Hydrothermal Activity at the Ultraslow-Spreading Mohns Ridge: New Insights From Near-Seaﬂoor Magnetics

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Abstract
Hydrothermal circulation is a process fundamental to all types of mid-ocean ridges that largely impacts the chemical and physical balance of the World Ocean. However, diversity of geological settings hosting hydrothermal fields complicates the exploration and requires thorough investigation of each individual case study before effective criteria can be established. Analysis of high-resolution bathymetric and magnetic data, coupled with video and rock samples material, furthers our knowledge about mid-ocean-ridge-hosted venting sites and aid in the interpretation of the interplay between magmatic and tectonic processes along the axial volcanic ridges. The rock-magnetic data provide constraints on the interpretation of the observed contrasts in crustal magnetization. We map the areal extent of the previously discovered active basalt-hosted Loki’s Castle and inactive sediment-hosted Mohn’s Treasure massive sulfide deposits and infer their subsurface extent. Remarkably, extinct hydrothermal sites have enhanced magnetizations and display clear magnetic signatures allowing their confident identification and delineation. Identified magnetic signatures exert two new fossil hydrothermal deposits, MT-2 and MT-3. The Loki’s Castle site coincides with negative magnetic anomaly observed in the 2-D magnetic profile data crossing the deposit. First geophysical investigations in this area reveal the complexity of the geological setting and the variation of the physical properties in the subsurface.

1. Introduction

Marine magnetic data provided one of the most powerful tools in the development of plate tectonic theory (Vine & Wilson, 1965) and have largely contributed to mid-ocean ridge (MOR) research ever since. Discoveries of hydrothermal activity along the MORs and the resource potential associated with these processes have brought more extensive and detailed exploration to these deep and remote environments. Early studies only attributed hydrothermal activities to fast spreading ridges. Reports of hydrothermal venting at the slow and ultra-slow spreading Mohns Ridge: New insights from near-seafloor magnetics. Geochmistry, Geophysics, Geosystems, 20, 5691–5709. https://doi.org/10.1029/2019GC008439
challenges associated with it. Detailed magnetic data helps us in constraining both areal and depth extent of the identified deposits.

Regional, publicly available bathymetry (Norwegian Mapping Authority, 2015), electromagnetic and magnetotelluric data (Johansen et al., 2019), reflection seismic data (Bruvoll et al., 2009) proved to be highly instrumental in understanding and describing large-scale processes driving hydrothermal circulation. However, the localization of the associated deposits within the permissive tracts, favorable for exploration, is still not well understood and mainly based on probabilistic assessment rather than on geological and physical characteristics (Juliani & Ellefmo, 2018). Here, we use the interpretation of high-resolution bathymetry and near-seafloor magnetics from the confirmed active and inactive hydrothermal sites and adjacent axial volcanic ridges to further our understanding about the factors controlling the occurrence of such deposits. By doing so, we contribute to the current knowledge base in a local context of the Mohns Ridge geology, and the global context of mid-ocean-ridge venting. The data examination provides a few insights on subsurface processes of hydrothermal circulation and its interplay with tectonic and magmatic processes at the slow-spreading ridges.

Figure 1. Location of the near-seafloor surveys. (a) Regional bathymetric map of the Mohns Ridge northernmost segment resolved at 100 m (Norwegian Mapping Authority, 2015). Red lines mark survey outlines. Active hydrothermal venting site, Loki’s Castle, is denoted by red filled circle, extinct venting site, Mohn’s Treasure, by yellow filled circle, an orange circle denotes the location of sediment core sample where sulfide layer was found around 1.5-m subsurface (Pedersen, Rapp, et al., 2010). Both flanks of the rift and the valley itself are covered by distal parts of Bear Island Fan sediments (Bruvoll et al., 2009). AVR stands for axial volcanic ridge. (b) Regional overview map of the Mohn’s and Knipovich ridges. The black rectangle marks the location of panel a. Red circles denote active hydrothermal venting sites, yellow circle—extinct hydrothermalism sites (Beaulieu & Szafranski, 2018). The black dotted line marks the spreading axis. Blue arrows denote the North American and Eurasian plate-movement directions relative to a fixed hotspot reference frame (Gripp & Gordon, 2002).
2. Geological Setting

The study area is located at the northern part of the Mohns Ridge where the MOR transitions into the Knipovich Ridge after bending ~80° along axis strike (Figure 1a). The Mohn-Knipovich Bend was formed as a result of the major plate boundaries reorganization, involving a 30° shift in the plate motion, followed by the initiation of oblique spreading of the previously orthogonal spreading Mohns Ridge and the inception of the Knipovich Ridge at about chron 13 (38 Ma; Talwani & Eldholm, 1977; Vogt, 1986). The Mohns Ridge is an ultraslow and obliquely spreading ridge with a full rate estimated at ~15.6 mm/year for the last 10 Ma (Moser et al., 2002; Vogt, 1986). Topography is rough and has a pronounced difference between the ridge flanks, reflecting the complexity of the spreading history of the Norwegian-Greenland basins. The asymmetry is expressed at multiple levels and is attributed to the oblique and asymmetric motion of the European and North American plates rather than asymmetric sediment loading, which barely follows the basement topography (Johansen et al., 2019; Talwani & Eldholm, 1977; Vogt et al., 1982). Both flanks of the rift valley and the valley floor are covered by sediments from the Bear Island Fan with thickness reaching up to ~800 m with larger volumes deposited on the eastern side (Bruvoll et al., 2009).

Transform faults do not dissect the ridge, yet the MOR is characterized by linked magmatic (volcanic) and amagmatic (tectonic) segments (Dick et al., 2003). Topographic highs present in the axial valley of the study area are interpreted as being volcanic in origin (Crane et al., 1999; Géli et al., 1994). Abundant volcanic features such as prominent cones, flat-topped volcanoes, and volcanic ridges, are observed in the bathymetric data and have corresponding short-wavelength anomalies in regional magnetic data (Géli et al., 1994; Pedersen, Rapp, et al., 2010) that support the hypothesis that the two domed elongated edifices discussed in this paper are neovolcanic axial volcanic ridges (AVR1 and AVR2). The life cycle of an AVR alternates between magmatic and tectonic phases, following the intermittent magmatic and tectonic focusing and defocusing along the axis due to restricted magma supply (Parson et al., 1993). The area is seismically active—earthquake epicenters located within the ridge valley closely correlates with the major faults and volcanoes at the graben floor, suggesting a tight link between melt placement and faulting processes (Hopper et al., 2014; International Seismological Centre, 2018; Johansen et al., 2019). The interplay between these processes is of major importance for hydrothermal circulation along the ridges (McCaig et al., 2007).

