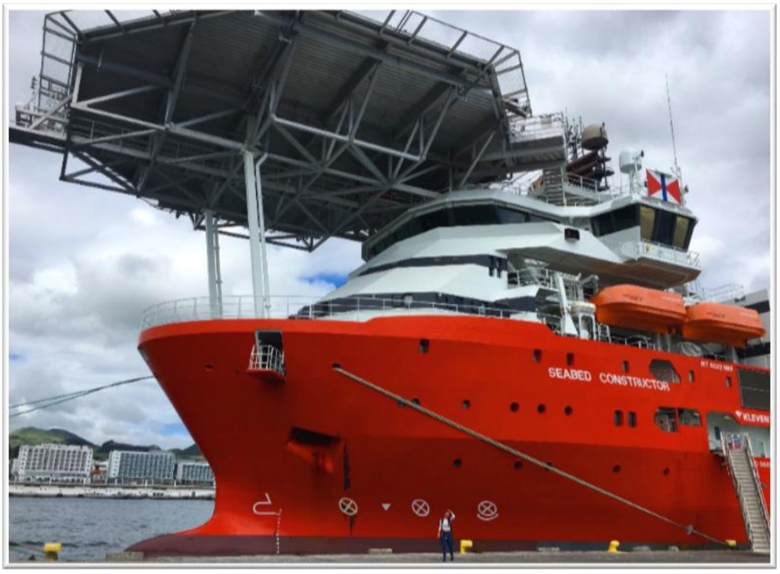

Cruise Report

Mid-Atlantic Ridge 44° N

August – September 2017

NTNU

OCEAN INFINITY

SWIRE SEABED

ISSN 2535-2520 - NTNU Cruise Report

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Summary:

This cruise is a result of successful collaboration between NTNU Ocean pilot project Deep Sea Mining and Ocean Infinity, ocean exploration company. It took place at the Northern part of Mid-Atlantic ridge in August - September 2017. From the board of Seabed Constructor, a multi-purpose offshore vessel, a total area of 20 km by 0.6 km was surveyed with the use of an autonomous underwater vehicle (AUV). Along with AUV data, we collected two rock samples and video footage from the axial volcanic ridge (AVR) using a remotely operated vehicle (ROV).

Cruise objectives were:

- Collect data and samples from the mid-ocean ridge rift valley;
- Test new technology: multiple AUV survey;
- Knowledge and experience exchange: learn more about technological advances in the industry and their approaches for future collaborations in similar kinds of operations.

The data acquired during the cruise include high-resolution bathymetry; acoustic backscatter images; sub-bottom profiler cross-sections; magnetic field measurements (3 components); water column measurements (temperature, conductivity, sound velocity, and hydrostatic pressure). PhD and postdoc candidates of Deep Sea Mining pilot at NTNU will use these data for their research.

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Executive Summary

August to September 2017, NTNU in collaboration with Ocean Infinity (OI) successfully conducted a survey at the Northern part of Mid-Atlantic ridge (MAR) around 44° N latitude. Survey was operated from the board of Seabed Constructor, a multi-purpose offshore vessel, and has covered an area of 20 km by 0.6 km. Four main lines were completed together with three cross-lines. Along with AUV data, we collected two rock samples from the axial volcanic ridge (AVR) using a remotely operated vehicle (ROV). Seafloor samples will be used to constrain interpretations of the remotely acquired data.

The main target of the survey was a mid-ocean ridge rift valley – spreading center of the Atlantic Ocean. The cruise was of geological/geophysical nature and pursued following objectives:

- Collect data and samples from the mid-ocean ridge;
- Test new technology: multiple AUV survey;
- Knowledge and experience exchange: learn more about the industrial approach in ocean floor surveying and current technological developments for future collaborations in this kind of operations.

Although due to technical challenges, the survey did not involve several AUVs running simultaneously as it was planned before the cruise, having several AUVs onboard allowed us to learn more about the technology, and to analyze possibilities for the future operations, which will be discussed in the chapter 2.5.

Cruise Participants

Ocean Infinity carried out mobilization, calibration, and data acquisition. More information on these procedures, other technical details, and the staff involved can be found in separate reports [10, 11]. This report covers scientific part of the cruise, which NTNU was responsible for. There was only one university representative onboard during the mission. Nonetheless, this project, everything from the idea to its implementation, involved more people than that – all listed below.

Table 1. Cruise participants.

Full Name	Organization	Role Onboard/Onshore	E-mail
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Acknowledgements

Being a result of shared curiosity and passion towards the ocean depths and technology, we believe that this collaboration is a great example of successful dialogue between "industry" and academia, and what can be achieved in such symbiosis. We are very grateful to Ocean Infinity and Swire Seabed for taking us onboard for this operation, and being perfect hosts.

Huge thanks to NTNU team for providing me with an honorable opportunity to represent the University in this project. It was a challenging yet incredibly interesting project that pushed my professional and personal development a lot. Thank you!

Health, Safety, and Environment

The cruise was completed without any accidents. It took place in the end of August and September at 43-44°N latitudes. This time of year weather conditions are moderate in the area, an average wave height and wind speed were always within operational limits.

Host vessel and the companies represented onboard, all have very high standards in HSE. Fieldwork was carried out in compliancy with the HSE regulations defined by Ocean Infinity and Swire Seabed. NTNU representative onboard followed all HSE regulations, including the use of personal protection equipment (PPE). Risk analysis was performed before the cruise according to NTNU regulations. All personnel who had not sailed on the vessel within the last 6 months had a compulsory vessel induction and familiarization tour.

1 Background

Research cruises are one of the key activities in ocean investigations. However, due to high costs and risks involved, it is also a very rare opportunity for researchers to collect data, especially in deep parts of the ocean. It is very fortunate, when industry and academia come together for contributing to ocean research. This cruise was a result of successful collaboration between NTNU Ocean pilot project Deep Sea Mining (DSM pilot) and Ocean Infinity, ocean exploration company.

DSM pilot is a multidisciplinary project developing new solutions for evaluation, exploration and extraction of seafloor minerals under societal responsibility for the environment and the common heritage of mankind [3]. There are three main types of seafloor mineral deposits: polymetallic nodules, ferromanganese cobalt crusts, and seafloor massive sulfides (SMS). Among all these commodities, DSM pilot focuses on SMS deposits that are associated with hydrothermal venting at mid-ocean ridge settings. Therefore, there is a strong interest towards mid-ocean ridge systems, which, nevertheless, is not limited to their resource potential. There is also a huge fundamental scientific interest toward mid-ocean ridge systems, and this cruise was aimed to serve to that too.

With water depth of more than 500 meters (744 – 3169 m in this case), ship-borne water surface methods become not sufficient for the clear target investigations. An AUV proves to be an ideal platform for such purposes, especially considering that it allows carrying out different types of data acquisition simultaneously (e.g. magnetic, sonar, water chemistry etc.).

1.1 Survey area

The target of investigations was located at the Northern part of MAR rift valley. Survey area was a 20 km long x 0.6 km wide box oriented perpendicular to the ridge axis (see table 2). This section of mid-ocean ridge has reported hydrothermal activity manifestations – yellow and red points on the map (see fig. 1).

Table 2. Survey general information.

Survey Area	Northern Mid-Atlantic Ridge
Coordinates	Start: 28°32,55'W - 43°58,91'N (28,5425°W - 43,9819°N) End: 28°17,85'W - 43°58,72'N (28,2974°W - 43,9550°N)
Box Dimensions	20 km L × 0.6 km W → 4 main lines + 3 cross-lines
Survey Type	Scientific Investigation – Geology

The choice of a survey area was based on:

- Information availability. Background information like at least large-scale bathymetric maps were required for the cruise planning.

- Exploration aspect. We could not go blind, but we did not want to use this unique opportunity to survey over well-studied parts of the MAR either. The ocean is too unexplored to waste possibilities like that on scrutinizing only certain patches.

- Hydrothermal activity. Being a part of Deep Sea Mining research group, we could not help but choose a profile in a hydrothermally active segment. Even though this part is not the most active part of the MAR, it still has some indications of hydrothermal venting (see fig. 1) along it.

- Geological diversity. After narrowing down our search, we opted for the most diverse in morphological, petrological, and magnetic sense profile. We based our assumptions on the information we found in Nuno Mendes Simao's master thesis [10] (see fig. 4).

