MILJØ-
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RAPPORT

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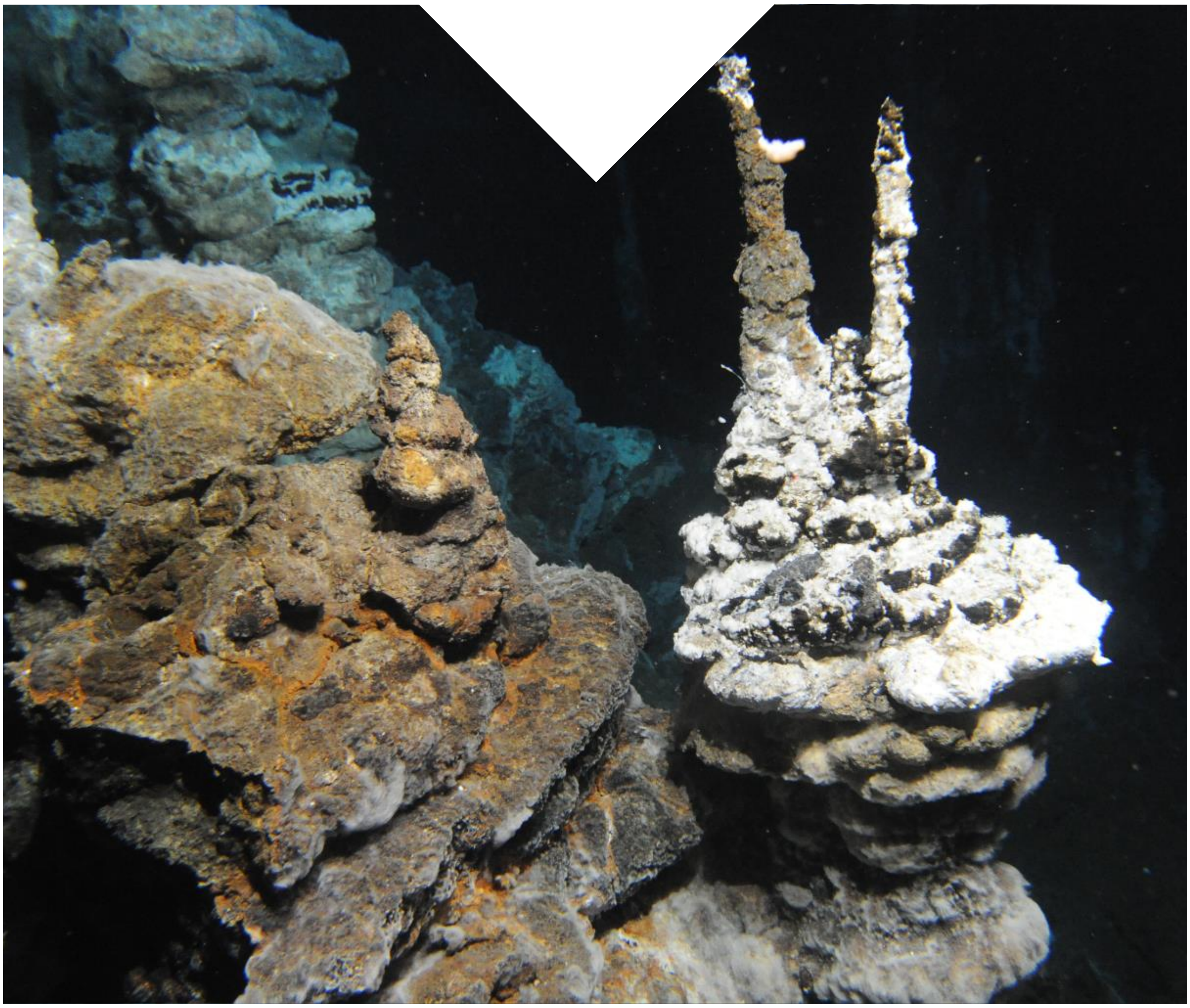
# Environmental challenges related to offshore mining and gas hydrate extraction



# KOLOFON


**Utførende institusjon**

Centre for Geobiology and Centre for Deep Sea Research, University of Bergen

**Oppdragstakers prosjektansvarlig**

Hans Tore Rapp

**Kontaktperson i Miljødirektoratet**

Ingrid Handå Bysveen

| M-nummer | År | Sidetall | Miljødirektoratets kontraktnummer |
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**Forfatter(e)**

Bernt Rydland Olsen, Ingeborg Elisabeth Økland, Ingunn Hindenes Thorseth, Rolf Birger Pedersen, Hans Tore Rapp


**Tittel - norsk og engelsk**

Miljøutfordringer relater til utvinning av mineraler og gass-hydrater fra havbunnen
Environmental challenges related to offshore mining and gas hydrate extraction


**Sammendrag - summary**

Denne rapporten oppsummerer dagens kunnskap om forekomster av mineraler og gasshydrater på havbunnen i norske farvann, og gir en oversikt over dagens kunnskap og kunnskapshull relatert til biologiske samfunn (arter/naturtyper) som kan forventes å bli påvirket som følge av framtidig utvinning av mineraler og gass-hydrater fra havbunnen.

This report summarizes the current knowledge of known resources of deep-sea minerals and gas hydrates in Norwegian waters and the biology and ecosystems represented in such areas. The major gaps of knowledge regarding the biodiversity is identified; the distribution, function as well as the goods and services provided by these ecosystems.



**4 emneord**

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Centre for Geobiology and Centre for Deep Sea Research, University of Bergen

# Innhold

**Sammendrag**

Denne rapporten oppsummerer dagens kunnskap om forekomster av mineraler og gasshydrater på havbunnen i norske farvann, og gir en oversikt over dagens kunnskap og kunnskapshull relatert til biologiske samfunn (arter/naturtyper) som kan forventes å bli påvirket som følge av framtidig utvinning av mineraler og gass-hydrater fra havbunnen. Rapporten gir en oversikt over hva som gjør disse samfunnene spesielle, hvilke trusler representerer denne typen næringsaktivitet i slike områder og hvilke hensyn som bør tas, før, under og etter næringsaktivitet.

Langs den arktiske midthavsryggen og langs den norske kontinentalsokkelen og kontinentalskråningen finnes det en rekke unike men dårlig kjente økosystem og naturtyper. Områder med varme og kalde gassoppkommer og områder med metanhydrater er ofte kolonisert av svært spesialiserte organismer, og gir opphav til en rekke sårbare marine økosystem i områder som ofte sammenfaller med fiskerier, olje- og gassutvinning og fremtidig utvinning av mineralressurser. Selv om disse områdene er kjent for sitt biologiske mangfold, økologiske betydning og bioteknologiske potensiale, har det så langt vært begrenset forsknings- og forvaltningsfokus på disse økosystemene i norske havområder.

**Summary**

This report summarizes the current knowledge of known resources of deep-sea minerals and gas hydrates in Norwegian waters and the biology and ecosystems represented in such areas. The major gaps of knowledge regarding the biodiversity is identified; the distribution, function as well as the goods and services provided by these ecosystems. It also aims to identify the main threats and impacts posed upon these ecosystems by future gas exploitation, and mining of deep sea minerals and outlines environmental elements to be considered before, during and after mining/extraction activities.

A high variety of unique and by far unexplored extreme deep-water ecosystems and nature types are found in along the Arctic mid-ocean ridge and along the Norwegian continental shelf and slope. Areas with hydrothermal vents, methane seeps/areas with methane hydrates often host assemblages with very specialized biota, and form a variety of vulnerable marine ecosystems in areas which often coincide with fishing, oil and gas exploitation, as well as future mining of deep sea minerals. Even though their biodiversity, ecological importance and biotechnological potential is assumed to be high, these ecosystems have so far received relatively little scientific or conservation attention in Norwegian waters.

**Report rationale**

Mineral deposits and gas hydrates are presently non-utilized resources, but may be subject to commercial exploitation in the future. However these resources are often found in very inaccessible and poorly known areas. These areas host ecosystems that are potentially vulnerable to the physical impact caused by utilization of these resources. Therefore it is instrumental to conduct thorough Environmental Impact Assessments (EIA) and that the EIAs are based upon solid basic science. This report aims to provide an overview of current knowledge and gaps regarding biological communities from both deep-sea mineral deposits/hydrothermal vents and gas hydrates. Furthermore it aims to provide information that can serve as a first step towards a knowledge-based management plan and future EIAs for areas hosting these resources.

**Report limitations:**

The report covers the Norwegian Economical Exclusive Zone (EEZ), Svalbard EEZ as well as areas within the Extended Continental Shelf and international waters along the Arctic Mid-Ocean Ridge (AMOR). Norway regulates the Norwegian national waters in addition to the Svalbard waters, while the International Seabed Authority (ISA), established under the United Nations Convention on the Law of the Sea (UNCLOS) article XI (1994), regulates the international waters (Allen 2001). Furthermore, the report is restricted to known resources of Seafloor Massive Sulphide deposits (SMS-deposits) from active hydrothermal vents and known gas hydrates resources along slopes of the Norwegian coast and western part of Svalbard. The report does not cover polymetallic crust resources discovered along the Jan Mayen Ridge and the Jan Mayen Fracture Zone as there yet is very limited knowledge about these resources and the associated biota.

