Characterisation of Megabenthic Community Structure at the Fåvne Hydrothermal Vent Field, with Implications for Environmental Management of Seabed Mining

Sofie Gjærløw

Thesis for the degree
Master's in Marine Sustainability, SDG350
University of Bergen
Centre for the Study of the Sciences and the Humanities (SVT) & Department of Biological Sciences

Supervisors: Pedro Ribeiro, Steinar Sanni & Kjetil Rommetveit
Spring 2023

Acknowledgement

Firstly, I would like to express my sincere gratitude to my supervisors for their guidance and support throughout the course of my master thesis. I am especially grateful for their willingness to share their expertise and knowledge in their field, which has enriched my understanding of the subject matter and enabled me to develop a deeper appreciation for the research process. I want to give a special thank you to Pedro for his support, time, commitment and mentorship throughout my thesis. I am honoured to have had the privilege of working under his supervision.
Thibaut Barreyre deserves recognition for his kindness in sharing his research with me.

I would also like to extend thanks to my family and friends for their support, encouragement and understanding throughout my academic journey. Their kind words and belief in me have been a source of motivation. Thank you for cheering on me through hard times and helping me realise my dreams.

Fieldwork and data analysis for my thesis was financially supported by the Eco-Safe Ridge Mining project (funded by the Research Council of Norway through grant agreement 326881).

Abstrakt

Det er en økt interesse for dyphavsmining i norske farvann for bruk av mineraler rettet mot det grønne skiftet. Imidlertid er det bekymringer knyttet til bærekraft av slike aktiviteter. Denne studien bidrar til karakteriseringen av bentiske samfunnsstrukturer ved Fåvne hydrotermale felt, lokalisert på den arktiske midthavsryggen, som et bidrag til å informere om forvaltning og konserveringspolitikk. Forskningen innebar innsamling av data ved hjelp av fjernstyrte undervannsfarkoster (ROVer) på en dybde på omtrent 3000 meter, annotering av bilder, utarbeidelse av en artskatalog og utførelse av kvantitativ dataanalyse. Resultatene viste at basalt hadde det høyeste artsmangfoldet og artsrikdommen, mens inaktivt sulfid hadde den laveste. Den ikke-metriske flerdimensjonale skaleringsplottet (non-metric multidimensional scaling, nMDS) avslørte betydelige forskjeller mellom aktive ventiler og bakgrunnshabitater, der individuelle bilder viste betydelige variasjoner. Det var en tydelig forskjell i arter som bidro til forskjellene mellom leveområdene, spesielt hos amfipoder sp. indet og gastropoda sp. indet.

Funnene antyder at det er betydelige kunnskapshull som må fylles før noen dypvannsaktiviteter kan starte. Et moratorium kan være nødvendig for å tillate ytterligere forskning på potensielle ødeleggende økologiske effekter, da teknologiske fremskritt og gjenvinning kan redusere behovet for mineraler. Generelt sett fremhever denne studien den potensielle påvirkningen av dyphavsmining og behovet for forsiktighet og ytterligere forskning på dette området.

Abstract

There is an increased interest for deep-sea mining in Norwegian waters due to the potential use of minerals in the green shift. However, concerns have been raised regarding the sustainability of such activities. This study contributes to the characterisation of benthic community structure at the Fåvne hydrothermal vent field located on the Arctic Mid-Ocean Ridge as a contributor to inform management and conservation policies. The research involved collecting data using remotely operated vehicles (ROVs) at a depth of approximately 3000 metres, annotating images, making a morphospecies catalogue, and performing quantitative data analysis. The results showed that the basalt had the highest species diversity and richness, whereas the inactive sulphide had the lowest. The non-metric multidimensional scaling (nMDS) plot revealed significant differences between active vents and background habitats, with individual images displaying considerable variations. There was a clear difference in species contributing to dissimilarities between habitats, particularly the amphipods sp. indet and gastropoda sp. Indet.

The findings suggest that there are significant knowledge gaps that need to be addressed before any deep-sea activities can commence. A moratorium may be necessary to allow for further research on potential destructive ecological effects, as technological advances and recycling may reduce the need for minerals. Overall, this study highlights the potential impact of deep-sea mining and the need for caution and further research in this area.

Content

Introduction

1.1 The green shift

The planet is facing great destruction due to anthropogenic activities, notably the burning of fossil fuels, which results in greenhouse gas emissions. Emissions are accelerating global warming, habitat loss, biodiversity loss, reduction in Earth's resources and unsustainable consumption (Laffoley et al., 2020). The challenges have accelerated the green shift, the progression towards a more sustainable and climate-friendly society with sustainable consumption, a sustainable economy and lower emission of greenhouse gases.