Loki’s Castle is an active high-temperature hydrothermal venting field discovered in 2008 (Pedersen, Thorseth, et al., 2010). It occurs at the northernmost AVR of the Mohns Ridge that rises approximately 1,300 m above the rift valley floor at 2,000-m depth. This AVR is locally perpendicular to the spreading direction and reaches around 30-km length. Topographically the ridge is composed of hummocky terrain with notable tectonic disruption. En echelon faults can be traced along the entire ridge, which is locally covered by fresh lava flows. Volcanic cones, smaller ridges, flat-topped volcanoes are common features. Sediment thickness varies across the area providing information on the relative age of the underlying volcanic features (Mitchell et al., 1998). Geochemical analysis of the hydrothermal fluid collected from the black smokers, that is, end-member volatile concentrations, supports magmatic influence in the area (Pedersen, Thorseth, et al., 2010), confirming that Loki’s Castle is a basalt-hosted site. There are also indications of fluid interaction with ultramafic rocks and a significant footprint of sediment influence (Baumberger et al., 2016), which likely results from the deep fault and across-axis circulation as shown in a recent deep electromagnetic imaging study across the ridge by Johansen et al. (2019).

Unlike the AVR hosting Loki’s Castle, the southern neo-volcanic ridge (AVR2) is less pronounced and exhibits terrain strongly dominated by young pillow flows. The tectonic disruption here is less prominent than at the northern AVR and is primarily attributed to syn-magmatic tectonism. Vertical disruption is not significant, whereas crustal fissures are a common observation. The AVR extends for approximately 25 km in a northeasterly direction and is locally orthogonal to the spreading direction and rises on average 500 m above the valley floor. The summit is located at the center of the neo-volcanic zone, at 2,500-m water depth reaching around 800 m above the valley floor.

Mohn’s Treasure area is the most geologically distinctive among three study areas as it is situated at the flank of a rift valley, west of the AVR2. The general trend of the major extensional fault creating the inner wall of the axial rift is about 039°N. The area is predominantly composed of lithified and partly lithified sediments that represent distal parts of Bear Island fan deposited in the rift valley, subsequently uplifted by the marginal faults, and then mass wasted (Pedersen, Rapp, et al., 2010).
3. Data Collection and Processing

Near-bottom high-resolution magnetic data, bathymetry, and rock samples were collected during the MarMine cruise onboard Polar King multipurpose vessel in 2016 (Ludvigsen et al., 2016). Data acquisition was carried out using an autonomous underwater vehicle (AUV) Hugin by Kongsberg Maritime. Two heavy-duty remotely operated vehicles (ROVs), Triton XLX and XLR, were used for sampling and video surveying.

A total of five different AUV dives are presented in this paper and are grouped according to their location into three survey areas: Loki's Castle active venting site: Survey Area 1 (AVR1); Mohn's Treasure extinct venting site: Survey Area 2; axial volcanic ridge (AVR2) exploration areas: Survey Areas 3a and 3b (Figure 1). The AUV surveyed along parallel profiles spaced by 150 m apart (250 m for Surveys 3a and b) at the nominal altitude of 100 m above the valley floor, ranging from 40 to 270 m. The bathymetric data were provided by a combination of EM 2040 multibeam echosounder and interferometric side-scan sonar HISAS 1030 (both provided by Kongsberg Maritime). Resulting bathymetric maps were gridded at 1 m each, except for the Mohn’s Treasure site where the grid resolution is 4 m due to the difficulties experienced by the AUV while surveying a steep slope. The regional overview bathymetric map is a ship-based grid resolved at 100 m collected for the Norwegian Petroleum Directorate in 2000 (Norwegian Mapping Authority, 2015).

3.1. Magnetic Data

The high-resolution vector magnetic field data were collected using a self-compensating three-axis fluxgate magnetometer system developed by Ocean Floor Geophysics that was rigidly mounted inside the AUV. The dynamic range of the magnetometer covers ±65,000 nT with a resolution of 0.01 nT, and ± 0.5 nT peak-to-peak noise level. Raw data consisted of magnetic intensity for three components, and vehicle attitude data (heading, roll, and pitch) that were logged simultaneously and interpolated to the magnetic data sampling rate of 19 Hz. The topography of the seafloor acquired by the multibeam echosounder was sampled to 1-m cell size grid (and 4 m for Survey 2).

Even though the AUV body is made from nonmagnetic carbon fiber laminate and synthetic foam, the propulsion motor and other payload sensors still affect the magnetic measurements. At the beginning of each survey, calibration maneuvers were performed to estimate the best correction for the vehicle-induced field and its interaction with the Earth’s magnetic field. It involved flying a square pattern with the change of both the heading and altitude, creating a set of reciprocal lines. Recorded data were then used to calculate correction terms to remove the influence of the vehicle movements and the heading effects on the measured magnetic data as described by Honsho et al. (2013) and Bloomer et al. (2014). The maneuver and correction were performed for each dive separately. The level of noise related to the platform in the recorded data was estimated to be ±10 nT. The correction removed most of the false maneuver-related short-wavelength apparent anomalies and improved the noise level marginally.

No crossing tie-lines were performed during the survey to correct for variations of the Earth’s magnetic field due to ionospheric influences and/or ocean current induced magnetic fields; neither there was a base station on the seafloor. Geomagnetic Observatory recordings of the magnetic field at Bjørnøya and Tromsø, and calibrated variometers at Longyearbyen and Jan Mayen showed moderate magnetic activity during the surveys with a peak magnitude of around 100–150 nT (Tromsø Geophysical Observatory, 2018). However, no correlation was found upon visual inspection when comparing the diurnal data with recorded magnetic field data, and consequently, no such correction was performed on the data. The compensated magnetic field data for all datasets were low-pass filtered to remove residual uncompensated vehicle motion noise at wavelengths shorter than 50 m using a Butterworth filter.