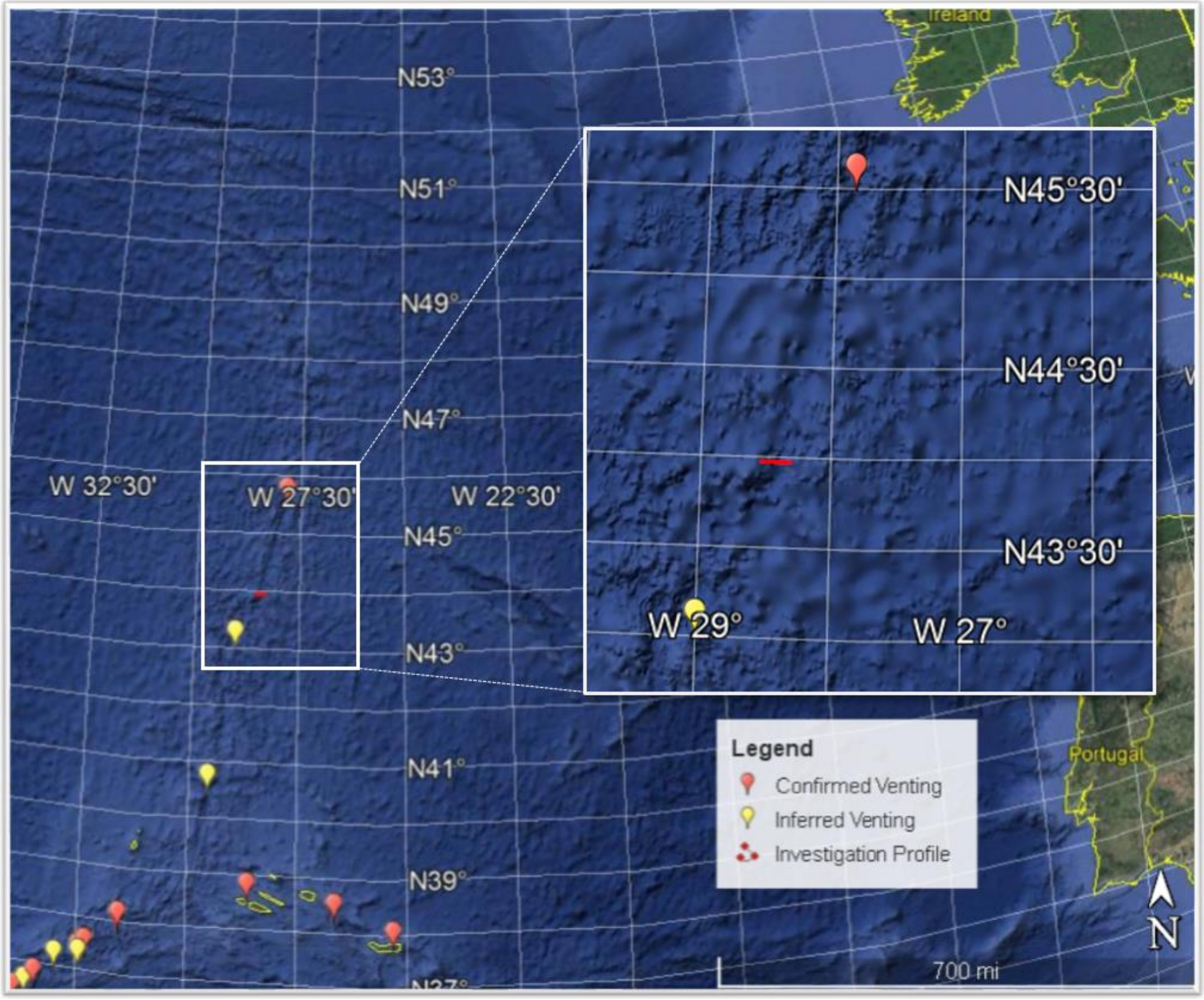

Fig. 1. Survey overview map (Source: Google Earth).

1.2 Scientific Background and Rationale

Mid-ocean ridge setting exhibits a wide range of interesting geological features and morphology, from recent volcanism and tectonism to hydrothermally modified seafloor, and sedimented seafloor. It is here the ocean crust is being created as the plates separate at rates from centimeters (ultra-slow spreading ridges) to 10s of cm/yr. (ultra-fast spreading ridges). Basaltic magma rises to the seafloor through the fractures created by tensional stress of tectonic plate pull, producing enormous volcanic eruptions of basalt, and building the longest mountain chain in the world (fig. 2). Despite being such a prominent feature on our planet, much of Mid-Ocean Ridge remains unexplored, which is why any contribution is very important and meaningful.

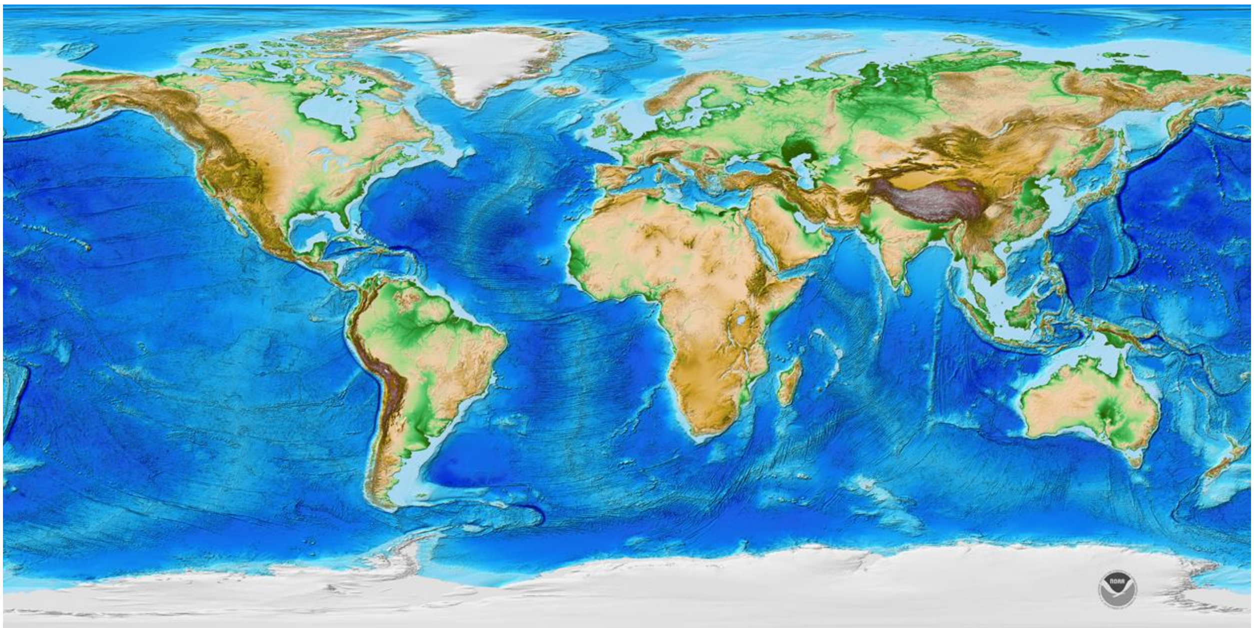

Fig. 2. World topographic map [8].

With the discovery of mineral resources in deep unexplored parts of the ocean, like the mid-ocean ridge, ocean exploration and research started to move. More than 300 sites of hydrothermal activity and seafloor mineralization are known on the ocean floor [7]. Expeditions with the potential of exploring valuable resources have raised more interest among governments and businesses over the last decades and become a reliable tool to open a window through which we can study mid-ocean ridges. One of the motivations of this cruise was to better understand a mid-ocean ridge setting as in basic research question, and explore it in the applied science context. Potentially, three main types of marine mineral deposits have economic interest for mining: polymetallic nodules, ferromanganese cobalt crusts, and Seafloor Massive Sulfides (SMS). The SMS deposits can be found in mid-ocean ridge setting and are dependent on hydrothermal activity (see global distribution in fig. 3).