Humanity has depended on fossil fuels for many years, but with environmental challenges, innovation is needed. The oil age is coming to an end and will be partly replaced by metals, where the metals in question will be able to generate and restore renewable energy and will not be used up as oil but have the ability to be recycled. This is one of the arguments for why mineral exploitation can be an essential part of a circular economy; even so, it raises another issue, where shall we acquire all the metals needed? According to an estimate by the World Bank, clean energy technologies will need 3 billion tons of minerals and metals to keep the temperatures from rising above 2 degrees Celsius (Hund et al., 2020) and even more to meet the limit of 1,5 degrees Celsius aim of the Paris Agreement.

A comprehensive analysis carried out in 2008 revealed that the direct and indirect greenhouse gas emissions of metals and the mining industry accounted for 9.5% of global energy use (Nuss & Eckelman, 2014). Comparing land-based mining with seabed mining, advocates argue that seabed mining provides a lower carbon footprint, generates less pollution, leads to far fewer human accidents, has a minimal impact on the ecosystem services, helps to stabilise the price and does not inflict any cultural movement (Paulikas et al., 2020). However, these arguments are inadequate and are not supported by fact-based studies.

At the same time, another report commissioned by a deep-sea mining company indicates that the extraction of half of the polymetallic nodules on the Clarion-Clipperton Zone (CCZ), a submarine zone in the centre of the Pacific Ocean, would provide enough minerals to make one billion electric cars (Paulikas et al., 2020). Moreover, the greenhouse gas emission from this extraction was reported to be only 30% of that from land-based mining (Levin et al., 2020). The company that commissioned the report has two contracts to explore in the CCZ and could have a lot to gain from this extraction. Not more than 50 years ago, when UNCLOS was established, it was thought that there was no life in the polymetallic-nodule zones (Levin et al., 2020). However, research conducted over the last 40 years has shown that areas in the CCZ have high biodiversity, and 50% of species larger than 2 cm, as well as 34 out of the 36 single-celled organisms found, were new to science (Levin et al., 2020; Kaiser et al., 2017). Moreover, studies show that polymetallic nodules provide a habitat for a diverse epifauna community (Vanreusel et al., 2016).

Because of the increased demand for mineral resources, new technology, e.g. underwater survey vehicles and sensors and deep-sea drilling technology, has opened up the possibilities and interest in exploiting minerals on the deep seabed.
The deep sea is categorised as the ocean below 200 metres and covers more than 95% of Earth's biosphere, making it the world's largest biome, nonetheless, the least explored one (Levin, 2019). It has often been viewed as a dark, toxic and lifeless environment, but on the contrary, the deep sea is inhabited by bustling wildlife and resources that affect humans in different ways (Thurber et al., 2014). These areas have been unavailable to humans for a long time; however, new technology and research have made exploring deep-sea biology and looking for mineral resources possible. So far, only 5% of the seafloor has been explored and studied in the last 50 years (Levin, 2019), which means several habitats, ecosystems and novel biodiversity remain undiscovered. Research conducted in the deep sea has challenged outdated hypotheses and theories (Anderson & Rice, 2006). The deep sea has been found to have diverse ecological communities and landscapes that have been poorly investigated, leaving a considerable knowledge gap related to these vast areas (Amon et al., 2022).