Within Norwegian waters it is primarily the SMS-deposits along the Arctic Mid-Ocean Ridge that have been given attention. From that area four active and two inactive vent sites with SMS-deposits are known. The report will focus on these habitats, with special emphasis on the active localities. Climate change aspects of the gas hydrate resources will not be discussed, although there are concerns regarding the utilization of methane from a climate change perspective.

As SMS-deposits and areas with gas hydrates are two very different ecosystems these will be treated separately in two different chapters (part A and B).

**Definitions/abbreviations:**

| | |
|---|---|
| AVF | -Aegir's Vent Field |
| Ag | -Silver |
| AMOR | -Arctic Mid-Ocean Ridge |
| Au | -Gold |
| Baseline | -Natural conditions, often presented as a time series |
| Breccia | -Breccia is a clastic sedimentary rock similar to conglomerate that can be formed in a variety of ways |
| Chalcopyrite | -Copper Iron sulphide |
| Co | -Cobolt |
| Cu | -Copper |
| EIA | -Environmental Impact Assessment |
| EEZ | - Economical Exclusive Zone |
| Fe | -Iron |
| Galena | -Lead sulphide |
| Hyaloclastite | -hydrated tuff-like breccia |
| ISA | -International Seabed Authority |
| JMVF | -Jan Mayen Vent Field |
| LCVF | -Loki's Castle Vent Field |
| Marcasite | -Iron sulphide |
| Mn | -Mangan |
| Pb | -Lead |
| Pyrite | -Iron sulphide |
| Pyrotitt | -Iron sulphide |
| SMS-deposits | -Seafloor Massive Sulphide deposits |
| Sphalerite | -Zink sulphide |
| SSVF | -Seven Sisters Vent Field |
| UNCLOS | -United Nations Convention on the Law of the Sea |
| Zn | -Zink |

# 1. PART A - Mineral Resources

The main types of mineral deposits in the marine environment currently being considered for exploitation are SMS-deposits, Mn-nodules and Co-rich crusts. In Norwegian waters the main focus has so far been on SMS deposits. Seafloor massive sulphide deposits generally contain metals such as Fe, Cu, Zn, Pb, Ag and Au, and are found in both active and extinct hydrothermal systems. Hydrothermal systems are associated with plate boundaries at Mid-Ocean Ridges, volcanic arcs or at back arc spreading centres (e.g. Rona 2008; Hannington et al. 2011; Hoagland et al. 2010). They form when seawater circulates through the seafloor and reacts with the surrounding rocks. The seawater is heated by an underlying magmatic source and may reach temperatures above 400˚C. Due to the increased temperature the fluids will rise towards the seafloor, and when the warm fluids meet the cold seawater the dissolved metals precipitate as metal sulphides (e.g. Rona et al. 1987; Alt 1995; Wheat and Mottl 2000; Kelley et al. 2002; Früh-Green and Bach 2010). This precipitation process occurs either at the seafloor as chimney-like structures or below the seafloor. There are several types of systems depending on geological setting, depth and the temperature of the hydrothermal fluids. In general deep and high-temperature systems have higher concentrations of Cu. At present there is no commercial exploitation of SMS deposits. However, Nautilus Minerals expect to start mining the Solwara 1 hydrothermal deposits outside Papua New Guinea in 2018.

The first discovery of a deep-sea hydrothermal vent and its associated life was in 1977 at the Galapagos Rift (Lonsdale 1977), leading to a renewed interest for deep-sea biology, which today is a very vibrant field of research. Hydrothermal vents and organic falls are ephemeral habitats that are colonized by organisms relatively fast (Vrijenhoek 1997). Their temporal nature is dependent on the underlying geology, and while some vents are fairly recent, other vent areas have existed for several tens of thousands of years. Organisms living there are adapted to the low stability and the ephemeral nature of the hydrothermal vents (and other reducing habitats) (e.g. Smith et al. 1989; Vrijenhoek 1997). Hydrothermal vents are of ephemeral nature as venting may cease because of changes in tectonic activity. From an evolutionary perspective there seems to be a quite rapid adaptation of organisms to a life at hydrothermal vents. This is possible because most invertebrates have a short life span and a short reproductive cycle (or reproduce often), and a single vent site that has existed only a brief moment in geological time scale has served as a stable habitat for perhaps thousands of years or generations. Hydrothermal vents are of different age; while older ones over time become less active and colder, new ones are established and a new colonisation process starts. Each vent can be considered a stepping-stone in the colonisation process, and e.g. Smith et al. (1989) and Tandberg et al. (2013) also include fall biota and cold seeps among the stepping-stones because of the somewhat similar reducing conditions. The temporal overlap between these stepping-stones makes it possible to maintain deep-sea chemosynthetic ecosystems in an area in spite of the relatively short lifetime for each “stone”. The adaptation and specialization at hydrothermal vents is made possible by some key factors. First is the temporal overlap mentioned above, i.e. a new vent or fall is colonized before the first becomes extinct.

Secondly, that reducing habitats[1] are widespread, even though hydrothermal vents are normally located along mid-ocean ridges. Thirdly, that many of the organisms have life history strategies and adaptations supporting pelagic transport (high genetic connectivity), so that they are always potentially ready to colonize new sites regardless of the instability within individual sites. The key to continuity is nevertheless a sufficient number of suitable hydrothermal habitats within an area reachable by larvae, and continuous supply of new large falls such as e.g. whales and tree trunks.

Thus, if we can consider the vents to be biologically stable even though vents are ephemeral we then need to ask what role the vents do play in a broader perspective such as e.g. plankton life history and if for instance they may be a buffer against the low organic input during the low productive season? Are hydrothermal vents and other chemosynthetic ecosystems housing unique, isolated niches for small and fragile assemblages of biota, or are they part of a larger, vital community that is able to provide the stability needed over time for genetic adaptation and endemism? Do the vent organisms illustrate that marine invertebrates in general are resilient to rapid environmental changes or are the vent adapted animals rather the exception? And more importantly, are the vent communities resilient enough to resist the extra impact that mining may represent? These are important environmental questions that are concerning both scientists, management bodies and the general society, and this report aims to give a short summary of current status of knowledge, identify knowledge gaps, and to pinpoint the most important concerns to be taken into consideration in the context of mining of deep-sea mineral deposits in Norwegian waters.

[1] Reducing/chemosynthetic habitat: environment that contains reduced abiotic chemical species like methane and sulphides which chemotrophic microorganism can convert to organic energy.

## 1.1 Geographical location of known mineral resources of potential commercial value in Norwegian waters

Several active and inactive hydrothermal systems have been discovered along the Arctic Mid-Ocean Ridge (AMOR) (Pedersen et al. 2010a, 2010b). These vent fields are located within the Norwegian EEZ or at the Extended Continental Shelf. So far two inactive and four active hydrothermal systems with potential mineral resources have been detected at the Kolbeinsey-Ridge and the Mohns- and Knipovich Ridges (Table 1, Figure 1).

**Table 1 Known active vent fields with associated Seafloor Massive Sulphide-deposits (SMS-deposits) along the Arctic Mid-Ocean Ridge.**

| SMS-deposit locality | Year of discovery | Hydrothermal Vent Field | Ridge | Depth | SMS-deposit locality |
|---|---|---|---|---|---|
| **Troll Wall** | 2005 | Jan Mayen Vent Fields (JMVF) | Mohn Ridge | 500 meter | Troll Wall |
| **Soria Moria** | 2005 | Jan Mayen Vent Fields (JMVF) | Mohn Ridge | 700 meter | Soria Moria |
| **Loki's Castle** | 2008 | Loki's Castle Vent Field (LCVF) | Knipovich Ridge | 2400 meter | Loki's Castle |
| **Perle and Bruse** | 2013 | Jan Mayen Vent Fields (JMVF) | Mohn Ridge | 500 meter | Perle and Bruse |
| **Seven Sisters** | 2013 | Seven Sisters Vent Field (SSVF) | Kolbeinsey Ridge | 140 meter | Seven Sisters |

These vent systems are found in a range of environmental settings, ranging in depth from 140-2500 m depth and with vent fluids ranging in temperature from few degrees to 320°C.
The systems are found both along faults and on volcanic structures, and so far purely basalt-hosted systems as well as basalt-hosted systems with sediment influence have been found. There are, however, indications for several unexplored active hydrothermal vent fields along the Mohns- and Knipovich Ridges (chemical indicators have been detected in the water column), and it is also likely that a number of extinct fields are present in the same area.