Due to autonomous character of the data acquisition in a relatively poorly known and very rugged topography—the NMA 2015 bathymetric map of 100-m grid resolution was used for survey planning and navigational purposes—recorded survey altitudes were not consistent with the nominal constant drape values. While direct effects of vehicle behavior like heading change, pitching, rolling, and vehicle-induced field noise was taken care of in the first steps of the processing sequence, nonconsistent terrain clearance caused a loss of signal resolution and distortion of some anomalies. To account for these issues, we used the CompuDrape extension integrated into Oasis Montaj software suite (Paterson et al., 1990). It computes the continued field at a set of different levels then interpolating the values on a specified draped surface.
pointed out by several studies (Cordell, 1985; Pilkington & Roest, 1992; Pilkington & Thurston, 2001), even though this method is not very rigorous mathematically it proved to work well in practice. It maintains the data resolution compared to other upward continuation approaches. An example of the drape correction applicability test is illustrated in Figure 2. Having measurements at two different altitudes at the Loki’s Castle survey allowed us to test this method. We compared the continued field intensity profiles using low- and high-flight modes data. Assuming the drape-fixed TMI profile from high-flight data is close to ideal, as the terrain clearance is highly consistent for the most part, and thus the corrections were minor (Figures 2b and 2c), the comparison of this profile and the TMI profile computed from the low-flight data, acquired 40 m lower on average, demonstrates satisfactory results and the utility of the approach. A standard deviation lies within 150 nT for all profiles with two flight-modes tested. However, the decline in the resolution for larger altitude difference is considerable. As this method involves both a downward field continuation and a more stable upward field continuation, careful attention was given to the choice of the new observation height. This choice was based on the dominant altitude value, and the magnetic frequency content to minimize downward continuation noise amplification and upward continuation signal loss. Thus, the drape recomputed nominal altitude was set to 100 m for surveys 1, 2, and 3a, 150 m for the Survey 3b, and 60 m for Loki’s Castle low-altitude dataset. Given the average variation in the flight altitude for all surveys and the frequency content of the signal of interest, the results of this method are satisfactory. We also tested both line- and grid-based approaches on the data, displaying better results in the former approach since grid-based draping tends to amplify interpolation errors, especially in case of bigger difference in altitude between the adjacent lines, producing errors in the computed gradients orthogonal to the lines.

Subsequently, a microleveling correction was applied to the profile data to reduce the long-wavelength noise caused by the discrepancy between adjacent survey lines (Ferraccioli et al., 1998; Minty, 1991). The TMI data was then transformed into magnetic anomaly data by removing the mathematically approximated geomagnetic field—International Geomagnetic Reference Field (IGRF; Thébault et al., 2015). In the end, a reduction to the pole (RTP) transformation (Baranov, 1937) was applied by placing magnetic anomalies over their sources. The magnetic field direction in the survey area was assumed to have a declination of 2° and inclination of 80°. Finally, the resultant magnetic anomaly data were interpolated onto 30 m spaced grid (40 m for Survey 3b) by a minimum curvature algorithm.

Other techniques used in this paper have qualitative or semi-quantitative character, utilize total magnetic field derivatives for the interpretation and include tilt derivative (Miller & Singh, 1994), analytical signal (Nabighian et al., 2005; Roest et al., 1992) and Euler deconvolution (Reid et al., 1990; Thompson, 1982). The analytic signal is independent of the inclination of the magnetic field and of the source magnetization. Following the assumption that the isolated anomalies are caused by vertical contacts, the analytic signal can be used to estimate depth using a simple amplitude half-width rule (Roest et al., 1992). Euler deconvolution is an automated technique for depth estimation that is based on Euler’s homogeneity relationship and does not require any a priori knowledge of the geology (Thompson, 1982). However, the depth resolution is limited by the grid spatial resolution. The data were analyzed using the standard Euler deconvolution for contacts and step-like structures (Reid et al., 1990) to aid interpretation of the gross structural trends. The Located Euler deconvolution, which locates confined peak-like structures in the data, was performed to examine cylinder-like structures that are assumed to represent the geometry of the studied deposits. In the case of Loki’s Castle, we used the measured vertical gradient obtained by calculating the difference between the two datasets of low- and high-flight modes and dividing it by the difference in their nominal altitudes instead of using the calculated vertical derivative.

The magnetic tilt derivative enhances the magnetic fabric. Originally introduced by Miller and Singh (1994), it has the useful property of being positive over the source, and negative outside the source region, crossing through zero at, or near, the edge of a vertical-sided polygon. TDR aids in mapping subtle basement fabric through enhancing small-amplitude signals so weak magnetic bodies such as hydrothermal deposits are treated with the same weight as strong magnetic bodies (Verduzco et al., 2004). The combination of these attributes provides a useful tool for data enhancement and further interpretation and mapping of geologic features.
The 2-D magnetic forward modeling has been carried out using the GM-SYS Profile Modeling module integrated in Oasis Montaj software package. This type of analysis is used to calculate the magnetic response from a geological model and compare to the observed data. The method is based on calculation algorithm developed by Talwani and Heirtzler (1964) and refined according to Rasmussen and Pedersen (1979). The geologic model whose upper boundary is constrained by the observed topography was adjusted by a semi-automatic trial and error approach to ensure the best fit.

3.2. Rock Samples

All rock samples collected from the Loki’s Castle hydrothermal venting site are non-in-situ grab-samples. A total of 25 samples were measured for their petrophysical properties and represented mudstone, hydrothermally altered basalt, and highly heterogeneous loose probable-chimney fragments from the mound flanks (Snook et al., 2018).

One sample from the Mohn’s Treasure site is a drill-core that was first video recognized as a basalt (Figure 3d shows the drilling site): black hard rock that did not break or crumble in ROV-manipulator as immediately happened to sedimentary or hydrothermal rocks in the area (Ludvigsen et al., 2016). Upon closer examination, including petrophysical measurements at the Norwegian Geological Survey (NGU), this sample was recognized as a claystone. This fact changed our understanding of the lithology presented in the Mohn’s Treasure area and largely contributed to the interpretation of hydrothermal deposits and their magnetic signatures.