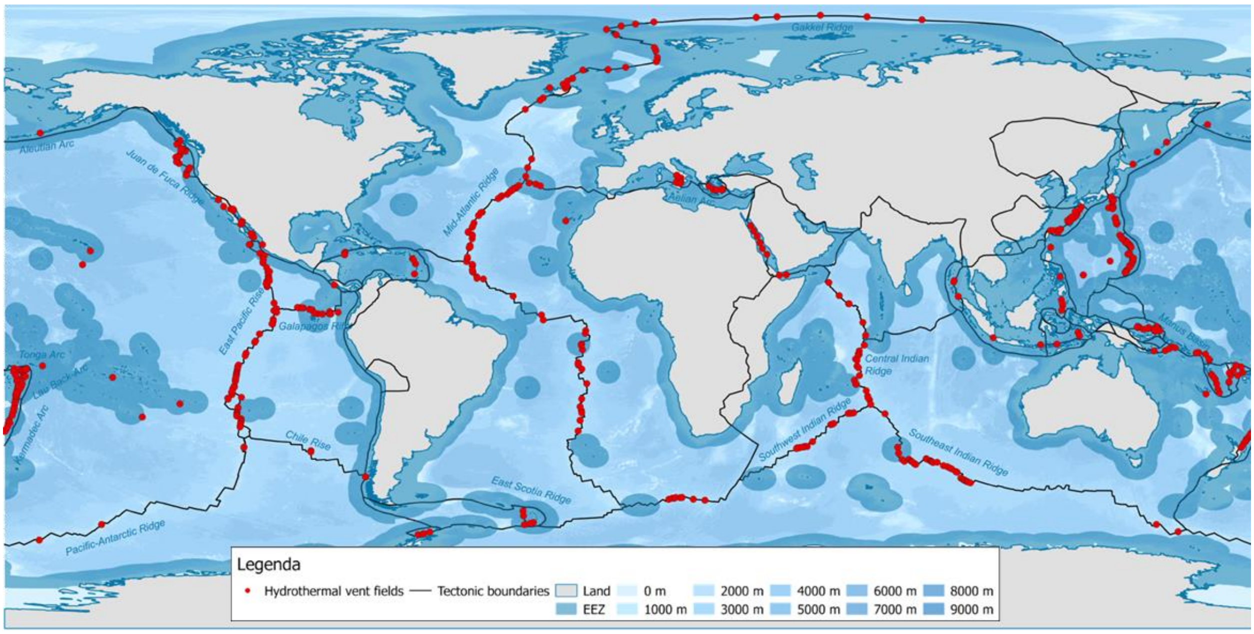

Fig. 3. Hydrothermal fields global distribution.

Mid-Atlantic Ridge is classified as a slow-spreading ridge having spreading half-rate around 2-4 cm/year. For decades, it was widely believed that slow-spreading ridges do not have hydrothermal activity. The heat source - magma chambers, more local and deeper, were thought not to allow the hottest fluids to reach surface. In 1985, the discovery of two fields of black smokes on the MAR showed that hot hydrothermal activity was a general phenomenon on the ridges. Since then, many discoveries have been made. The combination of topographical and thermal effects often focuses hydrothermal convections on high, hot spots of volcanic segments. However, as sites are known at the base and summit of the walls of the axial rift, their position is therefore not only controlled by volcanic activity, but also tectonics [13]. Therefore, it is important to understand and decipher the morphology across the whole width of mid-ocean ridge rift valley.

Acquisition of detailed bathymetry is required for morphological analysis of mid-ocean ridge environment. This data will help us get better understanding of the mid-ocean ridge system and analyze processes potentially leading to formation of mineral deposits based on surface expression.

High-resolution (1.5 m bin grid) near bottom acquisition – sonar imaging combined with magnetic field measurements – provides a powerful tool for us to examine morphology and structure of the ocean floor allowing to infer the processes of its formation and evolution. This data will also be used for structural concept models building that will be potentially used in geophysical modeling.

Side-scan and sub-bottom profiler data will be helpful in understanding rock type distribution, and in sediment variation analysis.

As seen in fig. 4, the chosen segment of the rift valley is a seismically active segment, and in fact, one of the most active ones. Black dots in the figure represent AuH seismicity recorded by SIRENA array with at least four hydrophones. This work [10] also shows that the western flank of the described rift valley exhibits a core complex. They believe that seismic events hypocenters can be situated along the detachment fault that could reveal this core complex.

Magnetic data from the core complex area is extremely important as it is expected to be very diverse along the profile and will contribute to our understanding of the detachment fault related systems. Along with acoustic information, this data will provide us fundamental knowledge about detachment fault related systems.

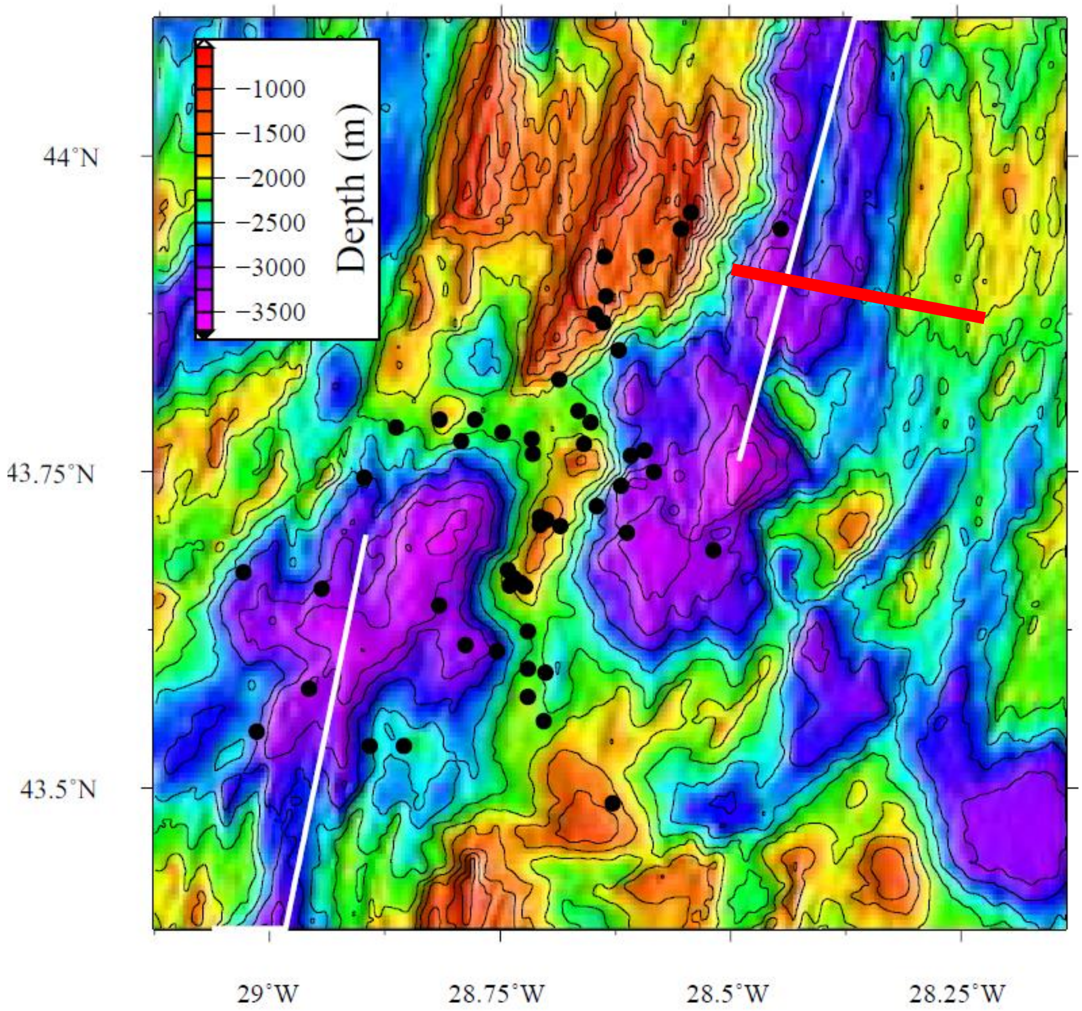

Fig. 4. Bathymetric map of the north Azores part of the MAR segment.
Black dots – seismic events; white lines – MAR segmentation according to Maia et al. (2007); red line – approximate location of the survey line [10].

There are similarities between Norwegian part of the rift valley and the one under investigation. Thus, we will be able to use this data as an analogue for the Norwegian case studies (core complex morphologically similar to the one in Norwegian waters). However, differences between these two settings (Norwegian part is an ultra-slow spreading system in contrast to the faster southern part) can complement our knowledge about the mid-ocean ridge setting in general.