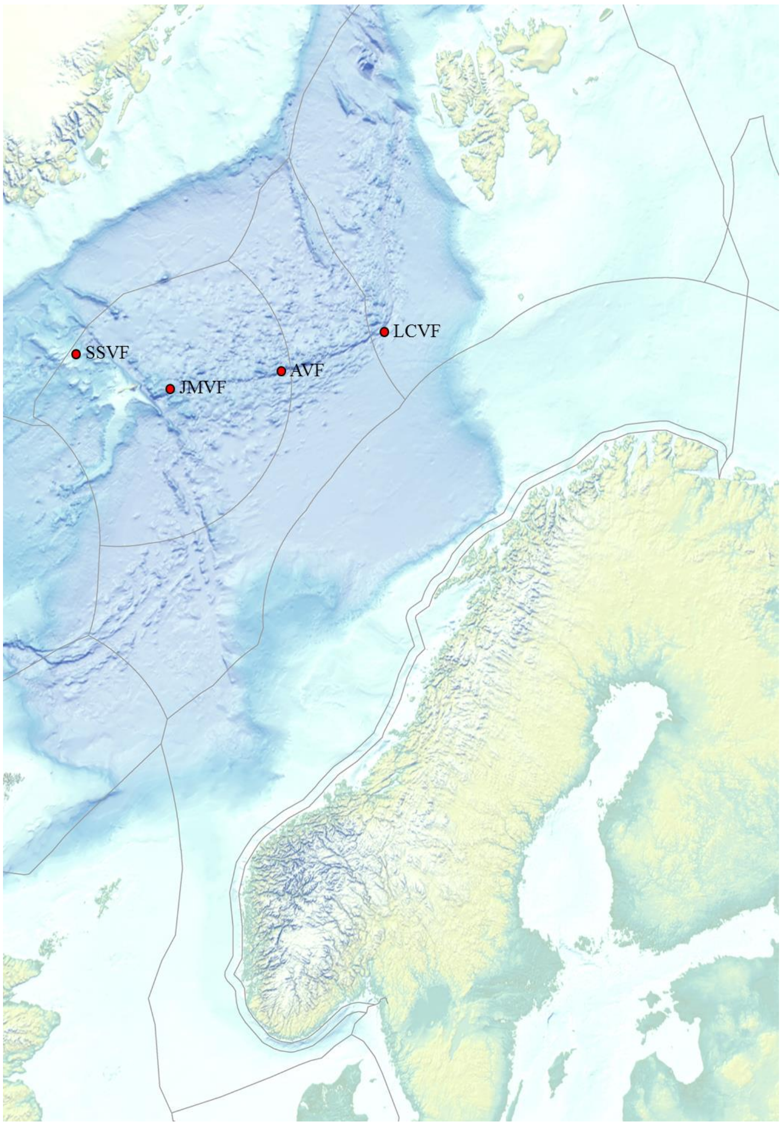


*Figure 1 Map of known locations of SMS-deposits within the Nordic Seas and along the Arctic Mid-Ocean Ridge (AMOR), which is shared between Norwegian and International waters. The lines indicate the EEZ of Norway and Svalbard.*

There is also potential for finding vent fields in a range of different settings, including systems related to ultramafic rocks and sediment-hosted systems along the AMOR. At present there are no well-documented quantitative estimates of the mineral resources associated with any of these systems in the Norwegian waters. Existing resource estimates are not based on empirical studies.

# 1.2 Seafloor Massive Sulphide-deposits – Vent sites, threats and environmental impact

## 1.2.1 Vent sites

Seafloor Massive Sulfides (SMS) discovered this far in Norwegian waters are located at the northern Kolbeinsey Ridge and along the entire Mohns Ridge that define the central parts of the Arctic Mid-Ocean Ridge system (AMOR) (Pedersen et al. 2010b). Within this area there are six confirmed active hydrothermal systems. Four of these are within the Norwegian EEZ, one within the fishery protection zone of Svalbard and one is located at the Extended Continental Shelf at the central part of the Mohns Ridge. These six sites cover a wide geographic range as they are spread from Eggvinbanken at the northern Kolbeinsey Ridge in the southwest, and from the Jan Mayen area north-eastwards along the Mohns-Ridge to the southernmost part of the Knipovich Ridge. There is great variation in depth and oceanographic settings for the different sites. The fluid composition is also highly different between sites, resulting in a large variation in the composition of the SMS-deposits. A summarily description of the different sites is presented below.

**The Seven Sisters Vent Field (140 meters depth**

Seven sisters vent field (SSVF) is found on the Kolbeinsey Ridge (Figure 1). It is a shallow (~140 m), relatively high temperature system (~200°C) hosted in mafic volcanoclastic rocks. It is suggested that the mineralization is the result of magma-dominated processes with signatures atypical from those usually found in a slow-spreading mid-ocean ridge setting (Marques et al. 2015). Sulphide minerals (marcasite, pyrite, chalcopyrite and sphalerite) are present in minor amounts (often <5%) in mineralized volcanoclastic breccias (Marques et al. 2015).
Biological samples from SSVF are scarce and there are no final and detailed species lists. The habitat is a mixed hard and soft substrate with variable topography. However, preliminary data and video footage suggest that background fauna from the surrounding area dominates the fauna (Figure 2) in the same ways as have been observed at the Jan Mayen Vent Field (below). The most conspicuous organisms are the very dense aggregations of sea anemones (mainly *Urticina eques* and *Hormatia* sp.) and colonial ascidians.

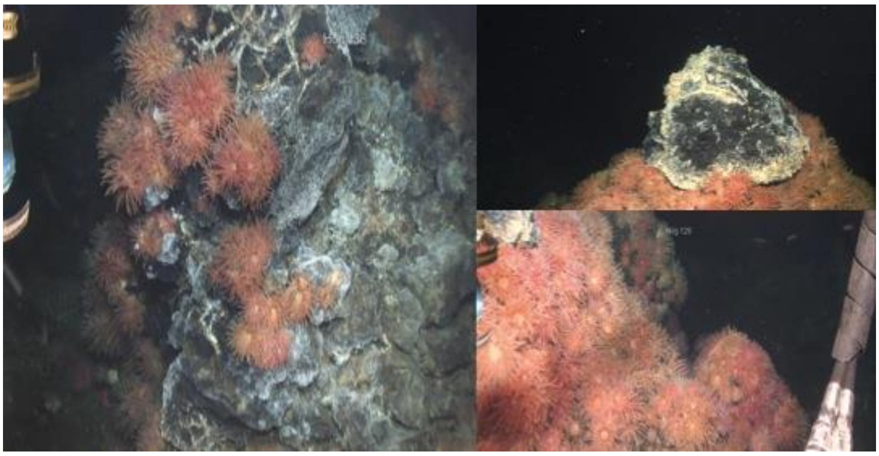

*Figure 2 Remote Operated Vehicle (ROV) images from the Seven Sisters Vent Field (SSVF). The dense coverage of anemones on the chimney walls except on the summit of chimneys, suggests that there are very steep temperature gradients in the system*

**The Jan Mayen Vent Fields (550 meters depth)**

The Jan Mayen vent field area (JMVF) is located at the Mohns Ridge at 71°N (Figure 1). It consists of at least three high-temperature vent fields: Soria Moria, Troll Wall and Perle and Bruse. The fields are found between 500 and 700 m depth and are of the white smoker type. The emanating fluids have temperatures up to 270°C, pH between 4.1 and 5.2 and high $CO_2$ contents (Pedersen et al. 2010b). The Troll Wall is the largest of the systems and is located in talus deposits along a fault at the eastern margin of a rift valley at approximately 550 m depth. It consists of at least 10 major active sites, each contain several chimneys, which are 5-10 m tall. The chimneys contain minor amounts of sphalerite and pyrite (Pedersen et al. 2010b). A diffuse, low-temperature (7°C) venting area, about 500 m west of the high-temperature venting, is characterised by a large number of iron-mounds that are deposited on top of hyaloclastite and basaltic debris in the rift valley (Möller et al. 2014). The Soria Moria is located in lava flows at the top of a volcanic ridge at about 700 m depth, and consists of at least two different venting areas with several 8-9 m tall chimneys (Pedersen et al. 2010b). The chimneys contain minor amounts of pyrite, phalerite and galena. The Perle and Bruse consist of two areas with several chimneys. The chimneys contain minor amounts of pyrite, sphalerite and galena. No resource estimates of the deposits have been made for any of the Jan Mayen Vent fields.

The JMVFs have a mixed hard and soft substrate with variable topography. The fauna of the Troll Wall and Soria Moria fields is a relatively well described in Schander et al. (2010). These vent fields, which were the first fields discovered at the AMOR (2005), are also the most visited/investigated fields in Norwegian waters. The discovery of a third field in 2013, The Perle and Bruse indicates that that our knowledge is limited in spite of frequent scientific cruises. Moreover, there are also organisms found only once suggesting differences within a short range and that we have not reached an asymptote regarding species richness. The overall fauna composition is nevertheless similar throughout the field with natural variation according to substrate, inclination and temperature. Apart from the bacterial feeding Gastropods *Skenea* spp. and *Pseudosetia griegi* as well at cladorhizid sponges the fauna is dominated by typical bathyal species from the surrounding waters (Schander et al. 2010; Sweetman et al. 2013) (Figure 3).

