grade	Mega
159	Mohn's Treasure	14	48	Manipulator	Crinoid	96% Ethanol molecular grade	Mega
160	Mohn's Treasure	14	48	Manipulator	Crinoid	96% Ethanol molecular grade	Mega
161	Mohn's Treasure	14	48	Manipulator	Hydrozoa	96% Ethanol molecular grade	Mega. Epibiont of crinoid
162	Mohn's Treasure	14	48	Manipulator	Sponge	96% Ethanol molecular grade	Mega. Collected with crinoids
163	Mohn's Treasure	14	48	Manipulator	Anemones	96% Ethanol molecular grade	Mega. Epibiont of crinoid.
164	Mohn's Treasure	14	48	Manipulator	Crinoid	96% Ethanol molecular grade	Mega
165	Mohn's Treasure	14	48	Manipulator	Serpulid	96% Ethanol molecular grade	Mega. Epibiont of crinoid

166	Mohn's Treasure	14	48	Manipulator	Hydrozoa	96% Ethanol molecular grade	Mega. Epibiont of crinoid.
167	Mohn's Treasure	11		Suction sampler	Dead Pectinidae shells		Mega
168	Mohn's Treasure	11		Suction sampler	Dead echinoids		Mega
169	Mohn's Treasure	9		Manipulator - Rock	Sponges	96% Ethanol	Mega
170	Mohn's Treasure	9		Suction sampler	Shrimp + Asteroid	96% Ethanol	Mega
171	Mohn's Treasure	22	S13a	Suction sampler	Holothurian	96% Ethanol molecular grade	Mega
172	Mohn's Treasure	22	S13a	Suction sampler	Holothurian	96% Ethanol molecular grade	Mega
173	Mohn's Treasure	22	S13a	Suction sampler	Holothurian	96% Ethanol molecular grade	Mega
174	Mohn's Treasure	22	S13a	Suction sampler	Holothurian	96% Ethanol molecular grade	Mega
175	Mohn's Treasure	22	S13a	Suction sampler	Holothurian	96% Ethanol molecular grade	Mega
176	Mohn's Treasure	22	S13a	Suction sampler	5xholuthurian	-20ºC	SIA
177	Mohn's Treasure	22	S13a	Suction sampler	9xholothurian	Formalin	Mega

Appendix C Cruise GIS documentation

During the cruise, collected data was processed and imported to the onboard GIS-system as fast as possible, in order to gain an overview of the operations, and plan further missions.

The data was imported in ArcMap 10.4 using a structure defined by the survey team for a fast and easy workflow. This structure divided the data into two categories: raster data (bathymetry etc.) and vector data (waypoints, events etc.), with additional sub-categories. Rather than sorting the data by location or area, the data is sorted by dive numbers for easy cross-reference with logs and other notes taken during the operations.

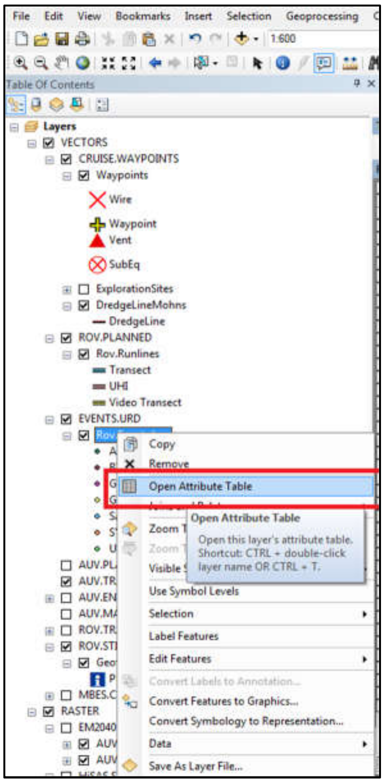
The final deliverable at the end of the cruise comes in two formats:

- An ESRI map package file (.mpk), which is an easily distributable file format, because it contains the map project and all the necessary data to open and view the GIS. It should be noted that map packages do not work with versions prior to ArcMap 10.
- The actual working folders and files that were used to build the GIS, but that are less suited for easy distribution.

1.1 Short guide to navigating the GIS

Following is a very brief description for navigating the GIS to display and obtain the most important information embedded in the data.