1.2 Hydrothermal vents

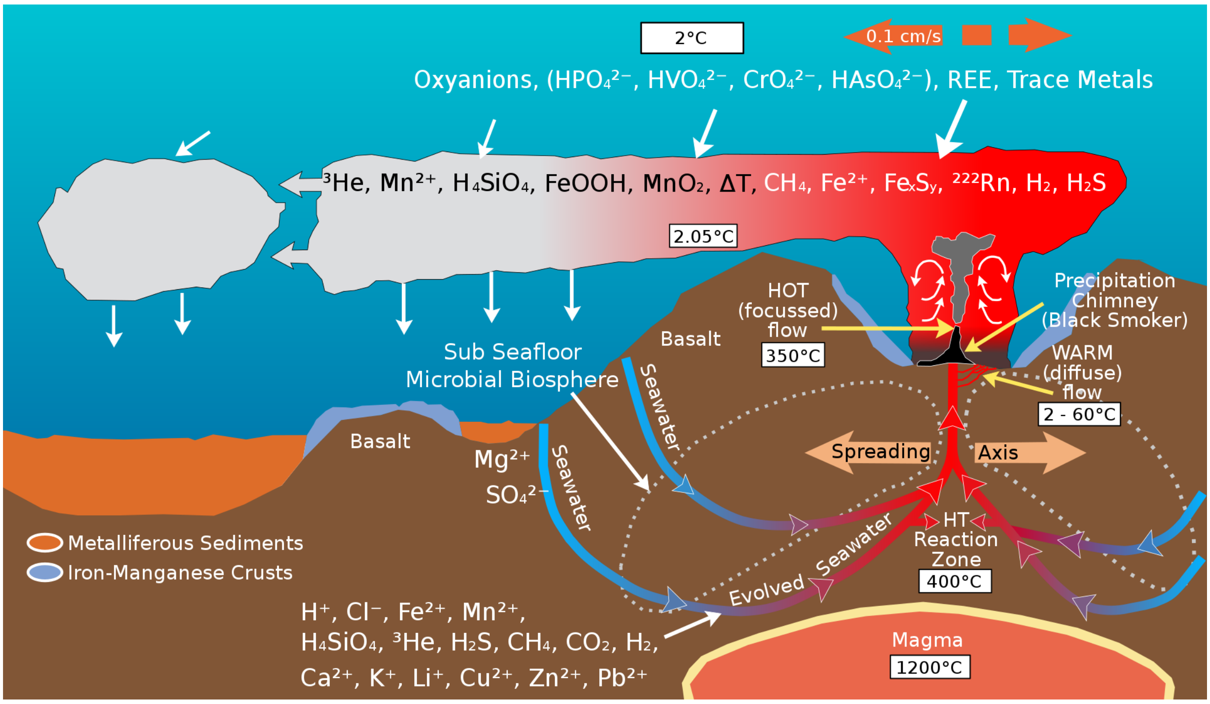


Figure 1. Schematic diagram of a hydrothermal vent system. From "Environmental Impacts of Nodule, Crust and Sulphide Mining: An Overview" by Weaver & Billet, 2019, p. 3 Copyright 2019, Springer Nature Switzerland AG.

One of the ecosystems in the deep sea is hydrothermal vent fields, which connect the geosphere, hydrosphere and biosphere (Pedersen et al., 2021). Hydrothermal vents are a place of activity along mid-ocean ridges and subduction zones where warm, mineral-rich seawater rush from the ocean floor (Figure 1) (Bang & Trellevik, 2022). The cold seawater enters a breach in the seafloor, where it is heated to temperatures reaching more than 400 ℃. Considering this warm fluid is now less dense, it ascends to the seafloor, where it is mixed with the surrounding seawater and constitutes a vent (Hannington et al., 2019). When the mineral-enriched seawater mixes with the cold seawater, the metals precipitate and are discharged as a hydrothermal plume looking like smoke released from a chimney (Ramirez-Llodra et al., 2020). A considerable amount of the particles from the plume is dispersed in the adjacent seabed, while the excess metals are discharged as metal sulphides and sulphites at the sites. Active-focused hydrothermal venting produces both black and white smoker chimneys (Petersen et al., 2016).

There are three types of deep-sea minerals of economic significance worldwide, namely manganese nodules, manganese crusts and polymetallic sulphides (Petersen et al., 2016). Polymetallic sulphides (PMS) are produced at active hydrothermal vents and can be composed of valuable minerals and metals such as copper, cobalt, zinc, nickel, lead, silver and gold (Tao et al., 2014). Polymetallic nodules are found on the abyssal plains at depths between 3000 and 6500 metres, and only 19% of all known nodules are within Exclusive Economic Zones (EEZ) (Levin et al., 2020). Manganese crusts are formed through the precipitation of minerals on steep slopes of seamounts where sedimentation rates are low (Petersen et al., 2016).