All petrophysical measurements were performed at the NGU petrophysical laboratory using commercial and proprietary instruments. Rock density, volume and porosity were determined according to the methodology of EN 1936:2006 (CEN, 2006) using Sartorius AX 4202 instrument. The rock-magnetic properties measurements included magnetic susceptibility (performed using NGU proprietary system) and magnetic remanence intensity (performed using a 3 × 3 component Sensys FGM3D fluxgate magnetometer system installed in a nullspace). The direction of the NRM could not be measured because the in-situ orientation of the samples was not known. The Königsberger ratio was calculated based on the average IGRF magnetic field intensity value for the area equal to 53,800 nT. Measurement uncertainties are presented in Table 1.

4. Results and Discussion

The surface geology at the Loki’s Castle, Mohn’s Treasure, and exploration site was video examined by the ROV mounted cameras. The observed geologic features can be grouped into five categories: (1) different

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**Figure 2.** Comparison between the measured- and constructed-drape TMI profiles in the rough terrain of Loki’s Castle: Line 5 in Figure 5. (a) Original TMI profiles are denoted by solid lines: low-flight mode is black, high-flight mode is red. Both modes were acquired with inconsistencies in altitude displayed in (b) and (c) panels. Dashed lines are obtained using a CompuDrape algorithm and correspond to the new constant altitudes above the seafloor: 60 and 100 m. (b) Bathymetric profile with original loose drapes for low- and high-flight mode surveys, in black and red solid lines respectively. Dashed lines mark fixed-drape profiles. (c) Original altitude distributions for low- and high-mode surveys for the displayed survey line with modal, median, and standard deviation values.
types of lava flows: low-relief sheet flows, lobate pillow flows, and interconnected lava tubes; (2) extensively fractured pillow-lava talus, truncated pillows, and basaltic breccia; (3) loose and partly lithified sediment cover; (4) lithified sediment; and (5) hydrothermal material including black and white smokers, broken chimney material, and sulfide deposits. Figure 3 shows typical photo-observations from each site.

Aside from geological expressions, all three study areas exhibit different biodiversity backgrounds. Since hydrothermal venting sites are also known as deep-sea "oases"—an abundant source of chemoautotrophic bacteria that attract underwater animals have developed to tolerate this extreme habitat and thrive (Fisher et al., 2013, and references therein), the presence of certain biospecies endemic to vent environments and their abundance become important direct characteristics of the present and or past hydrothermal activity. The video footage indicates that both Loki's Castle and Mohn's Treasure hydrothermal sites display notably greater abundance and diversity of species than the exploration AVR2 site where no hydrothermal activity was reported. At the same time, Mohn's Treasure (a comprehensive study on biodiversity and community structure is reported in Paulsen, 2017) and Loki's Castle are distinctive from each other, which can indicate different stages of hydrothermal activity, in addition to the difference in host rock and overall setting.
Loki's Castle active hydrothermal venting site. Detailed bathymetry and direct ROV observations reveal hummocky volcanic terrain composed of pillow flows of varying ages, locally covered by sediments. Extensional tectonics influence is pronounced in the normally faulted terrain (Figure 4) that alternate with recent magmatic activity centers. Observed lithologies include fresh and fractured pillow-basalts and breccia (Figure 3a), patches of loose and partly lithified sediment, and diverse hydrothermal material (Figures 3b and 3c). Loki's Castle deposit consists of two mounds that are situated in the middle of the AVR on a flat-topped seamount, just west of the rift. Each mound is approximately 150 m in diameter, overlapping by roughly 30 m as their centers are approximately 120 m apart. The detailed 1-m resolution bathymetry data provides a solid basis for the deposit detailed mapping.

| Description                              | IGSN | Volume (cm³) | Density (g/cm³) | Porosity (%) | Magnetic susceptibility (10⁻⁶ SI) | Magnetic remanence (mA/m) | Königsberger ratio |
|------------------------------------------|------|--------------|-----------------|--------------|----------------------------------|-------------------------|-------------------|
| Measurement uncertainty                   | 0.01 |              | <1,000–6%       | >1,000–0.6%  | <50–5%                           | >50–1%                 |                   |
| Mohn's Treasure: Claystone               | MT01 | 194.3        | 2.31            | 0.15         | 549                              | 3                       | 0.10              |
| Loki's Castle: Mudstone                  | 01   | 80.16        | 1.1             | 0.52         | 611                              | 14                      | 0.43              |
|                                            | 02   | 130.31       | 1.05            | 0.52         | 630                              | 6                       | 0.18              |
| Loki's Castle: Hydrothermally altered Basalt | 03   | 74.32        | 2.84            | 0.02         | 1,194                            | 2                       | 0.03              |
|                                            | 04   | 116.6        | 2.84            | 0.02         | 1,112                            | 10                      | 0.17              |
|                                            | 05   | 104.65       | 2.86            | 0.02         | 1,126                            | 7                       | 0.12              |
| Loki's Castle: Heterogeneous hydrothermal material | 06   | 115.15       | 1.62            | 0.14         | 451                              | 4                       | 0.16              |
|                                            | 07   | 112.22       | 1.58            | 0.16         | 538                              | 5                       | 0.17              |
|                                            | 08   | 122.53       | 2.07            | 0.24         | 583                              | 57                      | 1.82              |
|                                            | 09   | 115.6        | 1.84            | 0.21         | 559                              | 102                     | 3.39              |
|                                            | 10   | 98.15        | 1.65            | 0.1          | 557                              | 46                      | 1.54              |
|                                            | 11   | 101.09       | 1.95            | 0.22         | 543                              | 88                      | 3.01              |
|                                            | 12   | 129.58       | 1.54            | 0.13         | 503                              | 6                       | 0.22              |
|                                            | 13   | 191.7        | 2               | 0.14         | 518                              | 60                      | 2.15              |
|                                            | 14   | 182.08       | 1.51            | 0.16         | 465                              | 9                       | 0.36              |
|                                            | 15   | 119.85       | 1.49            | 0.21         | 460                              | 5                       | 0.20              |
|                                            | 16   | 69.12        | 1.62            | 0.19         | 474                              | 6                       | 0.24              |
|                                            | 17   | 93.29        | 2.08            | 0.1          | 497                              | 106                     | 3.96              |
|                                            | 18   | 125.62       | 2.12            | 0.16         | 641                              | 149                     | 4.32              |
|                                            | 19   | 137.57       | 2.22            | 0.1          | 624                              | 159                     | 4.74              |
|                                            | 20   | 113.59       | 2.25            | 0.14         | 676                              | 223                     | 6.13              |
|                                            | 21   | 141.03       | 1.67            | 0.19         | 527                              | 12                      | 0.42              |
|                                            | 22   | 128.37       | 1.85            | 0.15         | 490                              | 26                      | 0.99              |
|                                            | 23   | 140.57       | 1.9             | 0.11         | 447                              | 66                      | 2.74              |
|                                            | 24   | 125.46       | 1.5             | 0.24         | 500                              | 21                      | 0.78              |
|                                            | 25   | 117.35       | 1.42            | 0.27         | 513                              | 23                      | 0.83              |