2 Technology

With water depth of more than 2 km on average and topography as rough as 2.5 km elevation difference along the profile, only high-tech solutions could allow us to fulfill our scientific goals. For this cruise, we had an opportunity to use the finest equipment existing on the market. The latest model of Hugin AUV was the platform we used to investigate the ridge valley. Some technical characteristics of an AUV and other equipment are presented below. More information about these items can be found in the referred webpages.

2.1 Vessels

2.1.1 Ship

Seabed Constructor (fig. 5) is a multi-purpose offshore vessel owned by Swire Seabed and currently rented by Ocean Infinity. It is equipped with the most advanced vehicles and sensors currently available in the market.

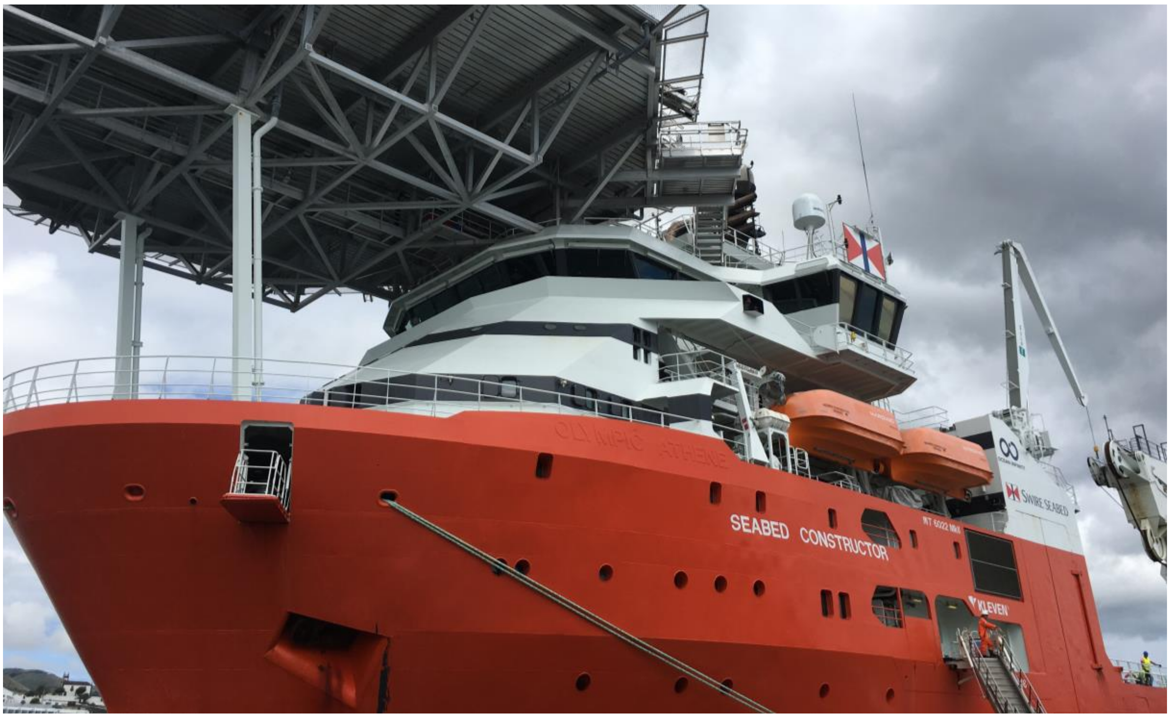

Fig. 5. Seabed Constructor. Photo: Anna Lim.

Table 3. Technical characteristics of the ship [4].

Length and Breadth	115.4 m × 22 m
Deck Space	1300 m^2
Moonpool	7.2 m × 7.2 m
Dynamic Positioning	Kongsberg DP2 Class System
USBL System	1 x Kongsberg HiPAP 502 1 x Kongsberg HiPAP 102
Main winch	250 t / 12 m radius
Accommodation	102 PAX
Helideck	26.1 m diameter (D-value) 16 t.

2.1.2 ROV

ROV, or remotely operated vehicle, was used for sound-velocity logging and collection of samples from the mid-ocean ridge crest (fig. 6).

Fig. 6. Kystdesign Supporter work class ROV. Photo source: [5].

Table 4. Technical characteristics of the ROV [5].

Model	Kystdesign Supporter
Depth Rating	6000 m
Dimensions (L×W×H)	2.75 × 1.7 × 1.65 m
Payload	400 kg
Through Frame Lift Capacity	3000 kg
Power	115Kw/150Hp

2.1.3 USV

Unmanned Surface Vehicle can be used for a wide range of services. In this cruise, they were planned to be used for accompanying AUVs to ensure constant and stable communication in case of using of several AUVs.

Fig. 7. C-Worker 7 Ocean Surveying ASV. Photo: Anna Lim.

Table 5. Technical characteristics of a USV. Source: [6].

Model	C-Worker 7 Ocean Surveying ASV
Length	7.22 m
Fuel Capacity	1200 L
Speed	2 kn (single engine running) 8 kn (both engines running)
Telemetry	Rajant Breadcrumb Multi-Frequency Mesh; Radio HiPAP 502 Receiver; HiPAP 102 Optional
Endurance	140 hours at 4 kn

2.1.4 AUV

The Kongsberg HUGIN 6000 AUV used for the survey is capable of performing high-speed surveys with navigation and payload data up to a depth of 6000 m. It has a hydrodynamic shape enabling a compact physical size while maintaining the ability to carry several types of sensors for synchronized and simultaneous operation. The payload used on the AUV is described in Table N.

Fig. 8. HUGIN AUVs. Photo: Anna Lim.

Table 6. Technical characteristics of an AUV [1].

Model	Kongsberg HUGIN 6000
Depth Rating	6000 m
Dimensions	6.4 m x 0.75 m (L x D)
Weight	1550 kg
Weight in water	Neutrally buoyant
Vehicle speed	2-6 knots
Energy	Pressure tolerant lithium polymer battery
Charge time	5-8 hours with single battery. *Ocean Infinity has two per unit and batteries can be swapped in 2-3 hours on deck time
Endurance	Up to 74 hours
Navigation	Kongsberg NavP aided Internal Navigation System (AINS) with Honeywell HG9900 Inertial Measurement Unit Acoustic positioning using cNODE and HiPAP Novatel GPS Forward Looking Sonar with advanced terrain following and collision avoidance Broadband 300 kHz Doppler velocity log Paroscientific Digiquartz depth sensor Underwater transponder positioning (UTP)
Communications	cNODE acoustic command and data link Wi-Fi Iridium UHF radio link

2.2 Geophysical equipment

When it comes to remote sensing in the ocean, acoustic methods are the most widely used since the first attempts to shed light on the depth below sea surface. Echo sounding is still the dominant method for bathymetric surveys, which we used along with other modifications of sonars: side-scan sonar, sub-bottom profiler (see table 7). Magnetometry is another method that is widely used for studying mid-ocean ridge environments. Magnetic anomalies interpretation allows determining of the seafloor age and the seafloor spreading rates.

Table 7. AUV payload sensors used during the cruise.

Sensor	**Model**
Multibeam Echosounder (MBES)	Kongsberg EM2040
Sidescan Sonar (SSS)	EdgeTech 2200 FS-AU
Sub-bottom Profiler	EdgeTech 2200 FS-AU
Magnetometer (SCM)	Ocean Floor Geophysics (OFG)
Doppler Velocity Log (DVL)	Teledyne RDI 300 MHN
Sound Velocity and CTD Sensor	SAIV STD/CTD SD204

2.3 Geodetic parameters

For the duration of the survey, the following geodetic parameters were used.

Table 8. Geodetic parameters.

Global Positioning System Geodetic Parameters	
Datum	International Terrestrial Reference Frame 2008 (ITRF 2008)
Spheroid	GPS80
Semi-major axis	6 378 137.000 m
Semi-minor axis	6 356 752. 314 140 347 m
Projection Parameters	
Grid projection	Universal Transverse Mercator
UTM Zone	26 N

Central meridian	27° 00’ 00’’ West
Latitude of Origin	00° 00’ 00’’ (Equator)
False Easting	500 000 m
False Northing	0 m
Scale Factor on Central Meridian	0.9996
Units	Metre

For vertical referencing, the GNSS data from the two Starpack GNSS systems were constantly logged using the NaviPac navigation and data acquisition software. The NaviEdit software was then used to reduce the ellipsoidal heights to water level using measurements from the vessels altitude sensor and vessel draft. These heights were adjusted to mean sea surface (MSS) using the global DTU10 mathematical model of the earth [11].