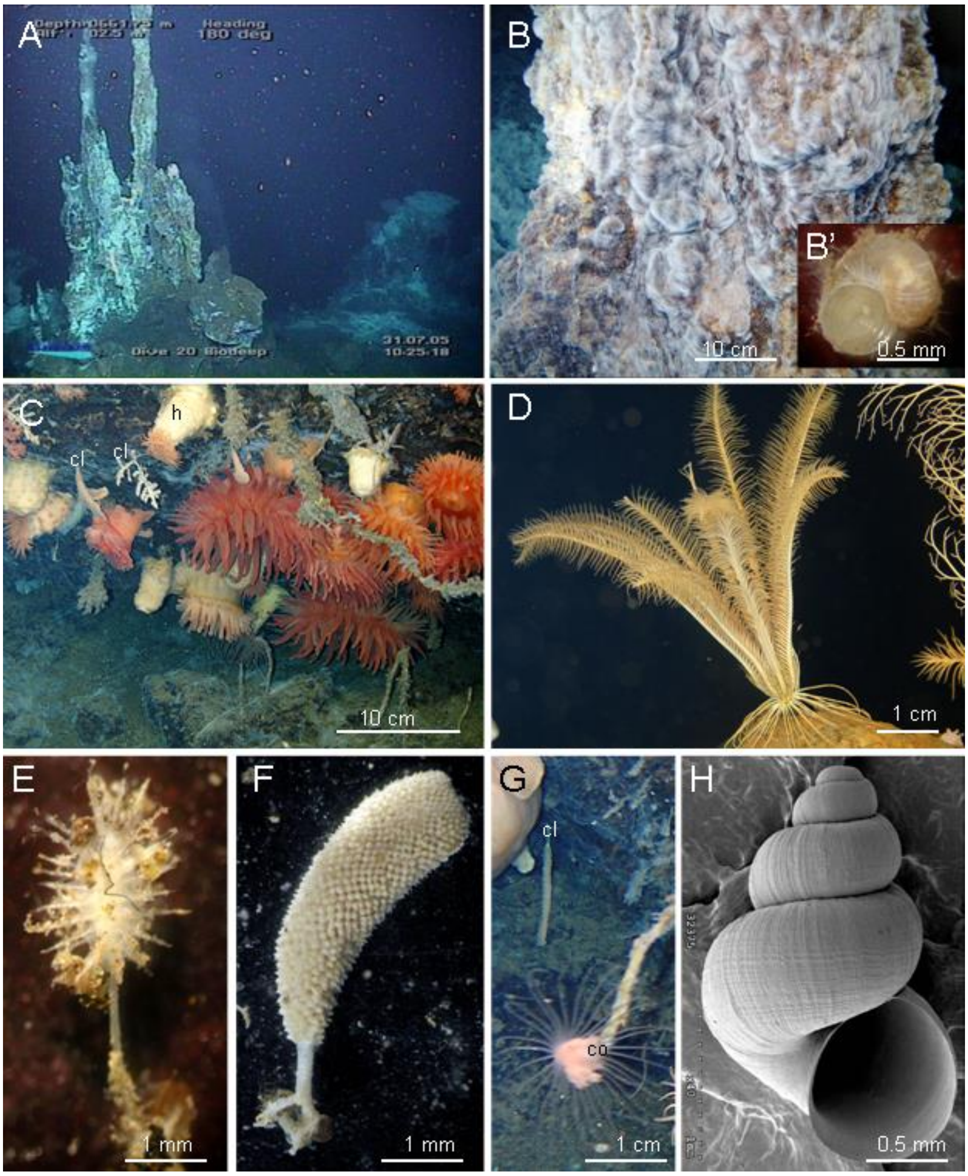


*Figure 3 Remotely Operated Vehicle (ROV) images from the Jan Mayen Vent Field (JMVF) (A-G). A. White smokers on the Soria Moria vent field. B. Chimneys covered by a dense mat of Beggiatoa-like bacteria. B'. A juvenile of Skenea sp. from the bacterial mats. Note the filamentous bacteria growing on the shell. C. Typical vertical rocky surface just some meters away from the chimneys. These surfaces are covered by large anthozoans (Hormathia sp. (h) and others), several species of cladorhizid sponges (cl) and the hydroid Corymorpha groenlandica (co). D. The crinoid Heliometra glacialis form dense aggregations surrounding the vent fields. E. Unidentified cladorhizid sponge found growing directly on a smoker. F. Sycon abyssale, one of the calcareous sponges common in the area. G. Corymorpha groenlandica (co) and a cladorhizid sponge (cl) hanging on a vertical surface. H. Pseudosetia griegi without bacterial filaments (SEM photo) (from Schander et al. 2010).*

**The Ægir's Vent Field**

The Aegirs Vent Field (AVF) was discovered in 2015 at 2200 meters depth at a volcanic ridge on the central Mohns Ridge. At present the only data collected is video footage and rocks for geological/geochemical characterization, and no data have so far been published from this vent field. Based on the very limited video footage available, the field appears quite similar in appearance regarding the fauna when compared to the Loki's Castle, but different from more shallow vent sites in the area (Figure 4). The amphipods observed close to the diffuse venting, and even close to the summit of a chimney, may be similar to one observed at the Loki's Castle Vent Field (LCVF), and the fish also seems similar to those that are found at LCVF. Due to the depth one would expect even more similarities with Loki' Castle, but it appears quite different, probably because there are no sedimentary areas with *Sclerolinum* fields at AVF.

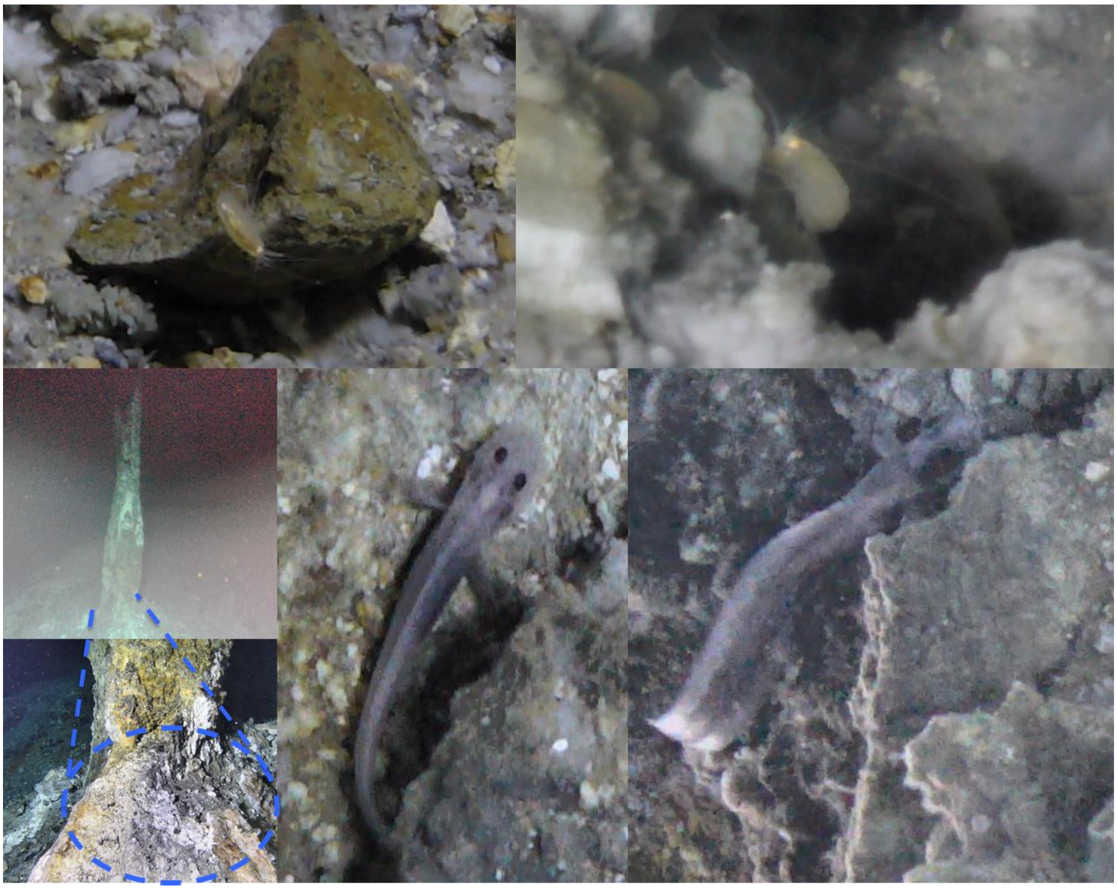

*Figure 4 These are the first images from the Aegir's Vent Field (AVF) discovered in 2015. In the upper part of the figure it is possible to see an amphipod close to diffuse venting (unknown temperature). The lower right part shows a fish (an eelpout) similar to those known from Loki's Castle Vent Field. This fish was highly abundant at this site. The lower far left part shows an overview of one the chimneys (approximately 10 m tall). The blue circle corresponds to the location of the fish and amphipods in the figure.*

**The Loki's Castle Vent Field**

Lokis's Castle is located at 2400 m depth at 73° N, 8°E at the Mohns Ridge-Knipovich Ridge transition at the crest of an axial volcanic ridge. It is a black smoker system with 5 chimney structures that are up to 11 m tall. The emanating fluids have temperatures up to 320°C, a pH of 5.5 and a chemical composition that indicates influence of buried sediments, probably from the Bear Island fan. The main sulphide minerals are sphalerite, pyrite and pyrrhotite. There are also minor amount of chalcopyrite present in the chimneys. A diffuse low-temperature venting area with numerous up to 1 m tall barite chimneys located on the eastern flange of the sulphide mound. The temperature of the fluids in the barite field emanating from the active chimneys is up to 20°C (Eickmann et al. 2014; Steen et al. 2016).