Note. Volume gives the bulk volume of the measured sample material. All samples are assigned International GeoSample Numbers (IGSN) with a prefix IELIM00.
Rapp, et al., 2010)—all these factors make a strong case for the formation of hydrothermal deposits in the studied area. We suggest that structural complexity associated with intensive faulting of diverse orientation, and transfer zones in particular, is the major factor in the localization of hydrothermal discharge on the seafloor and subsequent deposit formation.

Basalt-hosted hydrothermal sites are typically associated with a negative magnetic anomaly in normal polarity areas (Sztitkar et al., 2014; Tivey et al., 1993; Tivey & Johnson, 2002; Zhu et al., 2010). The reduction in magnetic intensity observed over such sites can be caused by several reasons and often results from a combination of them: hydrothermal alteration of titanomagnetite to less magnetic minerals (Ade-Hall, 1964; Pariso & Johnson, 1991); and formation of thick nonmagnetic hydrothermal deposits above deep-seated magnetic layers (Sztitkar et al., 2014); or the transient effect of thermal demagnetization of titanomagnetite in basalt as temperature of the circulating fluid in active sites—300+ °C—exceeds Curie temperature of titanomagnetite—120–200 °C (Kent & Gee, 1996).

Black smokers at Loki’s Castle release 310–320 °C vent fluid that makes it a high-temperature vent field and the thermal demagnetization effect viable. A semi-quantitative XRD analysis of a basalt sample collected from the flank of the hydrothermal mound (a parent sample for samples no. 03–05 in Table 1) shows following composition: albite (52.06%: interior; 48.08%: outer rim) and augite (34.31%: interior, 28.61%: outer rim), chlorite (10.2%: interior, 18.16% outer rim), quartz (3.43%, 5.15%: outer rim; B. Snook, personal communication, 2017). A significant amount of alteration products such as chlorite and albite in the studied basalt sample suggests that it was subjected to hydrothermal alteration (Humphris & Thompson, 1978). Basalt samples previously collected in the vicinity of the Loki’s Castle area were classified as typical tholeiitic basalt (Cruz et al., 2011). Magnetic properties of the same basalt sample split into three smaller samples (samples no. 03–05 in Table 1) coincide with the observation that chloritization and spilitization is associated with decreasing intensity of magnetization and Königsberger ratio (Opdyke & Hekinian, 1967). At the same time, the magnetic susceptibilities of the hydrothermal material and the mudstones, collected from the mounds, exhibit even lower values, on average twice as low as the altered basalt, and much lower than fresh mid-ocean ridge basalt (Ade-Hall, 1964). Each of these observations would indicate a magnetic low over Loki’s Castle. However, the magnetic signature of this particular area is quite complex—we do not observe a confined magnetic anomaly directly above the mounds (Figure 5), even though the reduction to pole procedure was performed and the geological area was formed during the normal polarity Brunhes epoch (Heirtzler et al., 1968; Ogg, 2012). Instead, we observe a long-wavelength magnetic anomaly low skewed in the southeastern direction perpendicular to the major fault and a much steeper southeastern side of the anomaly. The emerged indentation in the TDR map coincides with the eastern mound of the Loki’s Castle and could be explained by the presence of demagnetized sulfide mounds in the shallow part and potentially a hydrothermal fluid upflow zone shifted toward the eastern mound. Yet, the resolution and configuration of the magnetic survey requires close attention to the interpretation: the distance between the survey lines
equal to 150 m is comparable with the mounds size; the survey track lines are aligned with the main faulting
direction 044°. In fact, only one survey line runs over the deposit; however, it does not cross either mound
but goes between them, while the two adjacent lines run over the very edges of the mounds parallel to
the major faults defining the hosting structure (Figure 5). Such configuration of the survey does not allow
a 3-D reconstruction of the deposit.

The profile crossing the deposit (L3 in Figures 5 and 6) indicates a negative magnetic anomaly that coincides
with the Loki’s Castle deposit. Magnetization low is present and detectable in the profiles collected at differ-
et altitudes of 60 and 100 m above the seafloor. The observed difference between the two profiles in this
pseudo-measured gradient along the line 3 proposes that the anomaly derives from the shallow subsea-
floor source. Forward modeling was used to assess the hypothesis. While small variations in thickness of a layer
with constant crustal magnetization value (Zhang et al., 2018, and references therein) were enough to
explain the long-wavelength trends in the observed magnetic data, a short-wavelength anomaly over the
deposit and the pseudo-measured vertical gradient required a reduced magnetization body to generate suf-
cient contrast in the data. Figure 6 shows the magnetic signal calculated from such model. The uniformly
magnetized layer with a varying thickness represents recent extrusive basalts; a reduced magnetization body
represents a narrow alteration pipe associated with hydrothermal upflow zone feeding the broader shallow
mounds as in concept described by Tivey et al. (1993). Considering the small size of the mounds (~150 m
each) and short distance between them (120 m between the mound peaks), an alteration pipe is shared by
the mounds rather than they have two separate feeder zones. This conceptual model of the 137 data cross-
overs fits the data with the root-mean-square misfit of less than 100 nT after constant offset correction.
Magnetic susceptibilities required to match the observed anomaly amplitudes, however, greatly exceed
the range of susceptibility measurements indicating high remanent magnetization. The model is only able
to identify the bulk contrasts in the subsurface and reveal the complexity in the magnetization structure,
but it cannot uniquely resolve internal compositional and structural detail. Variations in both remanent
and induced magnetization corresponding to the changes in lithology could explain the observed signal
along with the variation in thickness. Closer line spacing and additional constraints are required to distin-
guish between different models and resolve the deposit in 3-D.