2.4 Survey layout and parameters

The primary goal of the survey was to collect data over the whole length of the mid-ocean ridge valley, which in this case was around 18 km long. We added 1.5 km at the western flank, and 0.5 km at the eastern to get the whole picture of the mid-ocean ridge setting in details. As for width of the survey box, we had to consider many different very tightly interconnected factors to fulfill our goal of both high spatial resolution and good coverage in very limited period. All these factors and dependent parameters are illustrated in figure 9.

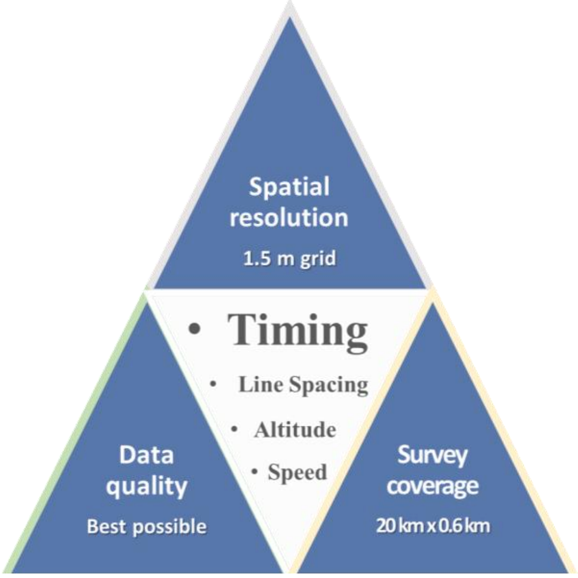

Fig. 9. Survey parameter-defining factors.

Horizontal and vertical resolution are defined by survey altitude and distance between the lines that should allow stitching separate lines into a map. Coverage mainly depends on the flight speed, which in turn is set based on topography and equipment settings such as ping rate, recording frequency etc.

Survey timing is the trickiest of all, as not only it depends on technical parameters and technologies reliability in general, but on weather conditions and other external factors.

Due to some of these external reasons, ultimately, we were allocated only 24 hours for the whole mission. This number governs everything else, so we had to adjust all parameters to fit this time frame (see table 9).

Table 9. Survey parameters and expected deliverables list.

Survey Parameters	Time frame	24 hours
	Range	150 – 300 m
	Line spacing:	140 m (~20% overlap)
	Altitude:	70 m
	Speed:	1.8 m/s
	MBES Beam angle:	55° Port 55° Stbd (110)
	Swath	180 m
	MBES Frequency:	400 kHz
	SSS Frequency:	75 kHz
	SSS Approx Range	350 m
Deliverables	• 1.5 m grid xyz of acquired bathymetry • Raw and compensated magnetic data from SCM • Raw and processed SBP data • SSS mosaic • Point data from CTD • AUV navi data (time, dept, alt, hdg, pitch, roll, speed) • Survey report • Surveyors log • Mobilization report (sensor offsets for all vehicles).	

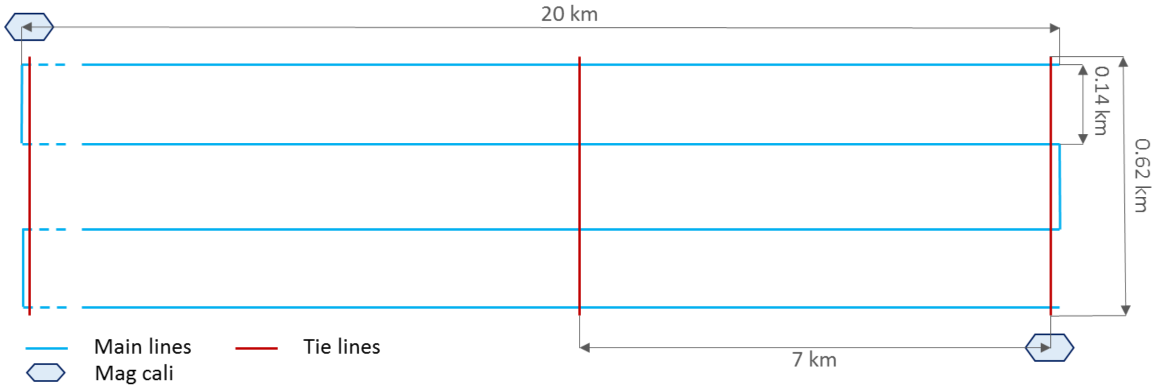

Fig. 10. Survey line plan.

2.5 Multi-AUV survey idea and it's challenges

Originally, our goals included testing out new technology, namely multiple AUV survey. We expected to use several AUVs simultaneously in order to cover bigger swath, and test the influence of simultaneous magnetic measurements on processing results improvement. Even though this plan has failed, it cannot be called a failure – we still got to learn a lot about such operations. We will discuss challenges associated with this kind of operation and recommendations for the future in this chapter.

While a single AUV use for ocean floor investigations is a known and consummate technology, having multiple vehicles working simultaneously without interfering with each other is a new and promising way of surveying.

In theory:

1. AUVs sequentially launched from the ship into water.

Issue #1. Even though AUV descent is a pre-programmed operation that does not require manned guiding, to ensure precise positioning at this stage AUV should constantly communicate to the ship. This means that launching time will not only include the actual launch time but the whole descent until AUV is safely at the start position at the sea floor.

Issue #2. Descended AUV can start acquisition right away, unless there is a need in running vehicles in parallel. In this case, each AUV should have a safe pre-programmed stand-by box. Even when the host vessel can allow for simultaneous launching of several AUVs, this operation will never be safe because of high risks of collision involved.

2. Start survey according to the line plan. Communication at this stage can be through unmanned surface vehicles (USVs) or other accompanying vehicle.

Issue #3. From this moment on, neither AUV coordinates nor the actual time of acquisition is corresponding to the estimations. Challenges like topography can cause AUV to deviate from the planned line, make loops in order to overcome steep slopes, or even make an emergency ascent.

Issue #4. With multiple AUVs in the water, survey parameters become not only dependent on desired data goals, topography etc., but on possible interference from other vehicles. This includes:

- Collision risk – physical interference between the AUVs.

- Acoustical interference. Each AUV is an active source of acoustical signal that can become noise for another vehicle if run too close to each other. Based on modeling and calculations the distance between any two vehicles should be at least **2 km** for chosen settings.

It is due to this limitation we could not perform a multiple AUV survey. Required resolution of 1.5 m required very tight survey line layout making it unsafe to use multiple devices. There was no layout solution that would not compromise the data quality, or the time of operation. One might think that with the length of a profile equal to 20 km, 2 km separation is a no-brainer but that is not true. Below is the explanation why.

AUV speed = 1.8 m/s = 6.48 km/h

Profile length = 20 km, then:

Theoretical time for one line completion ≈ 3.09 h

Theoretical time for separation distance of 2 km coverage ≈ 0.3 h

The most logical scheme would be to deploy, for instance, two AUVs with initial separation of 2 km and keep this separation during the whole mission like displayed in figure 11. However, as explained before, it is almost impossible to predict the exact location of an AUV: a) at the initial stage, when deployment time varies a lot; b) at the later stages, when topographical features can make an AUV to slow down, to make loops, or even to ascend; c) because possible time variations due to complications on the way are comparable with the time an AUV can pass a separation limit. Even if the separation along the runway is bigger than required 2 km, predictability of the AUVs still would not improve. Again, if the initial horizontal separation between two vehicles could be at least 2 km, or the length of the profile is much bigger than that, this scheme could have worked. In our case, this was not an option.