The discovery of Loki's Castle is perhaps the most ground-breaking discovery made during the investigations along the AMOR so far. It was the first black smoker vent system ever found on an ultraslow spreading ridge and it represented the first record of true vent-endemic macroorganisms along the AMOR (Pedersen 2010a, Tandberg et al. 2011, Kongsrud and Rapp 2012). The fauna is different from the surrounding deep-sea of the Nordic Seas and a preliminary characterization of the field suggest two zones; 1) black smoker chimneys with microbiota, but also with gastropods and amphipods, and 2) low-temperature venting with barite chimneys. The first is a hard substrate where the fauna is sparse in biomass, highly variable in abundance and generally low in diversity. The second is primarily a soft bottom habitat with a rather diverse and abundant fauna that is characterized by siboglinid tubeworms (*Sclerolinum contortum*), amphipods, gastropods and tube dwelling polychaetes (Pedersen 2010a, Tandberg et al. 2011, Kongsrud and Rapp 2012) (Figure 5). A complete inventory is on its way (Rapp et al. in progress).

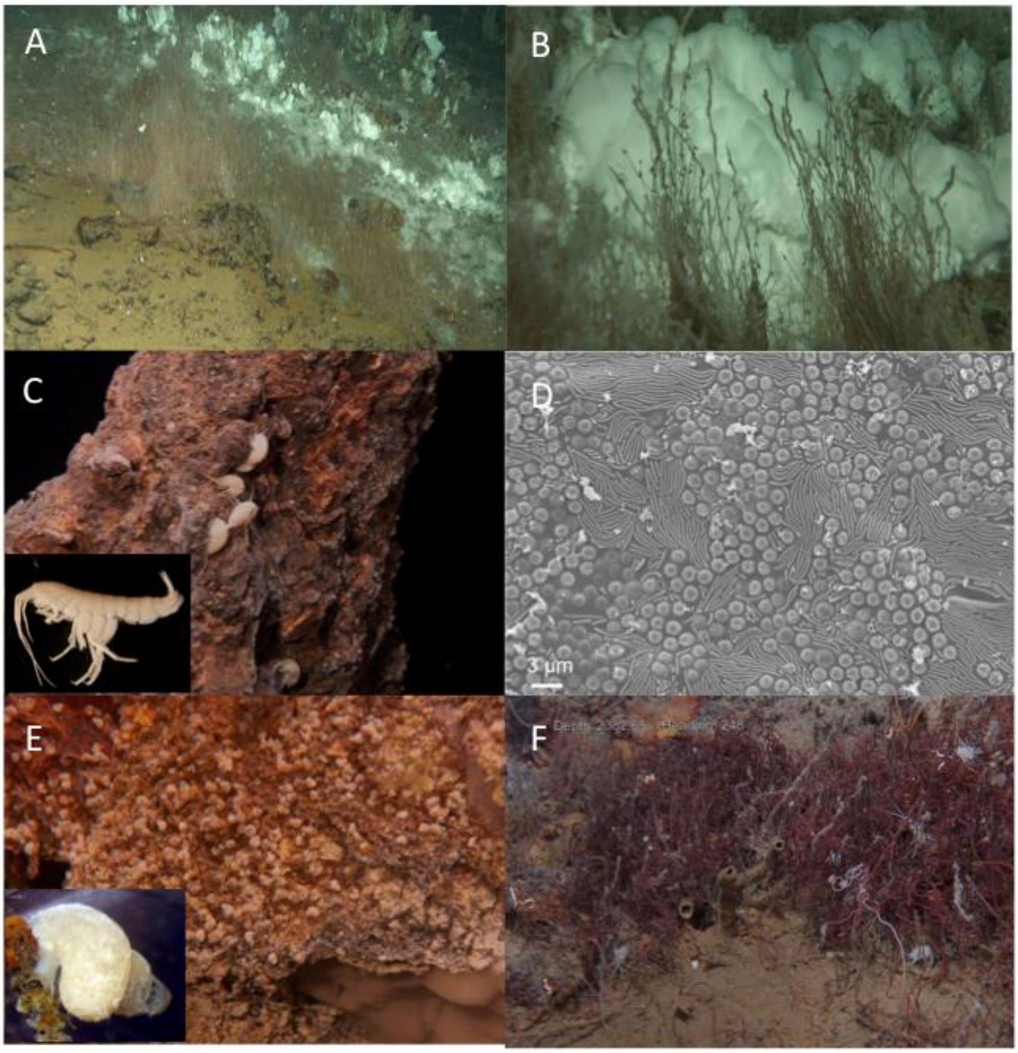


*Figure 5 Remotely Operated Vehicle (ROV) images from the Loki's Castle (LCVF). A-B illustrate the low temperature barite field, C illustrates a hydrothermal chimney and the vent amphipod Exitomelita sigynae. D shows an scanning electron microscopy (SEM) image of the gills of Exitomelita covered by sulfur- and methane oxidizing bacteria and E-F show dense aggregates of polychaetes and gastropods at the base of a chimney (Pedersen et al. 2010a).*

### The Copper Hill

The Copper hill is a massive sulphide deposit located at 72°N, 2°E, at a mineralized fault zone at the NW side of a rift valley at around 900 m depth. Some of the matrix-supported fault breccias dredged from the area are heavily mineralized and may contain up to 30 modal percent sulphides. The most abundant sulphide is chalcopyrite (Pedersen et al. 2010b).

There is no biological information from this location.

**The Mohn's treasure**

The Mohn's Treasure is a massive sulphide deposits located at 2600 m depth on the Mohns Rigde (73°N, 7°E). It is found at the edge of an inner rift wall suggested to be a mass-wasting feature composed of partly lithified sediment. It consists of fine-grained porous chimney fragments with fluid channels and is predominantly composed of pyrite.

There is no biological information from this location.

### 1.2.2 Threats and environmental impact

Basically mining consist of 1) physical intrusion in the habitat using large sized machinery, 2) transport of the cut rocks in a slurry towards the surface using a riser (pipeline), 3) dewatering on board the mining vessel and 4) transport the sulphides to a shore based treatment plant. The mining processes will expose sulphidic minerals to the oxic seawater. When sulphides are exposed to the oxic water they will oxidize and might release heavy metals to the environment. The sulphides will be exposed in scars where sulphides are removed in the mined area, in plumes of sediment that are up-whirled during the mining process and in plumes of very fine particles (< 8µm) released in water returned to the seafloor from the dewatering process. The water from the dewatering process may, in addition to fine particles, contain chemicals that potentially can be harmful to the environment. The plume might spread to a relatively large area surrounding the mining site, depending on the current conditions.

Threats and environmental impact from deep-sea SMS-deposit mining are categorized as direct and indirect. Direct impacts are the immediate loss of habitat (flattening of the 3D structure) and killing of organism by the machinery and smothering, while indirect effects include mechanical stress from sedimentation and biochemical stress through release of toxic metals to the water column (will affect both the benthic and pelagic system). The response of an ecosystem and individual species to these threats, alone or cumulative, is defining the vulnerability of the habitats.

- Direct impact
    - Physical destruction of the habitat.
    - Smothering of organisms
- Indirect impact
    - Mechanical stress from sedimentation and fine grained particles in the plume
    - Biochemical stress from toxic metals

*Habitat vulnerability*

Hydrothermal systems are considered to be adapted to frequent disturbance because of their ephemeral nature and location in regions of frequent earthquakes. The key to adaptation to a changing environment is an organisms' generation time or reproductive cycle. A resilient community is less vulnerable, but resilience depends on degree and character of disturbance, species composition and larval supply (Allison 2004).

Even though re-recruitment (genetic connectivity) depends on several factors that are linked to life strategy and dispersal capabilities (Boschen et al. 2013, Van Dover 2011), perhaps the most important factor, when mining causes disturbance, will be presence of nearby populations that secure supply of larvae. Subsequently, vents populated by fauna commonly found in adjacent waters will likely be re-populated quite fast after disturbance as long as the substrate is still suitable for settlement of larvae. One can therefore expect that both SSVF and JMVFs are potentially less vulnerable in terms of chance for re-colonization compared to the Loki's Castle and Ægir's Vent Field. Vents with more vent-specific fauna like at Loki's Castle are on the other hand expected to have a much lower potential for being re-colonized and the impact of mining may be much more severe on the endemic fauna in the region. Furthermore, response to threats (e.g. heavy metals) may be taxa-specific because of different reproductive strategies, larval dispersal potential, regional and local population density and competitiveness. Thus, tolerance of toxins (e.g. Kádár et al. 2005) and genetic connectivity will be important when one assess vulnerability. However, presently there are no published toxicology or connectivity studies regarding fauna from AMOR.

# 1.3 Environmental considerations and restitution potential

## 1.3.1 Before mining

At present no habitat vulnerability assessments have been conducted for vent systems and SMS deposits found along the AMOR. However, available information from other SMS-deposits and hydrothermal vents along the Mid Atlantic Ridge (MAR) as well as the Pacific may prove useful also for the AMOR systems. Nevertheless, as all vent systems have their own biological/biogeochemical characteristics, and are found in different geological and oceanographic settings, site-specific investigations should be conducted.