Mohn’s Treasure extinct hydrothermal venting site. Figure 7 shows an off-axis area of the mid-ocean ridge,
focused on the middle valley rift flank. The survey extends for 5,000 m along the rift valley wall fault and
3,600 m across it, which almost fully covers the whole rift flank from the crest of a rift-forming fault to the bottom of the axial rift valley, including approximately 500 m west from the crest. Morphologically most of the studied area is a mass-wasting feature resulting from slope failure and landslides. An integrated analysis of the detailed bathymetry, seafloor video observations, and drilling shows that this area is predominantly composed of lithified, semi-lithified and unconsolidated sediments. No volcanic manifestations are observed on the seafloor in this area. Drilling results show that the hard rock observed within the area is a sedimentary rock (claystone), which is commonly exposed by the faults or present as debris sparsely distributed along the slope, and with a distinctive angular shape in contrast to the rounded pillow basalt fragments abundant at the AVRs (Figures 3d–3f, photo observations from the area; Figure 7e, drilling site location). A seismic-stratigraphy study approximately 10 km north of the site reports that the sediment layer thickness on the western flank of the rift valley varies between 150 to 800 m (Bruvoll et al., 2009). Near-seafloor magnetic exploration registers much lower peak-to-peak dynamic range of the reduced to the pole anomaly values of approximately 3,000 nT (survey area: 17.8 km²), compared to the 7,000 nT observed over a much smaller area of Loki's Castle AVR survey (survey area: 1.15 km²), and 12,000 nT over the southern AVR2 (survey area: 28.6 km²; 3a; 7.26 km²: 3b). This could be explained by the presence of a thick layer of sediments separating basement rocks and the magnetic sensor in addition to possibly different
magnetization of the basement rock. Following the assumption that the subsurface structure of the studied rift flank segment is similar to the northern segment of the ridge imaged by reflection seismic (Bruvoll et al., 2009), an overall trend of magnetic intensity decreasing in the downslope direction as the thickness of mass waste material increases would be expected. Yet, magnetic data reveals the opposite tendency, suggesting that not only the volume of nonmagnetized material is influencing, but also the change in magnetization of the underlying crustal rocks. Available regional low-resolution aeromagnetic data (10-km line spacing and 300 m altitude survey; Olesen et al., 2010; Ogg, 2012) indicate that this area belongs to a transition zone between reverse Matuyama and normal Brunhes polarity epochs. We believe that the discussed survey covers this transition in high-resolution. Such a topic deserves a separate detailed discussion and tests. For the purposes of the current paper, we infer that the border between the normal and reverse polarity segments lies in parallel with the rift-forming fault presumably as denoted in Figure 7. Therefore, positive magnetic anomalies to the south and east of the assumed reversal border can be attributed to locally elevated magnetization, and vice versa for the upper part of the flank.

Figure 7. Mohn’s Treasure survey area in color shaded-relief representation, all illuminated from northwest. All grids are draped over bathymetry grid. Solid black line denotes survey track line with 150 m line spacing. Striped black line marks the extent of panels c and d. (a) Bathymetry resolved at 4-m scale. (b) Draped reduced-to-pole (RTP) total-field magnetic anomaly map gridded at 30 m, isolines drawn every 150 nT. (c) Analytical signal amplitude map. (d) Three-dimensional representation of the (b) panel segment marked by the striped black line. Black arrow tip points at the location of the hydrothermal material exposure documented in Figure 3f and marks the previously reported hydrothermal deposit Mohn’s Treasure. Red arrow marks the location of the drilling site where claystone core was retrieved. White question mark line denotes the supposed boundary between the normal polarity Brunhes and reverse-polarity Matuyama epochs. Green-red arrow points at the North.
The shapes of the positive anomalies depicted in Figures 7b and 7d do not give enough evidence to support a dike or sill intrusion; that is, there is no significant strike extent or localized character to the anomalies. We observe that these observations of two strong positive anomalies correlate with the presence of previously collected sulfide material at the same location (Pedersen, Rapp et al., 2010) and suggest that these sulfide deposits are creating a magnetic signal. This type of magnetic signature was observed in several locations around the world and is explained by the contrast between nonmagnetic sediments and the massive sulfide deposit usually containing highly magnetized magnetite, pyrrhotite (Gee et al., 2001; Körner, 1994; Pedersen, Rapp et al., 2010; Tivey, 1994). The interpretation for the smaller anomaly is confirmed by video material and sampling of hydrothermal material composed of pyrite and heterogeneous chimney material (Pedersen, Rapp et al., 2010) and corresponds to the Mohn's Treasure extinct hydrothermal field (MT-1 in Figure 7), as no water column indications of venting are registered at the site. The combination of the total magnetic field intensity data and its derivatives help to delineate the Mohn’s Treasure deposit as a causative body of approximately 200 m by 150 m. Euler deconvolution suggests that the depth to the source is around 15 m. This can be interpreted as the depth to the stockwork because the mound was largely weathered, by a combination of physical and chemical destruction of the magnetic minerals, and covered by a thin layer of sediments that leads to the increase of the distance to the source.

The bigger anomaly south-west of the Mohn’s Treasure deposit (Figure 7) consists of two smaller-wavelength anomalies approximately 350- and 400-m-long with peaks separated by approximately 800 m. These anomalies are slightly stretched in the downslope direction indicating influence of the dipping slope. All three seem to be separated from each other by faults. While Mohn’s Treasure is directly associated with the intersecting faults (Figure 7d), confirming the importance of structural control on the fluid flow by increasing permeability, impermeable faults may act as a seal preventing hydrothermal fluids from lateral migration (Knipe, 1992). The south-western anomalies have not been studied with the ROV during the cruise, and show no particular indications of past hydrothermal activity on the bathymetric data except for being associated with faults. However, the intensity contrast observed over these anomalies and the character of the magnetic signature of the Mohn’s Treasure make a strong case for interpreting these anomalies as another fossil hydrothermal deposit. On a larger scale, major rift-forming faults are recognized as major fluid pathways. The most recent electromagnetic data from the Mohns Ridge (Johansen et al., 2019) demonstrates the deep extent of the fluid circulation through such faults and its intensity across the ridge.