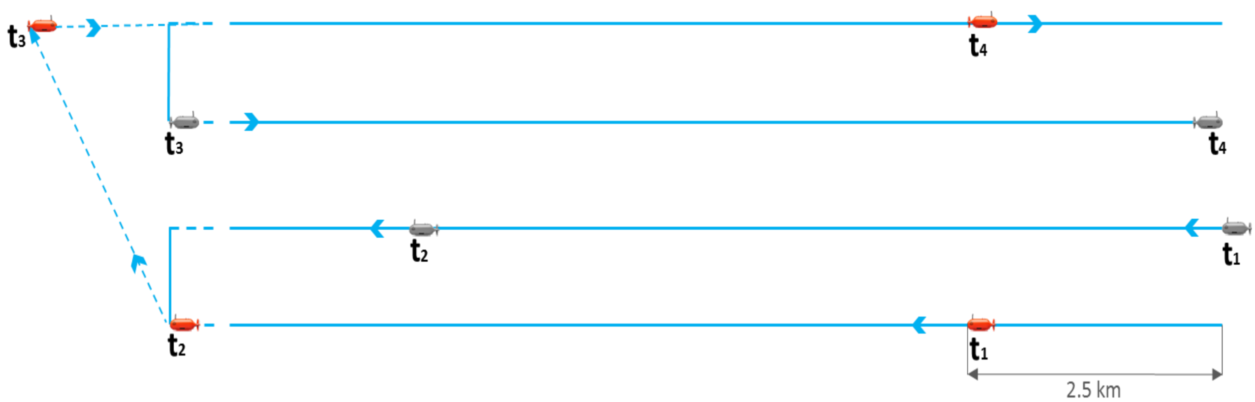

Fig. 11. Multi-AUV survey layout example.

3. AUV recovery.

Issue #5. It is a very unpredictable and time-demanding procedure. Even when everything goes according to the plan it can happen that AUV being at the water surface is not visible/hard to find because of the waves or anything else. In addition, it does require a certain skill to hook it up and bring onboard safely once it is found. Thus, it is hard to allocate the right amount of time for this part of the operation.

Issue #6. Same as in launching, to avoid the risk of collision, AUVs should be recovered separately in sequential order. This means that there should be allocated a stand-by box for each AUV at a safe distance from each other.

Issue #7. Battery life is limited. The newest HUGIN AUVs can endure up to 74 hours with all sensors operating, which is very impressive but still a limitation. In case there are no spare batteries onboard, charge time would take around 8 hours. All these should be accounted for during the planning of the mission.

To sum up, technology itself is working and working well, though one should remember about the limitations involved. Areal coverage per time and spatial resolution are still trade-off parameters for this setup. Yes, for bigger areas, where resolution requirements are lower, multiple AUV survey is the best solution timewise and therefore moneywise. For cases like the one described in this report, where the spatial resolution is a key parameter and has to be very fine, there is still work to be done on survey layout efficiency.

3 Results

The research cruise to the Mid-Atlantic Ridge conducted in August-September 2017 was a success. Even though not all three goals were fulfilled to the full extent, we consider that we achieved very good and important results. During the cruise multibeam echosounder, backscatter, side scan sonar, chirp sub-bottom profiler, and magnetometer data were acquired over four main lines, with a length of 20 km each, and three cross-lines, with a length of 0.62 km each. Magnetometer calibrations were carried out at the start, in the middle, and at the end of survey to ensure best results. Two samples of rock were collected from the top of an axial volcanic ridge during the ROV dive. The topography of the seabed in the area was rather challenging, with water depth ranging from 744 m at the shallowest to 3169 to the deepest. Nevertheless, the data quality is very good, consistent over the area, and promises good scientific results.

Due to technical challenges, the survey did not involve multiple AUV deployment as it was planned before the cruise. However, having six AUVs onboard allowed us to learn more about the technology and analyze challenges and possibilities for the future operations. In addition, this project initiated the communication protocol change that now allows 1km distance between two vehicles without sensor interference with given parameters.

This experience, along with the general experience of the survey, and constant knowledge exchange, became very important aspect of the project, and made it a great achievement of the close collaboration between the University and the Company.

3.1 Acquired data

The survey was conducted using one autonomous vehicle that served as a platform for different sensors. The track of the AUV is displayed below in figures 12 and 13. All acquired data were interpolated following data points along this line.

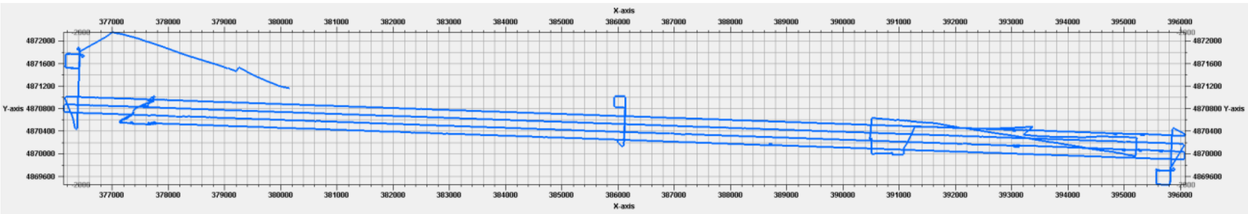

Fig. 12. AUV track – view from above.

The data quality was ultimately dependent on the AUV performance. Considering a rather low preset altitude of 70 m in the unknown and very steep terrain, AUV performed very well. As seen in figure 16, there are only few gaps in the data, where AUV had to fly higher to avoid collision. Remarkably, there was no emergency ascents during the operation.

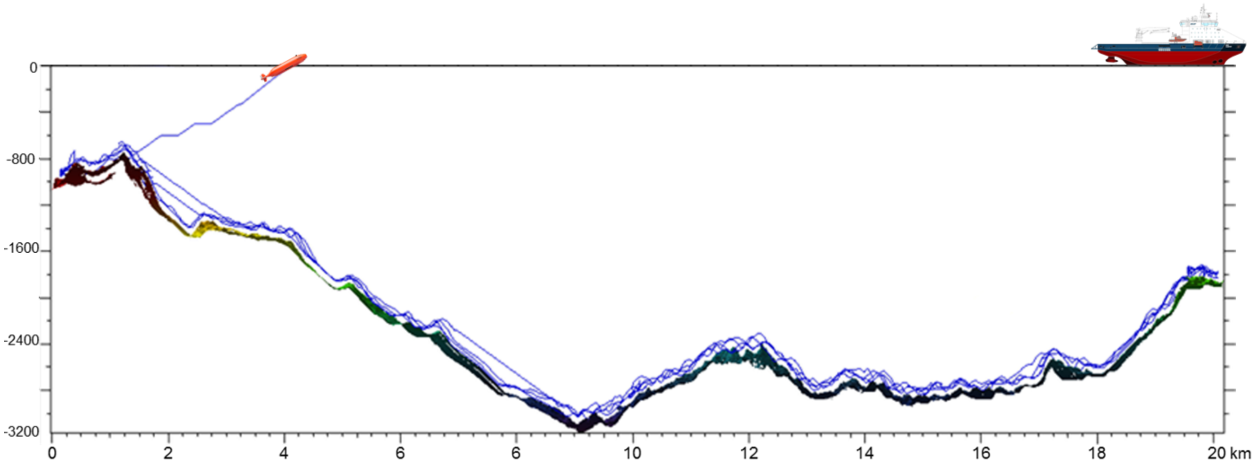

Fig. 13. AUV track over topography – view from South.

In figure 14, one can see the loops that AUV had to perform in order to climb some of the steepest slopes. Sometimes it would take 3-4 tries to succeed as seen in the figure. However, even such a complicated flight path did not upset the result data. The same part of the slope is shown in figure 15 – Example of bathymetric data in steep areas. Slope angle for this segment is around 45°, which makes the data acquisition process and the quality of results very impressive.