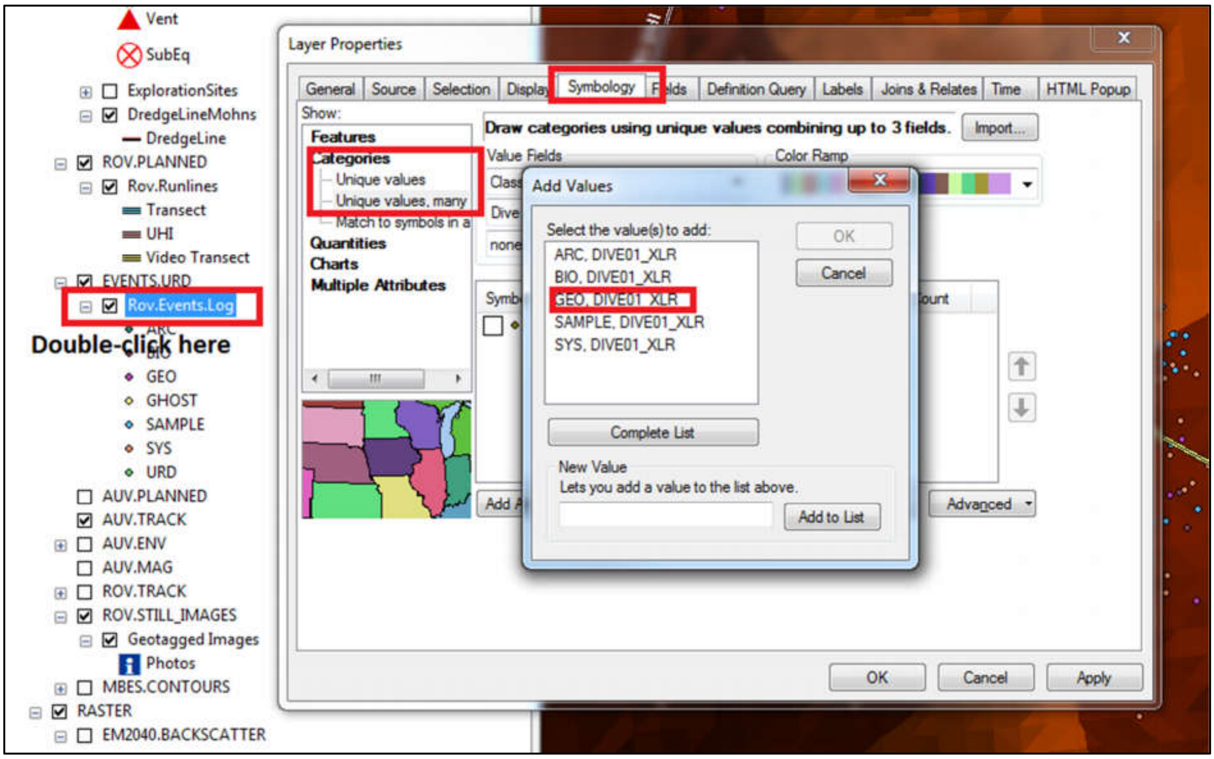
Layers: On the left side, all layers are shown in the layers panel and are easily toggled on or off by using the check-boxes. By expanding the layers using the + or – symbols, the user is able to choose between multiple types of data where possible (this applies mostly to the AUV dives where raster data has been processed to several resolutions).



Attribute tables: For point data, the complete attribute table can be viewed by right-clicking on the layer on the tab to the left and then choosing *Open attribute table*. All available information for the chosen layer is then displayed as a table and can be exported as a .txt file, which can be opened in e.g Excel.

Event Logs: The logged ROV events are found in the Events.URD layer. By default, the data is displayed by type of observation (BIO, GEO, SAMPLE etc). In order to only display certain types of events, the properties have to be changed. To do so, double-click the layer called ROV.Events.Log, found by expanding the Events.URD layer. In the window that pops up go to the *Symbology* tab and in the left side click *Categories.* Click "*Unique Values*". In the center of the window click the event you want to hide and then click *remove.* If you want to add an event click on the drop-down menu and choose from which category you wish to add the event from. Then click *add values* and choose the fields you wish to add. Click Ok.