Euler deconvolution estimates the depth of the sources to be around 100 m assuming a cylindrical geometry, and twice as much for the spherical shape of the causative body. Since very little is known about the preservation of hydrothermal deposits after the venting activity has ceased and the deposits have been transported away from the ridge axis by seafloor spreading, the subsurface geometry is likely to be far more complex and should not be approximated by simple structures. Overall, close proximity of the anomalies, and their occurrence along one fault suggest that they belong to one plumbing system and share a fluid convection cell. Differences in the shape and intensity of the anomalies, and thus in the resulting depth estimations, their extent and relative position, could be a result of a different age of formation, and possibly reactivation of the hydrothermal activity. The southernmost anomaly MT-2 is adjacent to a deep landslide scarp. Such an extensive avalanche has resulted in a 75 m-deep fault scarp and should lead to the exposure of hydrothermal deposits, yet it is less pronounced in the magnetic intensity data. The analytical signal representation highlights the anomaly MT-3, whereas MT-2 is not resolved against the background. Due to the nature of the analytical signal, such effect can be explained by nonverticality of the source edges and the overall complexity of the shape of this body, also expressed by the scarp. Structural rotation has likely changed the direction of magnetization, which is not accounted for by analytic signal independent of the direction of magnetization. Another factor is the thinning of the magnetic source volume by an avalanche and its redistribution downslope. This relatively deep-seated collapse, with the magnetic anomaly centered on it, strongly supports the interpretation of the anomaly as a fossil hydrothermal deposit, and suggests a high proportion of hydrothermally altered material beneath it that eventually led to a collapse of the hydrothermally altered edifice.

Other anomalies observed in the upper part of the flank, presumably representing reversely-magnetized crust, need more careful analysis for further interpretation and are not discussed within this paper.

*Exploration of AVR2 and the implications for hydrothermal venting.* For the third study area, we use high-resolution bathymetry and magnetic data along the axial volcanic ridge (AVR2) (Figure 8) to investigate...
its detailed morphology and the variation of the magnetic field intensity in order to address the following questions: Are there significant anomalies that can be associated with hydrothermal activity? What are the magnetic signatures of the distinctive volcanic features observed in the bathymetry? Are there tectonic features associated with the anomalies? What are the implications of these observations for the hydrothermal venting?

Video footage and detailed bathymetry captures the northern half of the AVR₃ displaying classic features of the neo-volcanic zone associated with the slow spreading. Essentially, the topography is entirely controlled by volcanic processes, and is mostly composed of relatively fresh pillow lava flows with a thin sediment cover (Figures 3g–3i). From video survey observations, and based on the assumption that sediment cover degree is indicative of the lava flow age (Mitchell et al., 1998), the ridge appears to become younger toward the central part of it, as sediment cover thins out. There is a strong correlation between the topographic and magnetic profiles, even after the loose drape geometry was corrected to a constant terrain offset. The magnetic intensity, in this context, could be an indicator of the extrusive lavas thickness and volume of the magnetized material, where the peaks indicate the most recent lava deposition (Schouten et al., 1999; Zhang et al., 2018). The observed along-strike variations in magnetic intensity at the AVRs are consistent with the seismic refraction data from the Mohns Ridge acquired further south, showing an unusually thin, 2–5 km, yet highly variable oceanic crust (Johansen et al., 2019; Klingelhöfer et al., 2000). The dynamic range of the total magnetic field within this area is around 11,000 nT highlighting the volcanic nature of the area (Figure 8b).

Sulfide material discoveries on both sides of the AVR₃ (Figure 1)—western rift flank and the rift valley floor on the east (Pedersen, Rapp et al., 2010)—indicate the presence of a working plumbing system, that must have been active in the past. The cruise data, however, show no sign of a currently active hydrothermal venting—no water column anomaly was found in the survey area, and no visual evidence was found in the ROV footage. The abundance of fissures and recent lava flows suggests abundant dike intrusions and eruptions, which implies the presence of a magmatic heat source nearby which would drive hydrothermal fluid circulation. On the other hand, eruption events can cause a temporal or even permanent clogging of the hydrothermal vents, as well as cover mature deposits preventing their identification. Moreover, fresh volcanics that have not lost their reactive components are prone to faster clogging (Wolery & Sleep, 1976). Another explanation for the lack of hydrothermal venting at this AVR segment could be the lack of deep high-angle fault populations with diverse orientation, preferably intersecting faults. While downflow of the seawater is attributed to the porous flow mode, venting is mainly associated with the crack zones. Planar faults and fissures are not sufficient to sustain hydrothermal venting at neo-volcanic zones (Sleep & Wolery, 1978), though more likely to form deposits at the sediment-hosted environments where sediment-blanketing aids the process. Also, the cooler crust under the slow-spreading ridges requires an excessive depth of water penetration to harvest the heat. Comprehensive analysis of the area does not provide substantial data to attribute any of the observed magnetic anomalies to considerable hydrothermal deposits of more than 250 m across, given the survey configuration parameters.

However, each anomaly is associated with a distinct volcanic feature, for example, stand-alone volcanic cones or hummocks and their clusters, prominent linear fissure-controlled volcanoes following expected tectonic alignment, but also oblique, or even normal to the AVR edifices. The TDR of the total magnetic field data (Figure 8c) is very instrumental in constraining these features and identifying them in spite of the smaller amplitudes or shorter-wavelength. The deviations of volcanic lineaments and faults in the studied segment (31°NE) from the expected axial trend (39°NE) manifest the obliquity of the rifting, which is common in slow-spreading nontransform offsets and is explained by the oblique shear stress. Curved and sigmoidal faults also suggest the rotation of stresses between the offset spreading segments (Tyler et al., 2007). The stresses surrounding discontinuities and the rotation in the volcanic crust can create more complex cross-cutting fault populations that will grow in both horizontal and vertical direction forming soft-link relay structures, or evolving into hard-link relay structures at the later stages, promoting hydrothermal circulation.