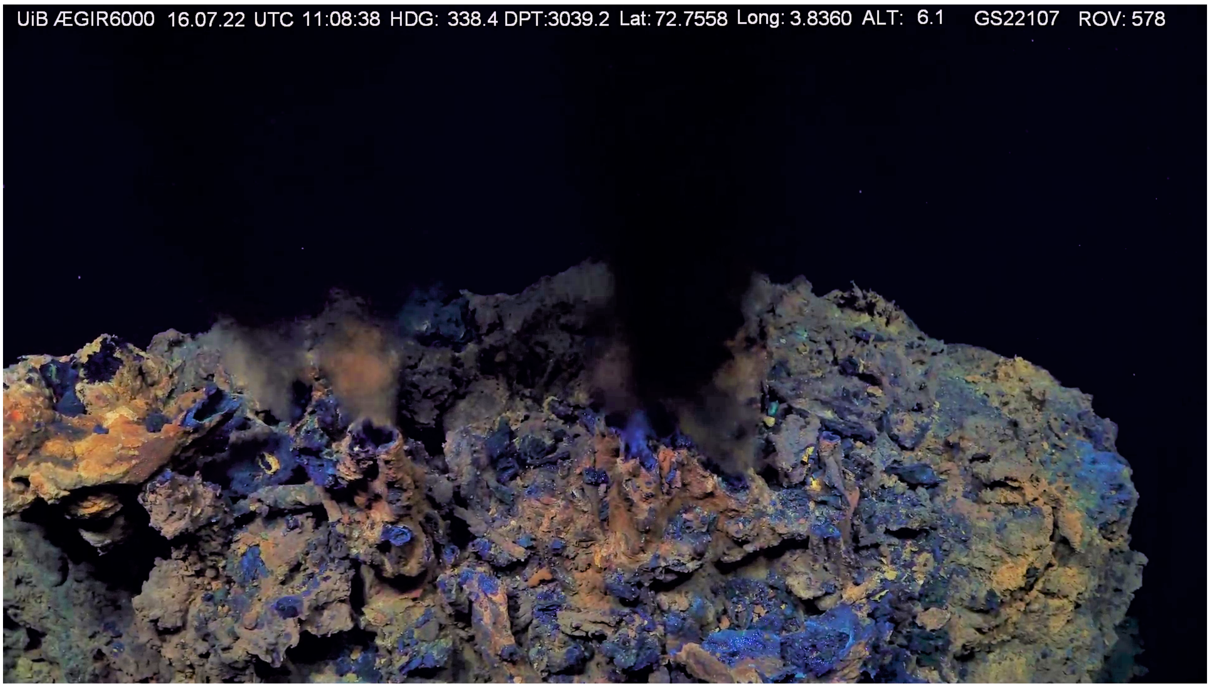


Figure 2. Active hydrothermal vent (black smoker) on the Fåvne hydrothermal vent field, Arctic Mid-Ocean Ridge. Image from ROV Ægir dive 578 during the UiB research cruise in summer 2022.

Hydrothermal vents can be divided into active and inactive vents. Black smokers can be active for less than a day to hundreds of thousands of years and are known for their active sulphide occurrences (Van Dover, 2019). At this time in research, there needs to be more knowledge about inactive vents, and it can be hard to determine if a vent is inactive. The ability to know for certain if a vent is either inactive or extinct has significant implications for deep-sea mining regulations (Jamieson & Gartman, 2020). When a vent goes from active to inactive, the venting ceases. The electrons are primarily derived from reduced iron and sulphur of solid metals rather than dissolved sulphide and other compounds already reduced as in active vents (Sylvan et al., 2012). Another way to determine if a hydrothermal vent is inactive is to examine the adjacent fauna. When a vent ceases, the biological communities will change from vent-endemic organisms thriving in warmer waters and dependent on chemosynthesis, e.g. thermophilic and mesophilic, to those living in colder waters, such as psychrophilic microbial taxa and background fauna (Van Dover, 2019).

On the other hand, active vents are easier to detect, and the research conducted on these habitats is more considerable than on inactive vents after their discovery in 1977 (Godet et al., 2011). Active vents can be detected by tracing hydrothermal plume anomalies in the water column using CTD casts or other sensors mounted on ROV or AUV (Autonomous underwater vehicle) tracking the plume, which is a possible method but not an easy way. Another method used to detect and explore new vent sites is by high-resolution underwater geophysical surveys using an AUV (Nakamura et al., 2013). Furthermore, active hydrothermal vents are unique, and there are more inactive than active vents on the seafloor (Hannington et al., 2011).

1.2.1 Hydrothermal vent fauna

There are many extremes in the deep sea; it is complete darkness, the average temperatures are less than 4℃, the lack of oxygen and an average pressure of 400 atm (pressure varies with depth and can range from 20-1100 atm in the deep sea), which makes this an environment not suitable for all organisms (Danovaro et al., 2014). Exotic oases and species like no other have been observed on the sites. Life in these extreme conditions depends on chemosynthetic microbes using chemical energy to produce food due to the lack of sunlight for photosynthesis. Vents contain considerable biomass, high productivity and highly adapted species. In the deep, dark oceans, there is usually food deficiency. However, ecosystems near the vents are exceptions due to the symbiosis with prokaryotes that transform hydrothermal

fluid into organic nutrients for other organisms in the food web to consume (Danovaro et al., 2014).
Most species living on active vents sites are specialised to these specific conditions, depending on venting fluids, and cannot survive in any other place (Van Dover et al., 2018).

Hydrothermal vent fields are often less than a few hundred metres in diameter, and the fields are generally spread on ridges approximately 100 km apart, meaning that they can be hard to detect (Pedersen et al., 2021). To date, more than 600 hydrothermal vents are known worldwide, and more are expected to be discovered (Boschen et al., 2013). The hydrothermal vent fields have been located at various depths, geological environments, temperatures, and water chemistry. Even though hydrothermal vents only cover roughly 50 km² globally, the habitat has an essential role in the discovery of life’s origin on Earth and in connection to the research of the possibility of life on other planets (Van Dover et al., 2018). Hydrothermal mounds are built from the mineral provision deriving from the vent. They can become several hundred metres in diameter with different habitats, such as the hard substrate, areas with vent deposits and more granular parts (Pedersen et al., 2021). Hydrothermal occurrences include several types of habitats where some areas are constructed of hard substrate, some rough deposits from avalanches and others are completely fine-grained. In addition, there are both active, inactive and extinct vents making up several different habitats and communities (Boschen et al., 2013).