*Short list of pre-mining tasks*

- Biodiversity inventories
- Seasonal data (biology, geochemistry)
- Time series (biology, geochemistry)
- Settlement and re-recruitment experiments
- Connectivity studies of key taxa (by use of molecular tools)
- Oceanographic data (hydrography and current regime)
- Establish monitoring parameters
- Test mining

Applying a precautionary approach is an obviousness when planning activities with a potential negative impact on the environment. In general that requires that thorough baseline studies are made prior to these activities. Baseline studies prior to SMS mining should also include localities beyond the actual ore, and mapping of the surroundings of the SMS-deposit in question will be important in order to be able to evaluate re-colonization from neighbouring populations/locations. Connectivity studies have proven important and are commonly used. Furthermore, the baseline would need to include hydrographical conditions in a large area surrounding the mining locality in order to be able to model and predict the extent of potential impact of both the mining/crushing activity itself as well as the dewatering process.

Species composition and community structure are highly important (and fundamental) elements in both the baseline studies and the later impact assessment. Furthermore, long-term studies are crucial to understand seasonal changes and natural fluctuations in species composition at these sites. Such studies will make it possible to distinguish changes that are due to mining impact from natural changes and fluctuations. At present there have been no quantitative or long term studies in these systems, and there is no information about the natural seasonal variation from any vent system or inactive SMS-deposit in our waters. Furthermore, there is no information published of larval development, reproduction period or distribution and settling of larvae on the AMOR hydrothermal vents (or SMS-deposits).

Solid data on hydrographical conditions will furthermore be important in order to model dispersal of the plume of fine-particulate matter from discharge water as well as the physical mining activity on the seabed. Natural sedimentation rates are not known from any of the AMOR localities and a base line with seasonal data should be established. Hydrographical data will also contribute to knowledge of directionality of connectivity between populations at neighbouring sites. However, gaining good hydrographical data from the Mohns Ridge appears to be complicated as the ridge is in the intersection of several deep-sea basins with very different water masses, as well as due to the very rough topography of the ridge and a complicated current regime. Observations of the plume at Loki's Castle have shown that the directionality of the plume is highly variable and long-term monitoring is therefore recommended.

Inventories and experiments (in-situ and laboratory) are useful, but a test mining should at some point be advised in order to test models, predictions, hypotheses and direct effects.

### 1.3.2 During mining

Monitoring will probably be the most important measure. However, methods for monitoring have to be established prior to mining as well as defining monitoring parameters. Existing methods and experience from monitoring impact of bottom fisheries and oil exploitation may to a certain degree be applied, but as additional challenges and impacts are expected, a more specialized monitoring program should be developed to cover deep-sea mining.

Secondly, from the knowledge acquired from the pre-mining studies one should establish mining methods for minimal impact on the community. In each area subject to mining certain areas should be kept undisturbed to secure fast re-colonization. In the case of single, isolated vent communities with a site-specific fauna mining should be avoided.

*Short list of pre-mining tasks*

- Continuous monitoring
- Neighbouring protected areas

### 1.3.3 Restitution potential

Restitution depends on several factors. These are linked to the impact and the resilience of the community. From a general point of view localities that have species commonly found in the surrounding waters will be re-colonized faster than localities with a vent-specific fauna (or even site-endemic fauna). The Jan Mayen Vent Field and SSVF are examples of localities that we expect to be quite resilient, while LCVF and ADVF hosts a much more specialized fauna with a very limited known distribution and may therefore be much more vulnerable. Furthermore, restitution potential is also linked to conditions left behind after a mining operation. The topography will be changed, and hard substrate that used to be peaks and moulds of old chimneys kept clean by currents, may now be flattened with an accumulation of soft sediments that are not suitable for a specialized vent fauna. The remaining sediments may also be unsuitable for organisms due to toxicity (particles from SMS-deposits are highly reactive). Potential for restitution is therefore expected to be highly variable and site specific.

# 1.4 Knowledge status and mapping

Mineral resource mapping is limited to the habitats mentioned in chapter 2. Other resources are likely to exist along AMOR and the Jan Mayen Ridge between Iceland and Jan Mayen However, no proper quantitative resource estimates have been made in any of the known localities so far and accurate resource estimates are therefore not possible to make with existing data. Attempts to make rough estimates on the volume and value of the deposits in Norwegian waters have been made, but until more thorough studies have been made these estimates should be treated with care.

Biological knowledge status is limited to the localities from chapter 2. Of these the Jan Mayen Vent Field is the most thoroughly studied site and the main datasets have been published. The Loki's Castle has by far the most specialized fauna and it has now been sampled adequately. Parts of the data are already published and a full review of the diversity, trophic interactions/ecology and connectivity of this fauna is in progress (Rapp et al. unpubl). The remaining vent sites are heavily undersampled and there is at present only limited information about these sites. Ecological studies are few and are limited to a preliminary JMVF food web study (Sweetman et al. 2013) and a species-specific plume food web study (Olsen et al. 2013). There are so far no published studies on the community structure of the vent fauna, but there are some studies of the microbial communities at JMVF and LCVF, covering both the benthic and pelagic parts of the vents (Jaeschke et al. 2012; Steen et al in press; Olsen et al. 2014).

There are very limited hydrographical data available. However, geochemical data have been published from some sites and more are in progress (Stensland 2013; Baumberger 2011; Thorseth et al in prep).

All information above concerns active hydrothermal vents, while there is very limited data available for the two inactive sites registered so far. In our waters we may divide the vent communities/fauna in three major types: 1) Species/fauna shared with non-vent habitats in the surroundings and fauna not depending on chemosynthetic production (majority of the taxa encountered at SSVF and JMVF), 2) a community with vent-specific species depending on chemosynthetic production and 3) a community adapted to inactive hydrothermal sites (Dover et al. 2011). The inactive sites in the Norwegian waters remain unstudied, and as mining activity will most likely mainly be confined to inactive sites, this lack of knowledge calls for new and comprehensive surveys in inactive areas.

More information and details about the biology of the various SMS-deposits/vents can be found in the publications listed below each site:

**Seven Sisters Vent Field (140 meters depth)**
Marques et al. 2015.

**Jan Mayen Vent Field (550 meters depth)**
Pedersen et al. 2010; Schander et al. 2010; Lanzén et al. 2011; Olsen et al. 2013, Sweetman et al. 2013; Olsen et al. 2014.

**Ægir's Vent Field**
No data published

**Loki's Castle**
Pedersen et al. 2010; Tandberg et al. 2011; Kongsrud and Rapp 2012; Jaeschke et al. 2012; Jorgensen et al. 2012; Dahle et al. 2013; Olsen et al. 2013; Olsen et al. 2014; Spang et al. 2015; Jørgensen et al. 2015; Stokke et al. 2015; Dahle et al. 2015; Georgieva et al. 2015; Steen et al. 2016; Kongsrud et al. submitted manuscript.

**Copper Hill**
No data published

**Mohn's treasure**
No data published

**Pelagic and plume communities**
Pelagic data is not within the scope of this report, but plumes are important links to the pelagic community and data from hydrothermal plume suggests that there is an aggregation of biota, probably because of increased production. The initial hypothesis about the AMOR plume communities suggested that it would be different compared to the background regarding diversity and abundance of organisms. This working hypothesis was based on similar patterns observed in Pacific hydrothermal plumes (e.g. Van Dover 2000). Echo sounder images (unpublished) at JMVF showed indications of higher abundances of mesopelagic fish and plankton above vents. Present results show, however, that the plume communities are not vent specific. Instead they may be more similar to the background community (Olsen et al 2014, unpublished data). However, good quantitative data are not available for AMOR hydrothermal plumes. Regardless if the pelagic biological communities are more specialized or more abundant compared to the surroundings, they will possibly be affected negatively by discharge water particles. Thus, plankton should be considered equally important as the benthic community. Plankton act like a natural link to higher trophic levels, and bioaccumulated heavy metals released through the mining process will be brought to higher trophic levels in the food chain.

**Summary of knowledge gaps:**

- **Inventory and baseline**
  - Full biodiversity inventories are at present lacking for most known sites (except JMVF and in part LCVF). Inter annual variation (base line data) in faunal composition and abundance remains largely unknown
  - The extent of hydrothermal activity in parts of the area is largely unknown and therefore it is at present not possible to designate "protected areas" between mining sites to ensure that endemic fauna is not lost and to make recolonization of mined areas possible.
  - Studies of the planktonic community surrounding vents and in the plumes are at present very limited
  - No studies have been conducted on inactive sites
- **Connectivity/phylogeography/biogeography**
  - Although the first studies on the connectivity and phylogeography of Arctic vent- and seep fauna have been initiated there is really a long way to go

before any conclusions can be made on the origins of this fauna, the degree of connectivity between sites at a local and Ocean scale, and what are the most important biogeographic drivers shaping the fauna composition in Arctic vents.

- **Seasonal data**
    - Sedimentation rates (both from above and because of sedimentation of the hydrothermal plume) are unknown.
    - No data on reproduction and timing of larval settlement
- **Experimental data**
    - At present there are no proper in situ studies on e.g. re-colonization or mining-sediment exposure.