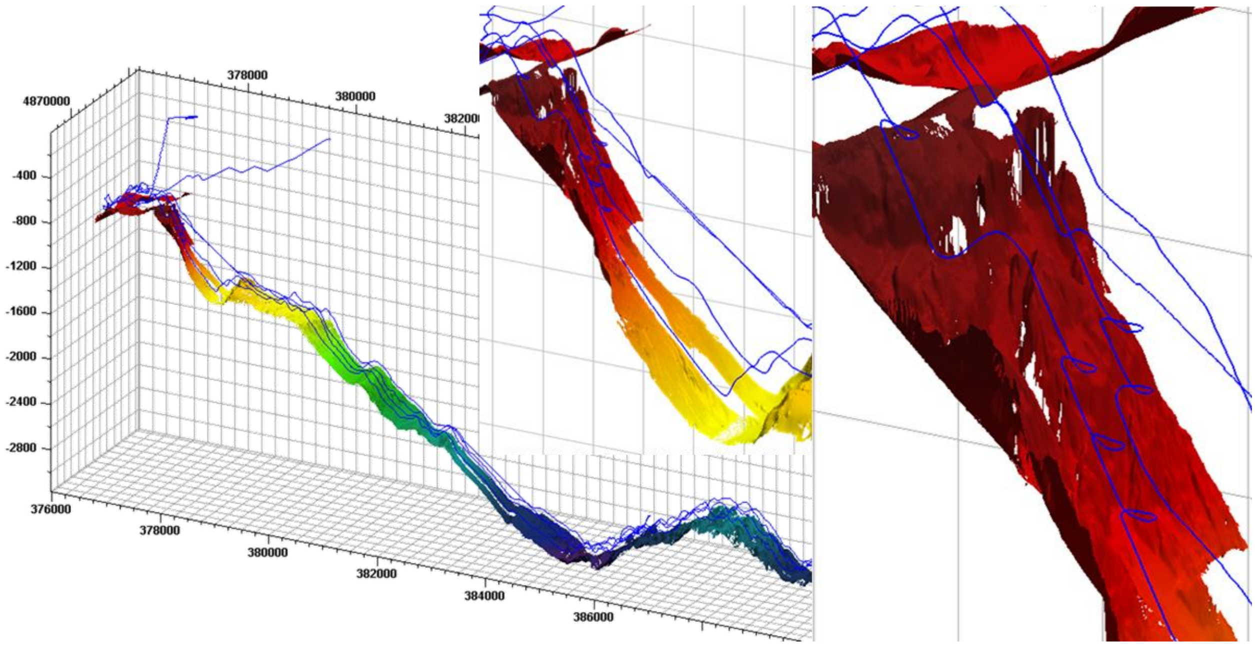

Fig. 14. Example of an AUV track against steep slope in 3D.

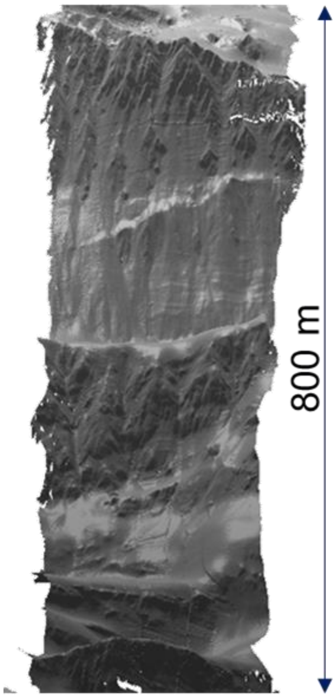

Fig. 15. Example of bathymetric data in steep areas – facing the slope from east.

As seen in figures 14-17, the data quality of the Multibeam Echosounder was very good throughout the survey. These data have been combined from several dives to produce a full coverage DTM of the surveyed area. The processed grid cell size equals to 1.5 m.

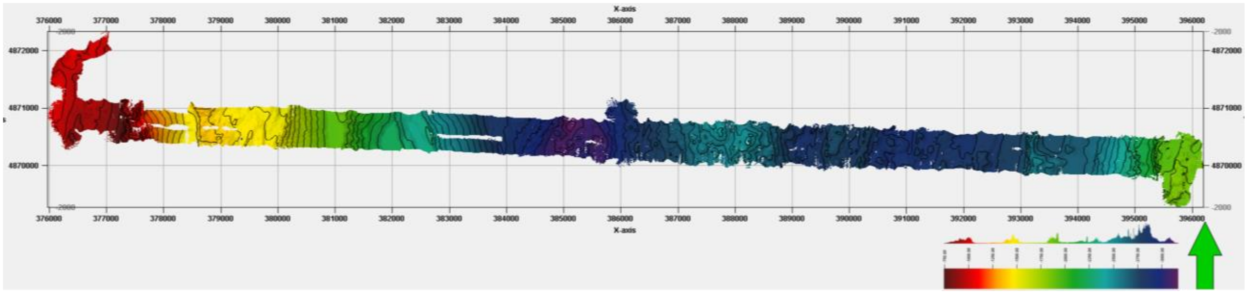

Fig. 16. Multibeam data coverage – view from above.

Fig. 17. Multibeam data example from the axial volcanic ridge.

The backscatter data was processed to provide the information on the seabed where the SSS was present. The data quality was good; however, some effects of the steep terrain were evident within the backscatter data. Good coverage was achieved by the backscatter providing reflectivity information across the survey area (fig. 18).

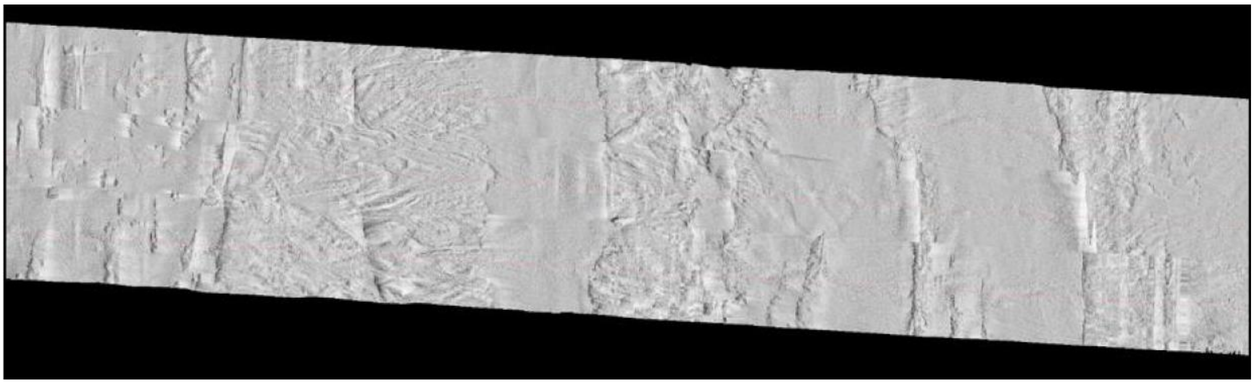

Fig. 18. Backscatter data example.

Due to the extreme nature of the topography of the ridge valley, side scan sonar data was not achievable on along the whole profile, only some patches of the flatter seafloor (see fig. 19).

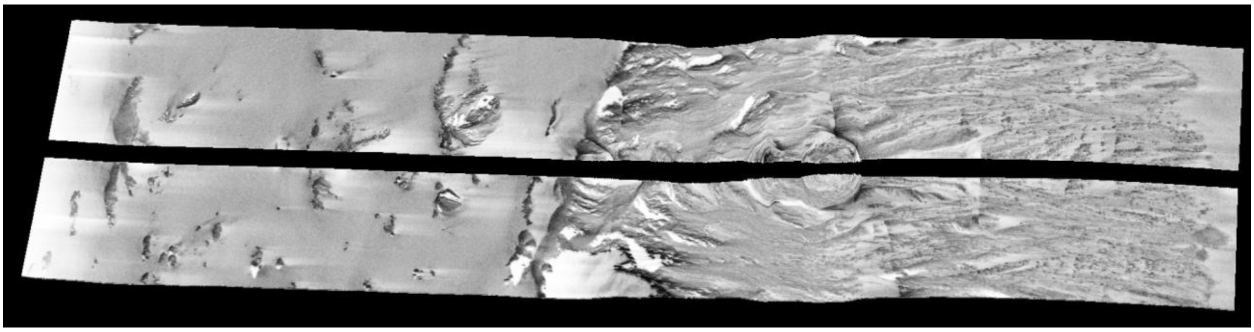

Fig. 19. Sidescan data example.

The sub-bottom profiler data was processed to provide information on the seabed subsurface. Due to extreme nature of the topography of the ridge, there were some difficulties tracking the seabed affecting the SBP data when the signal did not reach the seabed and thus the subsurface sediments. In general, good coverage was achieved across the survey area (fig. 20).