Because the mineral resources found on the active hydrothermal sites would not cover the demand for metal in the world (Van Dover et al., 2018), and due to the lack of chemosynthetic macrofauna on inactive vents, research suggests extinct vents are more suitable for mining (Jamieson & Gartman, 2020).

1.3 Sustainability aspects of deep-sea mining

The concept of sustainability has evolved over years of discussion in both scientific and political-institutional contexts, mainly under the UN umbrella, and the word's true meaning is not defined. Nevertheless, the concept of sustainability was first described in the Brundtland report in 1987, a report addressing the aim of a better life for humans (social and economic) as well as for nature (environmental) (Kuhlman & Farrington, 2010). The word “sustainable” is used in many contexts, from politics, product advertisements and companies, as an allurement for the individual to think they are doing something good for society. Since the Brundtland report, the definition of sustainability has changed several times, which can negatively affect the purpose of the term. The concept has always, by necessity, involved a central tension between conservation and development, protection and exploitation. The entire concept is contradictory as there is usually a conflict between conservation (“sustainability”) and exploitation (“development”). This conflict is not accidental to sustainability discussions, but intrinsic to them. Sustainability can be difficult because the goal of a sustainable society is immense and will accordingly be somewhat contradicting. E.g. the sustainable development goal (SDG) “decent work and economic growth” (SDG 8) and “life below water” (SDG 14) can be challenging to achieve at the same time considering economic growth can imply increasing levels of ocean exploitation leading to disturbances and pollution that can kill aquatic life as well as the potential destruction of habitats (Jun et al., 2021).

The International Seabed Authority (ISA) is the international organisation under the United Nations in charge of regulating and ensuring the seafloor's environmental protection. With the increased interest in seabed mining, ISA is working on composing regulations for mining in areas beyond national jurisdiction (Jamieson & Gartman, 2020).

The regulations will ensure that “no serious harm” will happen during deep-sea mining, but the legal term of what “no serious harm” means can be problematic in the deep sea where there is a lack of knowledge. According to The United Nations Law of the Sea Convention (UNCLOS), seafloor minerals should benefit all humankind. They are stated to be a “common heritage of humankind”; this includes both living generations and generations to come (Gollner et al., 2017), which seems to imply conservation and protection of the seafloor.

From 2001 to 2020, ISA granted 30 contracts for exploration in several areas of the world’s oceans (Amon et al., 2022).

Implementing the precautionary principle plays an important role in environmental uncertainty and gives an opportunity for conducting research ahead of the action. The United Nations has recognised the precautionary principle as an important concept in international law and policy, particularly in areas of environmental protection and public health. The UN states that “In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation” (United Nations, 1992).

The optimal way to handle mineral resources available near deep-sea hydrothermal vents with accountability towards the environment is by adopting a precautionary approach, which includes performing an Environmental Risk Assessment (ERA) for exploration and exploitation activities related to seafloor massive sulphide deposits (Collins et al., 2013). Wynne (1992) called this a preventive paradigm and highlights the delicate work of not knowing when one has enough knowledge to prevent environmental disservice. This raises the question of how to risk-assess something unknown. As shall be shown later, more recent concepts of risk assessment integrate uncertainty in the risk definition and analysis.

In current perspectives of offering scientific policy advice, it is a general assumption that science produces accurate, impartial and trustworthy knowledge. However, this is not how dealing with intricate policy matters in the real world usually unfolds. It can be full of uncertainties and disagreements, which can raise doubts if the provided information truly is impartial or credible (Petersen, 2000). Consequently, it is indispensable to assimilate a broad range of information before conducting scientific evaluations of complex policy issues. The information should include both firm scientific facts, expert opinions, provisional models and uncertain expectations (Van Der Sluijs et al., 2008).

Prevention of environmental disasters is one of the most important goals of new policies (Wynne, 1992). Uncovering the existence and type of uncertainty may be essential before exploiting anything else. It can be separated into four categories; Risk (knowing the odds), uncertainty (knowing parameters, but not the odds), ignorance (not knowing the unknown), and indeterminacy (causal chains) (Wynne, 1992). Ignorance may cause severe consequences regarding new technologies and can lead to a public trust problem towards public bodies.

1.3.1 Risks of seabed mining

There are several challenges concerning mining the deep sea, and some of the most significant ones are the unknown environmental consequences and expenses, highlighting especially the impact on biodiversity (Levin et al., 2020; Orcutt et al., 2020). The ocean mitigates climate change by absorbing atmospheric heat and anthropogenic CO2, and the deep sea absorbs a great deal of the heat and CO2. This implies that the deep sea contributes to regulating Earth's climate (Levin & Bris, 2015). Consequences originating from anthropogenic activity can reshape the biological pump and the nutrient cycle in the ocean, which can alter ecosystems and change populations (Danovaro et al., 2017). Due to the specialised hydrothermal vent fauna, suitable habitat is available in limited amounts. Therefore, the slightest change in a deep-sea ecosystem can make it impossible for organisms to thrive in the environment and lead to extinction (Levin, 2019).