# 2. PART B - Gas hydrates

Methane hydrates are structures where methane molecules are surrounded by a lattice of water-ice molecules in a cage structure (e.g. Englezos 1993; Sloan 1998; Koh et al. 2011). They are stable under specific temperature and pressure regimes where there is a sufficient methane supply (e.g. Kvenvolden 1993). This zone is referred to as the gas hydrate stability zone (GHSZ). Gas hydrates are primarily found in two areas; continental areas, including continental shelfs, where the surface temperatures are very low, and in submarine continental slopes and rises with low temperatures and high pressures (e.g. Kvenvolden 1993). The most common way of identifying potential methane hydrates in marine environment is through the detection of bottom simulating reflectors (BSR) in reflection seismic data (e.g. Buntz et al. 2003) that represents the transition between methane hydrates and free gas in the sediments.

Gas hydrates are often found in areas with hydrocarbon rich fluids seepage, also known as cold-seeps. Cold-seeps have been known for more than 30 years from most parts of the world oceans, and are associated with chemosynthetic fauna (Decker et al. 2012). Geochemical conditions are important contributors for the formation of the habitats of with this fauna, which is quite similar to what is found on hydrothermal vents. Unlike hydrothermal vents, that have a restricted radius, cold-seeps and the associated fauna are commonly found over larger areas. Due to the wide distribution of cold-seep faunas, gas hydrate exploitation may have different impact compared to mining of SMS-deposits. The physical impact itself is also assumed to be less extensive and will resemble more an oil drilling operation instead of a complete removal of the crust. In addition, some cold-seeps and gas hydrate areas are already relatively well studied and the habitats and communities at different sites bear more in common over a quite large geographic scale, suggesting that gas hydrate exploitation may be less controversial than deep-sea mining of SMS-deposits.

## 2.1 Geographical location of known gas hydrates of potential commercial value in Norwegian waters

Methane hydrates is a potential future energy source and it has been suggested that there is twice as much gas in hydrates as there is in all other hydrocarbon reserves combined (Koh et al. 2011). At present there is no commercial scale production of methane hydrates, but production tests have been initiated and commercial scale production is expected to start up before 2020 in Japan and Canada (Collett et al. 2015). However, there is no complete information available on the value and size of the resources present in Norwegian waters. Within Norwegian waters there are confirmed gas hydrates along Nyegga, Storegga

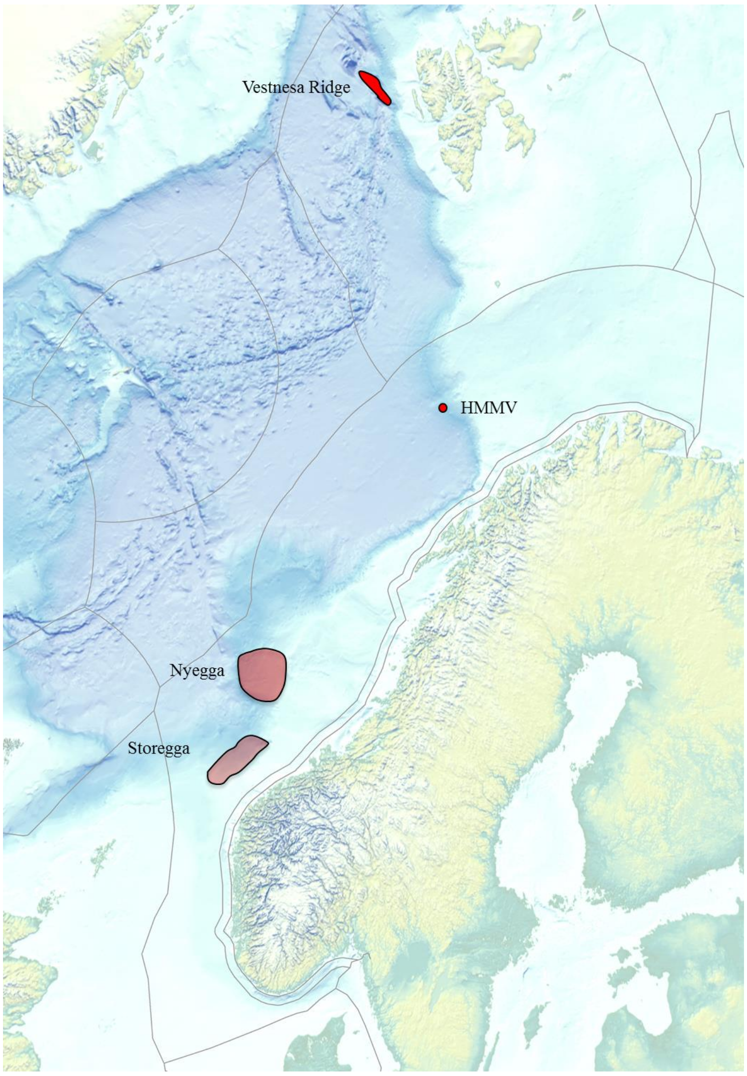


*Figure 6 Map showing the areas of gas hydrates. The lines indicate the EEZ of Norway and Svalbard.*

## 2.2 Gas hydrate habitats, threats and environmental impact

### 2.2.1 Habitats

Our knowledge about the gas hydrate habitats are linked to our knowledge of the cold-seep communities that coincide with three or possible more of the gas hydrate localities in this report. The cold-seep habitats are soft bottom habitats, however, recent studies characterizes them according to the biological communities they host instead of physical variables (Decker et al. 2012). The rationale for using biological communities instead of a stringent physical characterization is because of the biogeochemical link between the gases and the microbial communities. Specific bacterial taxa are adapted to utilize specific geochemical conditions, like for instance methane (or sulphide rich fluids), and eukaryotic fauna (e.g. >500 um) may in turn use the microbial flora in symbioses or through grazing, and the continuous supply of fluids maintains the community (Decker et al. 2011). Thus, the habitat is defined from the geochemical conditions rather than depth, sediment particle size, inclinations etc.

Furthermore, geographically separated localities are similar because these similar geochemical conditions support similar microbial communities associated with the same symbiotic fauna. In other words, at these localities, geology, microbiology and macro/mega fauna are strongly linked. Because of the lack of site specific fauna (with some exceptions) and similarities between the geographical localities the gas hydrate areas are treated as a whole in the remaining part of this report.

**Håkon Mosby mud volcano, Storegga, Nyegga, SW Barents Sea and Vestnesa Ridge, west Svalbard margin**

In Norwegian waters gas hydrate resources have been reported from the Nyegga/Storegga, Håkon Mosby Mud Volcano (HMMV), SW Barents Sea and Vestnesa Ridge along the Svalbard western margin (Figure 6).

The Nyegga and Storegga area is located on the Mid-Norwegian margin at the border between two large sedimentary basins; the Vøring basin and the Møre basin (Bouriak et al. 2000; Bunz et al. 2003; Zillmer et al. 2005; Hovland and Svendsen 2006). Gas hydrates in the area are inferred from BRS identification in an area between ~64.7 and 65.3°N, 4 and 6°E (Bouriak et al. 2000; Bunz et al. 2003; Zillmer et al. 2005). The Nyegga area is the only area within the Norwegian waters for which an estimation of in-place gas resources has been made (Senger et al. 2010).

Håkon Mosby Mud Volcano is located on the Norwegian-Svalbard continental slope (western Barents Sea) at 1250-1260 m depth. It is formed within a slide valley that incised the Bear Island fan. The sediment cover over the oceanic crust is 6 km thick (Hjelstuen et al. 1999). The gas hydrates at HMMV have been detected through seismic imaging and have also been cored (Ginsburg et al 1999; Vogt et al. 1999; Pape et al. 2013).

In the Barents Sea, methane hydrates are inferred in several areas in the SW parts from identification BSR and modelling of the gas hydrate stability field (Laberg and Andreassen 1996; Laberg et al. 1998; Chand et al. 2008; 2012; Rajan et al. 2013)

The Vestnesa ridge is a >2 km thick sediment drift located at 1000-2000 m depth. Gas hydrates have not been sampled but a prominent BSR from several seismic studies suggest that gas hydrates and gas accumulates are common in the area (e.g. Posewang and Mienert, 1999; Plaza-Faverola et al. 2015).

To our knowledge, no information is published about the biology of the Vestnesa Ridge. Yet, Centre for Arctic Gas Hydrate, Environment and Climate (CAGE) will expectedly in the near future contribute to clarify and describe the benthic community as part of their activity at this and other gas hydrate and cold-seep sites in the area.

Håkon Mosby Mud Volcano is, on the other hand, a well-studied cold-seep and gas hydrate locality, and are together with Nyegga and Storegga one of the best studied seep localities in Europeean waters (Decker et al. 2012, Portnova et al. 2014, Gebruk et al. 2003). Decker et al. (2012) suggested five main zones according to the dominating benthic community at HMMV; 1 - centre of the seep (volcano), 2-3 - bacterial mats, and 4-5 - habitat forming polychaetes of the family Siboglinidae (Siboglinid-fields of e.g. the symbiotic polychaetes *Sclerolinum contortum* and *Oligobrachia hakonmosbiensis*) (Figure 7). *Sclerolinum contortum* is also found at Nyegga and Storegga. The Siboglinid-field habitat supports a higher biodiversity compared to the both background and the more central, bacteria dominated part of the seep, and the Siboglinid-fields are similar between geographically distant sites (Decker et al. 2011; Portnova et al. 2014). Based on this, Decker et al. (2014) suggests that the community structure is controlled by geochemical conditions rather than geography and depth. Portnova et al. (2014) came to a similar conclusion based on Nematode assemblages from the Nyegga. Dense Siboglinid-fields at the low-temperature venting in the barite field at Loki's Castle, which are fundamentally different in depth and other physical characteristics, supports the conclusion that geochemistry is a strong structuring factor of the benthic community (Kongsrud and Rapp 2012, Steen et al. 2016).