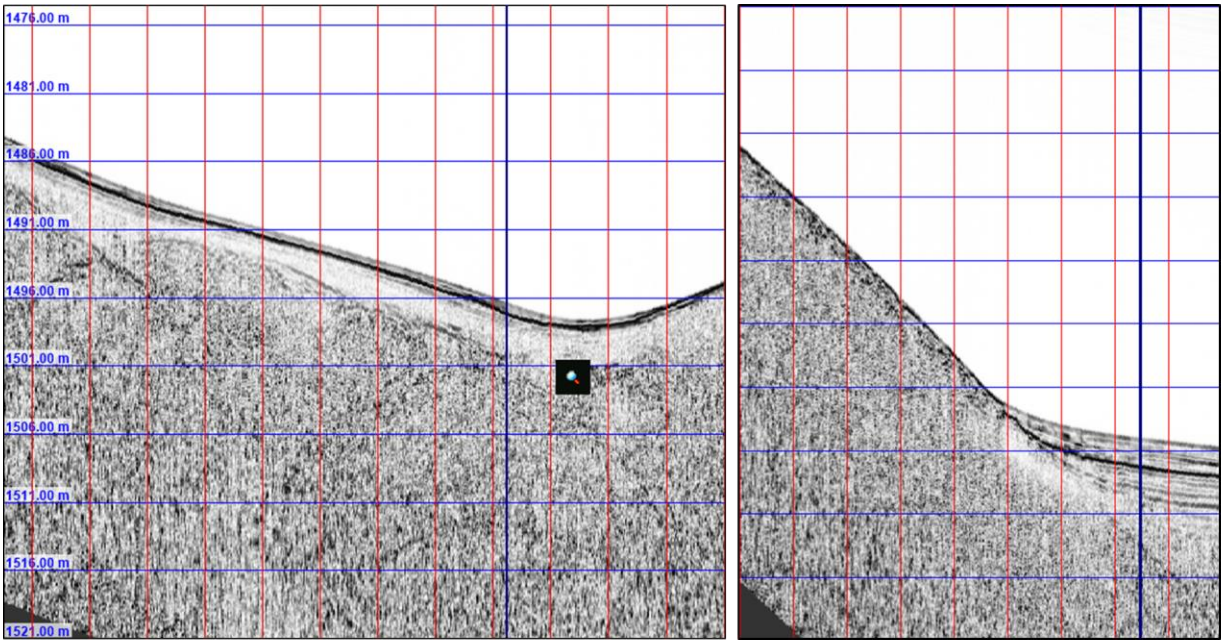

Fig. 20. Sub-bottom profiler data examples.

The magnetometer was acquired throughout the whole survey. Three calibrations were performed during the survey, at the start, in the middle, and at the end of it. The data has had real time compensation applied and to reduce the background magnetic field caused by the vehicle and the sensors within it. The data had little noise present and was good throughout (fig. 21).

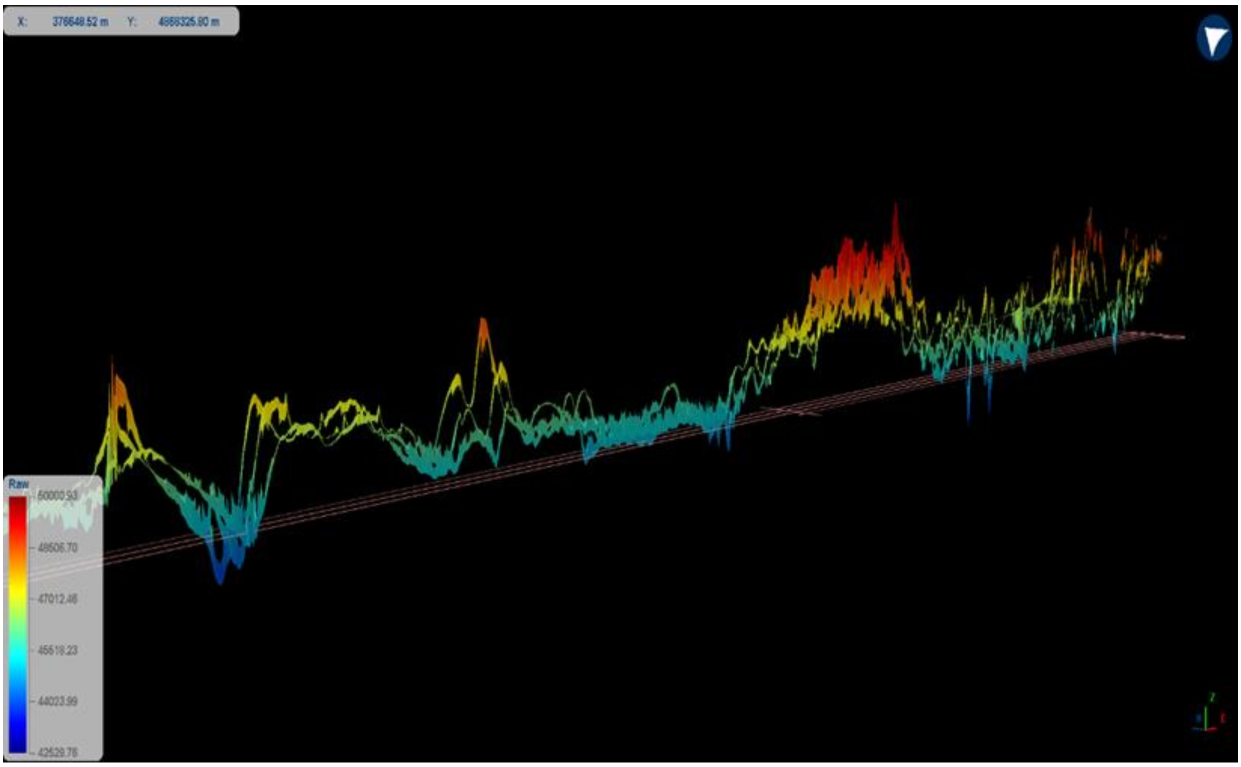

Fig. 21. Magnetic data example.

3.2 Collected Samples

Two samples were collected during the ROV dive. They were collected from the eastern flank of the mid-ocean axial volcanic ridge, close to the top of it. Two STD/CTD sensors were used for obtaining sound velocity, water conductivity, and temperature over the course of the dive.

Figure 22 displays the surroundings of where the samples were collected. Basalts (pillow lava outcrops are well distinguished on the screenshots) and fine marine sediments are most common rock types at the area.

Fig. 22. ROV images of the seafloor at the sampling area.

Collected samples represent fine-grained basalts with slightly different textures – one has vesicular texture (right sample on fig. 23), the other is aphanitic (left sample on fig. 23) when cut. They will be distributed for the general analysis, and petrophysical measurements (density, magnetic susceptibility and remanence, conductivity).

Fig. 23. Rock samples collected from the AVR.

4 Discussion and Future Work

Mineral deposits occurrence in deep sea is strongly dependent on magmatic and tectonic processes and, as a result, on the ocean floor topography. Mid-ocean ridge setting happens to have favorable conditions to accommodate most of the known hydrothermal deposits. In order to understand the factors that lead to formation of these deposits, and to deepen our knowledge of seafloor and its geological evolution in general, we needed an extensive acquisition.

Acoustic methods are reasonably dominant in marine acquisition. For this cruise purposes we used several of them: multibeam echosounder, side-scan sonar, and sub-bottom profiler. Contrasts in density, magnetic susceptibility provide reliable means of locating ore-bodies or other contrast geological features. As all methods are sensitive to different parameters, surveys require careful planning in terms of finding both the most informative combination of methods and a balance between spatial resolution and area coverage, which means finding the most economically efficient approach for a particular target. For this purposes, it was discovered that multi-AUV survey could become a very powerful tool. However, at the moment, it only proves to benefit bigger scale surveys.

The data and rock samples collection carried out during this cruise will be distributed among Deep Sea Mining pilot group participant for further research, which will result in several scientific publications. The samples have already been sent for the laboratory analyses and the results will be used to constrain magnetic interpretation, and to complement our knowledge about the given environment. Bathymetry will be widely used by the geologists and geophysicists in the group as it provides much valuable information that can be used in different applications from morphological analysis to geophysical modeling. Magnetic data will be processed and inversed to obtain susceptibility distribution in the subsurface.

In a situation, when seafloor is less explored than the surface of planet Mars (the entire ocean floor has been mapped to a maximum resolution of around 5 km, whereas more than 60% of Mars's surface mapped at a resolution of 20 m) we should use every opportunity to study deep oceans, and make it more and more efficient. Seafloor mineral resources is one of these opportunities that can bring industrial power and technologies, and academia together to produce better knowledge and solutions.

5 List of Abbreviations

Abbreviation	**Meaning**
AUV	Autonomous Underwater Vehicle
AVR	Axial Volcanic Ridge
CTD	Conductivity Temperature Depth
HSE	Health, Safety, and Environment
MAR	Mid-Atlantic Ridge
MBES	MultiBeam EchoSounder
NTNU	Norwegian University of Science and Technology
OI	Ocean Infinity
ROV	Remotely Operated Vehicle
SBP	Sub-Bottom Profiler
SCM	Self-Compensated Magnetometer
SMS	Seafloor Massive Sulfides
SSS	Side-Scan Sonar
USV	Unmanned Surface Vehicle

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8 List of References

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