Environmental impacts associated with other types of seabed minerals can be equally severe and irreversible. Because of the challenging environment in the deep sea and how difficult it is to reach, scientific research is slow and costly. Therefore, there has been limited scientific research on the habitats and the organisms living here. Active hydrothermal deep-sea vents are one of the most charismatic habitats with rare species and features. Disturbing these habitats can have severe and irreversible consequences.

Firstly, removing nodules on the seafloor changes the seafloor’s physical terrain and means the direct loss of habitats seeing that nodules work as a substrate for unique fauna (Vanreusel et al., 2016). Loss of habitats can significantly affect species abundance and generate lower genetic diversity and species distribution (Boetius & Haeckel, 2018). For example, more than 50% of all species in an observed area in the east part of CCZ above 2 cm depended on nodules as a source of surface (Amon et al., 2016). Furthermore, since the formation of nodules takes a significant amount of time, it can take millions of years before the fauna will return once the

nodules are harvested (Weaver et al., 2018). An additional manner in which benthic habitat modification can occur through physical alterations is through the deposition of overlying sediments before the extraction of nodules (Akvaplan NIVA, 2022).
The extinction of species can mean the potential loss of ecosystem services, such as services provided by microbial organisms through chemosynthesis, making nutrition available for the deep-sea environment. The essential services, especially Bacteria and Archaea, have been neglected and need to be addressed when assessing the potential environmental risk in regard to deep-sea mining (Orcutt et al., 2020). Extinction of species can also lead to the loss of potential essential biomaterials in pharmaceutical use. For example, Russo et al. (2015) found that organisms in the deep-sea can host organisms that prevent cancer cells from growing, meaning they can be used in novel cancer medicine.

Disturbance on the seafloor (collector plumes) or through, e.g. sampling of sediments, in addition to the discharge of the submerged vessel's pipes (midwater plumes), produces a sediment plume (a cloud of particles) which can impact the surrounding marine life (Levin et al., 2020; Akvaplan NIVA, 2022). Sediments are dispersed to adjacent areas where they sink and cover the seafloor and benthic fauna with a fine layer of particles. The particles can cause burial and contain contaminating toxins, and may have destructive effects on benthic communities (Weaver et al., 2022). Unfortunately, there is limited research on plume dispersal's effect on nearby areas. However, an initial report from 2001 states that the plume can influence ecosystems more than 100 km from the mining site (Rolinski et al., 2001). Some research is starting to be published, and a report from Muñoz-Royo et al. (2021) states that the plume's impact depends largely on the "environmentally acceptable threshold levels", how much sediment is being dismissed along with diffusivity, the speed the particles spread.
Deep-sea mining will cause other disturbances, such as noise, vibration and light pollution, with ROV and AUV exploration and exploitation and other deep-sea equipment and machines (Levin et al., 2020; Akvaplan NIVA, 2022). The increasing noise and vibration levels can harm several marine organisms, as sound is a common way of communicating underwater. The damage can be direct as interference of communication between organisms or indirect when animals are unable to detect a predator or prey (Weaver et al., 2018). According to Williams et al.

(2022), the noise generated from a single mining operation is expected to be more than the ambient noise levels typically observed during calm weather conditions within a distance of approximately 500 kilometres.

The possibility of the introduction of alien species is also a risk with deep-sea mining (Akvaplan NIVA, 2022). The disturbance of the seafloor and sediment plume can transport species by currents to new locations. The organisms may be invasive species establishing themselves in new locations where they potentially disrupt the local ecosystem. Additionally, the operation and construction of pipelines and cables can also create new habitats for species to colonise (Jones et al., 2017).

Life in the deep-sea is believed to recover at extremely slow rates, meaning that destruction and contamination in these areas may have devastating and possibly irreversible consequences (Weaver et al., 2022; Levin et al., 2020). Because of this, ISA and sovereign states considering seabed mining in their national areas, such as Norway, must constitute regulations as tools to be used in environmental management. However, due to the considerable knowledge gaps in the deep sea it is impossible to present an objective assessment of the different environmental challenges mining on the deep-sea can accelerate. Knowledge about the habitats and the organisms hosting these are some of the knowledge gaps that need to be filled for scientists to carry out evaluation regarding the exploitation of mineral resources. A report conducted by the Center for Deep-sea Research at the University of Bergen states that there needs to be a comprehensive mapping of organisms of all sizes, the density and composition of biological communities and their connectivity in the deep (Pedersen et al., 2021).