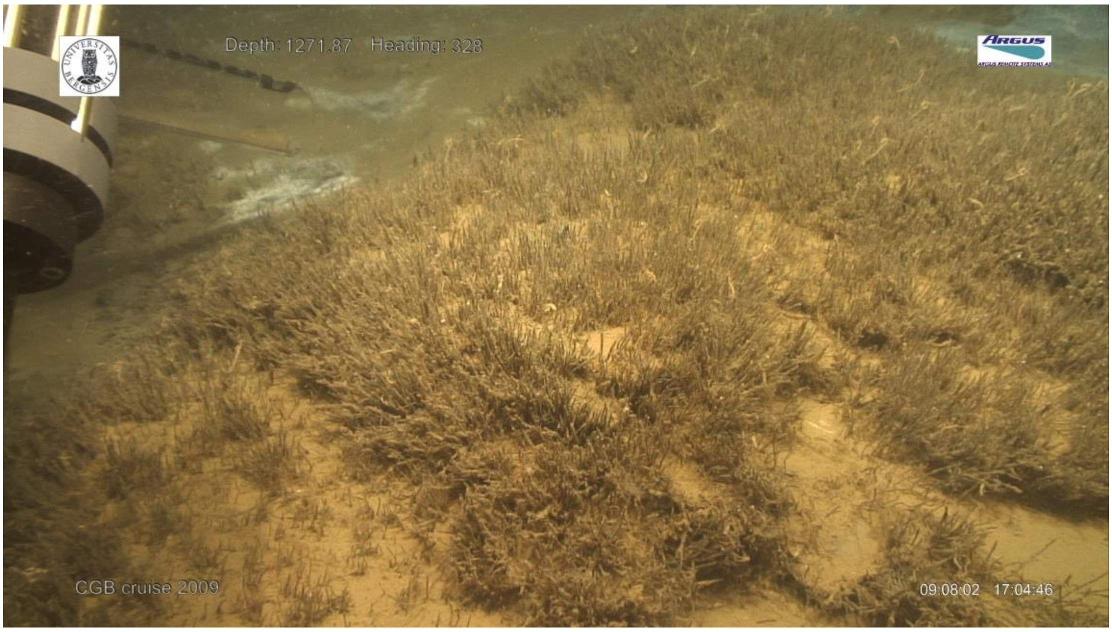


*Figure 7 Siboglinid fields at Håkon Mosby Mud Volcano (from a Centre for Geobiology cruise in 2009).*

### 2.2.2 Threats and environmental impact

The knowledge about how methane hydrates will respond to production activity is limited and therefore the knowledge about environmental impacts is also very limited. However, as for minerals the threats may be split in direct (acute) and indirect and it is likely that exploration of gas hydrates will meet many of the same environmental challenges that are met by the oil and gas exploration today including impacts from drilling activity and disposal of produced waters (Moridis et al. 2011). Yet, the major concern is that decomposition of hydrates might lead to sediment volume change, sediment instability, ground subsidence and slumping (e.g. Kvenvolden 1994, Lee et al. 2010; Song et al. 2014). This might lead to immediate destruction of habitats, and indirectly it will lead to large sediment plumes that will affect biological communities over a large distance. Several submarine slope failures may be connected to dissolution of methane hydrates (e.g. Maslin et al.1998; Sultan et al. 2004a, 2004b; Nixon and Grozic 2006; Dondurur et al. 2013).

- Direct impact
  - Physical destruction of the habitat (at drill site and by sediment slide).
  - Smothering of organisms in near surroundings
- Indirect impact
  - Mechanical stress from sedimentation and fine grained plume

*Habitat vulnerability*

To the best of our knowledge no studies regarding vulnerability of the cold-seep and gas hydrate communities exist. However, the fauna is linked to the geochemical conditions and one could therefore assume that the soft bottom Siboglinid communities will re-emerge if the geochemical conditions like the flows of hydrocarbon rich fluids continue after impact. Still, we do not know how long it may take before a re-colonization of the major fauna elements will happen and if there will be a full recovery of the community. Siboglinid-fields are relative common, and provided the directionality of the genetic connectivity (larvae drift) is favourable, re-colonization is not unlikely. To our knowledge no re-colonization, laboratory or in-situ experiments exist on these Siboglinid fields yet, however experimental investigation is part of CAGE's scientific aims. The vulnerability of the associated fauna from within the worm-fields or the surroundings may not be similarly resilient, and should be considered when assessing vulnerability.

As for the hydrothermal vents along AMOR, hydrographic conditions are significant because displacement of sediments (slides) may cause large plumes of fine sediments. These plumes may also represent a threat to coral reefs, sponge grounds and other potentially vulnerable nature types in the surroundings. Although coral reefs and sponge grounds are not directly linked to the cold-seeps they are commonly found on Nyegga and Storegga and these reefs and grounds are considered as very important habitats for several commercial fish species and they support a very high diversity of organisms when compared to the surrounding sedimentary areas. Although both sponges and corals are somewhat resilient to moderate sedimentation there are thresholds of how much they can handle over time. Common for both sponges and corals is the slow growth and regeneration, which suggest that they are vulnerable for the extensive physical stress that a hydrate harvesting and a potential underwater slide may represent.

## 2.3 Environmental considerations and restitution potential

### 2.3.1 Before exploitation

At present no habitat vulnerability assessments have been conducted for gas hydrate resources found in Norwegian waters. Nyegga, Storegga and HMMV are relatively well studied but gas hydrate exploitation impact assessments have not been part of these studies. Detailed inventories and spatial mapping should nevertheless be made along the other gas hydrate and neighbouring areas as well. Also, a complete inventory along the slope depth gradient should be included since a slide caused by gas hydrate extraction may cause a large-scale and long-term impact on wide areas beyond the drill site (both the physical mud/sediment slide and the plume afterwards). Investigation of the slope/sediment stability will be instrumental before extraction. The potential size of the slide will dictate impact of sedimentation and the size of the area that may be destroyed. The size will further suggest what we might expect in terms of recovery time.

Pre impact tasks shortlist:

Short list of pre-exploitation tasks (overlaps to a great extent those for mineral deposits)

- Species/biodiversity inventories
- Seasonal data (biology, geochemistry)

- Time series (biology, geochemistry)
- Settlement and re-recruitment experiments
- Conduct proper connectivity studies of a selection of taxa
- Hydrographical data
- Establish monitoring parameters
- Evaluation of potential sediment volume change and sediment instability

### 2.3.2 During exploitation

Monitoring will be the most important measure.

### 2.3.3 Restitution potential

Since the communities are linked to geochemical conditions it is likely to assume that the potential for re-colonization and recovery is not so bad in the areas of hydrate extraction. However, if a slide should occur we have no knowledge of how the large sediment plumes will affect the surroundings. However, we do not know anything about time scale of the impact and therefore it is also impossible to give any postulate accurate scenarios for re-colonization in sediment-affected area.

## 2.4 Knowledge status and mapping

Nyegga, Storegga and HMMV are fairly well mapped and there is some ecological information available, but a more complete inventory that includes the surrounding (and potentially impacted) waters is missing. Other known gas hydrate areas are poorly studied. Again, CAGE's focus on ecological studies along Vestnesa Ridge will hopefully contribute to fill some of these gaps of knowledge. Perhaps the most important data that is missing is time series (seasonal data) and proper baseline studies.

### 2.4.1 Summary of knowledge gaps

- **Inventory and baseline**
    - Full biodiversity inventories are at present lacking for most known sites (except HMMV and in part Nyegga). Inter annual variation (base line data) in faunal composition and abundance remains largely unknown
    - Studies of the planktonic community surrounding seeps/hydrate areas are at present very limited

- **Connectivity/phylogeography/biogeography**
    - Although the first studies on the connectivity and phylogeography of Arctic vent- and seep fauna have been initiated there is really a long way to go before any conclusions can be made on the origins of this fauna, the degree of connectivity between sites at a local and ocean scale, and what are the most important biogeographic drivers shaping the fauna composition in seep- and hydrate areas in our waters.
- **Seasonal data**

    - No data on reproduction and timing of larval settlement are available

- **Experimental data**
    - At present there are no proper in situ studies on e.g. re-colonization or exposure of sediments from the extraction process or the more large scale sediment disturbances expected from potential slides.

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**Telefon:** 03400/73 58 05 00 | Faks: 73 58 05 01
**E-post:** post@miljodir.no
**Nett:** www.miljødirektoratet.no
**Post:** Postboks 5672 Sluppen, 7485 Trondheim
**Besøksadresse Trondheim:** Brattørkaia 15, 7010 Trondheim
**Besøksadresse Oslo:** Grensesvingen 7, 0661 Oslo

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