Fissure-fed linear volcanic features are consistent with elongated magnetic highs across the survey, the intensity grows as it gets thicker toward the central part. Short-wavelength circular anomalies correspond to single volcanoes or small agglomerations of several cones, while longer anomalies spreading out from the central volcanic ridge have a smaller intensity and likely represent gravitational features, flows that
extend further from its steep-flanked source under gravity. Such flow was observed with the ROV tracing it to its steep-flanked source. Nontransform offsets can explain bigger volcanic features elongated normal to the AVR axis that connects abundant axial ridges with the new one.

A distinctive magnetic signature is observed over a flat-topped volcano identified in the Survey 3b. A ring-shaped feature as outlined in TDR map (Figure 9) with 1,000 nT contrast in intensity between its central part or caldera and a rim perfectly contouring the seamount. This seamount has typical dimensions of a flat-topped volcano (Clague et al., 2000): approximately 1.2 km wide and 200 m high with a central caldera drained inside by roughly 5 m. The detailed bathymetry shows traces of overflowing lava on its steep southwestern slope, with several fissures dissecting it in the NE direction subparallel to the AVR trend, and a small-offset fault (Figure 9). The formation of such a seamount requires the presence of a near-surface magma chamber feeding it through the development of ring-fractures (Simkin, 1973). The TDR signature potentially captures the presence of such circumferential feeders, and a fractured caldera above hot magma chamber in the center. The zero-values define the source edges as they are assumed to be vertical (Figure 9).

A presence of a flat-topped volcano suggests a presence of a shallow magma chamber, known to serve as a primary heat source for many active hydrothermal venting systems found along the mid-ocean ridges. The maintenance of a long-lived eruption is essential to form lava ponds and sustain magma supply creating repeated lava overflows that eventually reach the balance between the outward and upward growth forming a flat-topped seamount (Clague et al., 2000). This also indicates the presence of a sustained magma supply, implying a later adolescent stage of development of the AVR according to Parson et al. (1993). Yet, a small number of such volcanic features and lack of faulting, suggests that the AVR has not yet finalized its volcanic construction stage and has not entered the tectonic stage. The identified magnetic signature of a flat-topped volcano informs our interpretation of the Loki’s Castle hydrothermal field. The latter can be recognized as a flat-topped volcano that has been intensively faulted, suggesting that AVR1 has been subjected to tectonic destruction and is at later development phase than AVR2 (Parson et al., 1993). Morphological examination of the two AVRs and hydrothermal manifestations, or lack of thereof, suggest that later tectonic destruction phases of AVR development are more likely to sustain hydrothermal venting at the magma-starved ultraslow-spreading ridges than early phases of volcanic construction through increased population and complexity of the faults that weaken the crust and focus hydrothermal flow onto the seafloor.

Figure 8. Exploration AVR survey area in color shaded-relief representation, all illuminated from northeast. Black line denotes survey track line with 250-m line spacing. All grids are draped onto the bathymetry grid. (a) Bathymetry resolved at 1-m scale. (b) Draped reduced-to-pole (RTP) total-field magnetic anomaly map gridded at 30 m for Survey 3a and 40 m for Survey 3b, isolines drawn at every 150 nT. (c) Magnetic Tilt Derivative (TDR) map. The white striped line box indicates the extent of the data presented in Figure 9.
5. Conclusions

Near-seafloor magnetic data from the ultraslow-spreading Mohns Ridge is presented for the first time in this paper. Analysis of the high-resolution bathymetry and magnetic data enabled identification of hydrothermal deposits associated with both active and inactive hydrothermal venting sites, providing insights into magmatic and tectonic processes interplay along the axial volcanic ridges.

1. Loki’s Castle, an active hydrothermal venting field, consists of two likely interconnected sulfide mounds located on top of a relay structure at the downthrown block of a significantly faulted flat-topped seamount. Rock magnetics and profile magnetic data suggest a negative magnetization contrast associated with the basalt-hosted Loki’s Castle deposit. Forward 2-D modeling shows that a localized body having reduced magnetization fit the observed data as one of the concepts. Closer line spacing and stronger control on the altitude of the AUV is required to resolve the deposit in 3-D. Our current investigation can be used as guidelines for further data acquisition.

2. Mohn’s Treasure, a fossil sediment-hosted hydrothermal deposit, is associated with a positive magnetic anomaly coincident with sulfide samples recovered from the site. The anomaly is centered at a fault crossing on the slope of a mass-wasting deposit of the western rift flank. It accounts for an approximately 200-m × 150-m causative body buried by sediments at approximately 15-m depth. The site has enhanced magnetization and produces a clear magnetic signature enabling identification of two new deposits.

3. Two strong positive magnetic anomalies near the Mohn’s Treasure (MT-1) reveal new extinct hydrothermal venting sites, MT-2 and MT-3. They exhibit the same magnetic signature as the Mohn’s Treasure and structural indications of hydrothermal alteration like a deep fault scarp exposed by the collapse.

Figure 9. A flat-topped volcano in a 3-D view. (a) Color scheme corresponds to the change in the dip angle. This representation highlights volcanic nature of the topography: flat-topped volcano and its crater, overflowing lava lines, fissures and faults well-resolved at 1 m. High-resolution data gaps are interpolated using minimum curvature algorithm and marked by text. (b) Magnetic Tilt Derivative (TDR) draped onto the bathymetry grid with isolines at 0.1. The thick black line marks zero-crossing.
4. The increasing prevalence of faulting and its complexity has positive implications for hydrothermal discharge and potentially controls the occurrence of active hydrothermal venting field in the northern AVR, currently undergoing a destructive tectonic stage.

5. In contrast, the southern AVR can be classified as adolescent AVR still going through volcanic construction phase. It is devoid of faulting, shows no indication of on-going hydrothermal activity, even though there are manifestations of the extinct hydrothermalism just outside of it.

6. Potentially, hydrothermal activity along slow-spreading centers follows the cyclicity of the AVR development and is likely to appear and sustain itself during tectonic destruction stages. Structural complexity driven by intensive faulting becomes a major controlling factor on the occurrence of hydrothermal venting within a neo-volcanic zone.

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