1.3.2 Risk Assessment

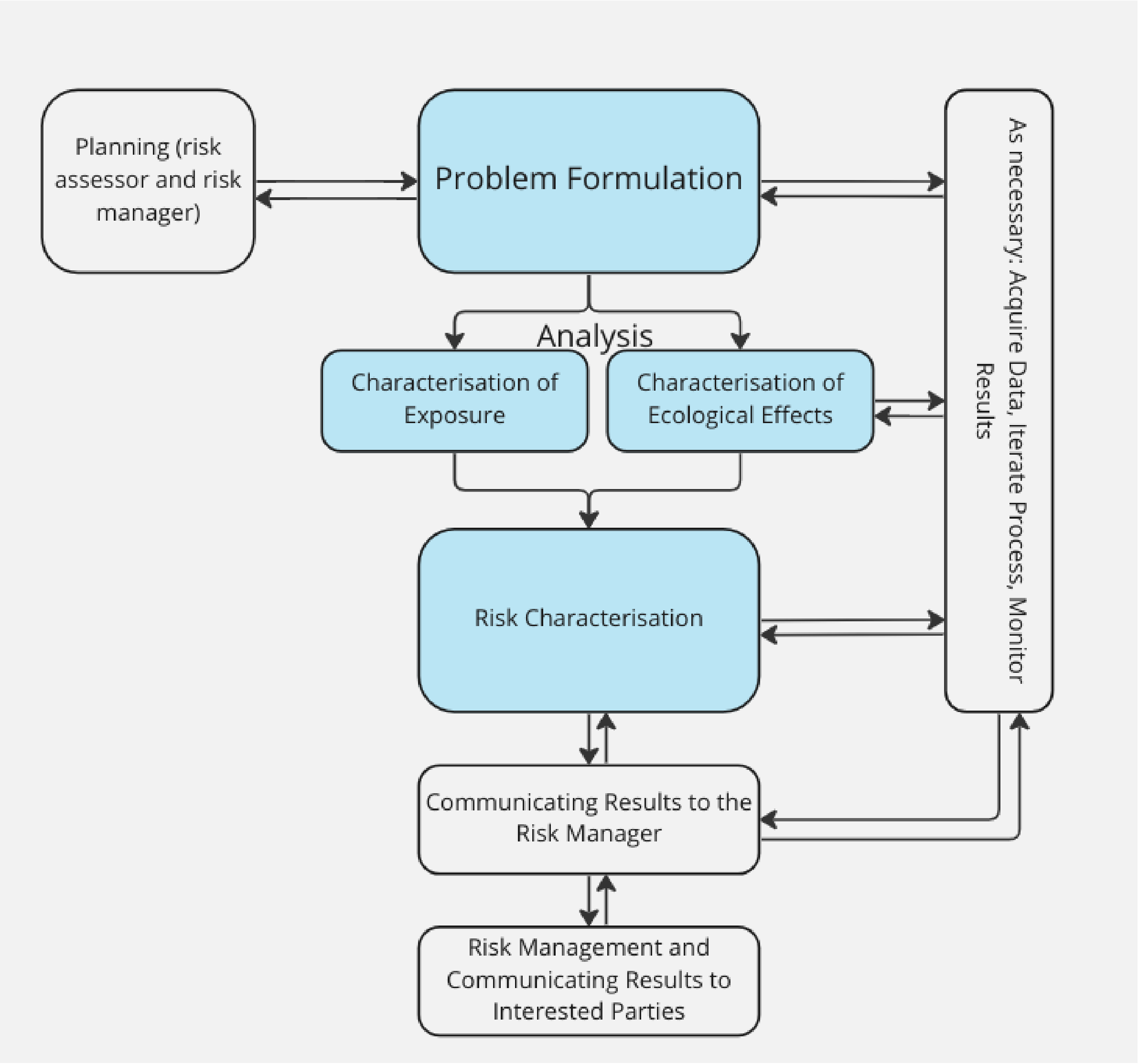


Figure 3. Traditional framework for environmental risk assessment. Blue boxes are the main phases of environmental risk assessment. Inspired by U.S. Environmental Protection Agency (1998).

Risk can be defined as the outcome or aftermath of an activity in relation to something valued by humans. The emphasis is frequently placed on somewhat unfavourable and undesirable outcomes or consequences (Society for Risk Analysis, 2020).

The traditional environmental risk assessment is an evaluation process to give assessments based on consequences and their probabilities of an activity with respect to something humans value or to ecological consequences due to one or more stressors. The process incorporates the organisation of data, information, uncertainty and assumption to see the potential connection between ecological change and the stressors. The environmental risk assessment can implicate one or several stressors, which can be chemical, physical or biological (U.S. Environmental Protection Agency, 1998). Figure 3 shows the steps in risk assessment, including the four main phases marked in blue; formulating the problem, assessment of exposure, assessment of the effect and risk characterisation.