In order to add events with multiple attributes you have to click "*unique values, many fields*" in the tab on the left side. In the uppermost dropdown menu, click the first category, for example "Class". In the next drop-down menu choose the second category, for example "Dive", and then click *add values.* You can now choose from a list of events that occur for your specific categories. For example: BIO, DIVE will give you the option to only show events that



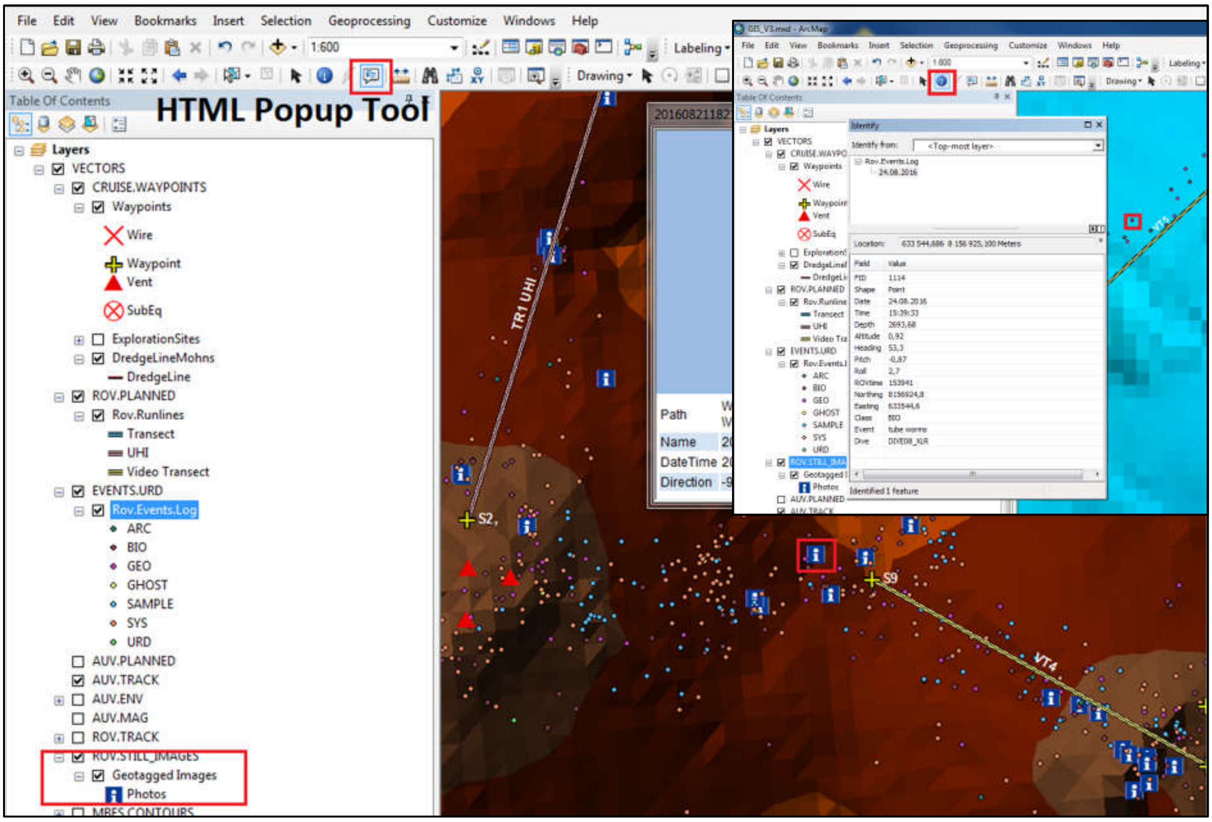
are logged as BIO for specific dive numbers (f.ex BIO events in Dive 8). Click *Complete list* to show all matching events in the list. Click the events you want to add and click OK.

If you don't know where the events are on the map or you can't find them, right-click on the layer and choose *Zoom to layer*.

To change the properties of the symbol that is used for the point, double-click the symbol in the layer window on the left side. The size, color and type of symbol can then be customized.

Geotagged photos

A selection of photos has been added to the GIS system and their locations on the map can be seen as on the map when toggling the layer ON. In order to view the photo associated with the location, click on the HTML Popup tool in the taskbar (see image) and then click on the desired point on the map. The photo and some metadata will be displayed.



Point information: If you wish to see the available information for a given point, this can be done by enabling the *Identify*-tool on the taskbar and then clicking on the desired point. A windows will pop up displaying all available information for this point. The displayed information is the same information that can also be found in the attribute table, however using the Identify tool is a much faster way to obtain information for a particular point.

To view the location in a different format (e.g decimal degrees) click the little arrow next to the location square and then choose your preferred format.