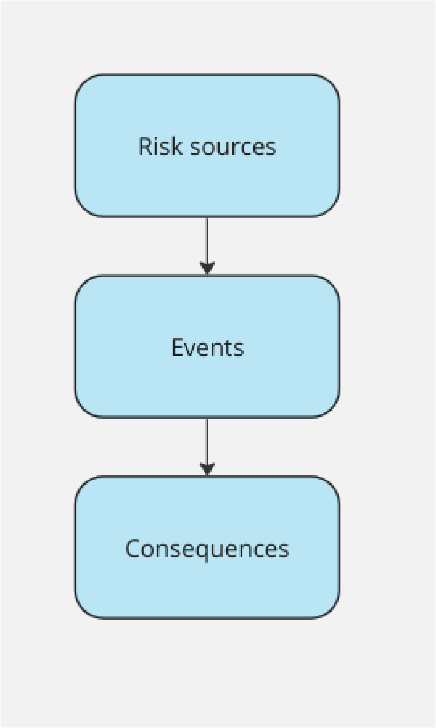


Figure 4. General features of the more recent environmental risk assessment. Inspired and modified after Aven (2014): Main features of a conceptual framework for linking risk, risk sources and events in line with the (C,U) perspective.

A more recent risk perspective is different from the traditional risk perspective in that the principal component of risk is uncertainty, while probability is currently considered a one-factor characterising certainty/uncertainty out of many. In the traditional risk perspective, on the other hand, probability and consequences are used as the main components (Aven & Renn, 2009; Society for Risk Analysis, 2020). From this, a more present-day definition of risk is “Risk refers to uncertainty about and severity of the consequences (or outcomes) of an activity with respect to something that humans value.” (Aven, 2023; Aven & Renn, 2009). While some environmental components, such as air quality and water pollution, are widely recognized as significant risks, other less obvious risks may also have significant impacts that are not seen so clearly as “something that humans value”. For example, the depletion of non-renewable resources or the loss of biodiversity could have long-term consequences for human well-being and ecosystem function beyond today’s understanding (Millennium Ecosystem Assessment, 2005). Therefore, it is important to consider and protect a wide range of environmental resources and components in order to manage environmental risks adequately. Consequently, the Eco-Safe project’s definition of risk is “Uncertainty about and severity of events and environmental consequences of deep-sea SMS activities”. From this definition, the risk has two dimensions: consequences and uncertainty associated with these consequences.

The more recent perspective considers risk as a complex and dynamic phenomenon that involves not only the uncertainty of occurrence and outcome but also the potential magnitude and consequences of that outcome, as well as the societal and ethical considerations surrounding it. This broader perspective acknowledges the need for a more holistic and integrated approach to risk management, which includes proactive measures such as risk prevention and mitigation, as well as stakeholder engagement and communication. The probability is less in focus and replaced with uncertainty (in particular, what are unknowns related to environmental resources that may be impacted by human activities; possible threats/events). From the modern risk perspective, identifying possible threats/events associated with the deep sea SMS activities and assessing the uncertainties related to these threats/events, both in the short term and long term, will be important.

The work in the Eco-Safe project will be mostly regarding hazard identification, meaning which disturbances (impacts/consequences) can be caused by different SMS activities (threats/events), describe the initial uncertainties (uncertainties/lack of knowledge associated with these benthic communities ahead of my analysis) about them, and based on benthic community analyses made in my thesis, increase the knowledge about them, and thereby reduce some of the uncertainty, which can be further used to mitigate the risk. Link to the project’s webpage: https://ecosafe.w.uib.no/

In the more recent risk terminology, it can be stated that risk is a two dimension component consistent with consequences (C) and associated with uncertainty (U), and vulnerability can be associated with this as it can conceptually be perceived as conditional risk (C, U|RS/A), which means that the consequences (C) and the related uncertainties (U) conditional on a risk source (RS) and/or on the occurrence of a threat/event (A) (Society for Risk Analysis, 2020). In relation to deep-sea mining, examples of risk sources can be SMS (seafloor massive sulphides) particles, and events can be the spreading of SMS particles from excavation.

When RS', A' and C' have been specified, a measure of uncertainty (Q) describes a forthcoming event or situation of these risk sources/events/effects. The measure of uncertainty (Q) can, for example, be probability. Q and the specified RS', A', and C' will always be based on background knowledge (K) based on approved data. As a result of this, we can assert that uncertainty characterisation is given by the consolidation of K and Q (Society for Risk Analysis, 2020). One of my contributions will, therefore, improve K and Q.

The modern risk concept appears suitable to portray deep-sea mining, and it appears more appropriate for the aim than the traditional one. For the framework in Eco-Safe, one can put it like this: for SMS mining, the description of risk (R') for a particular event (A') (e.g. releasing SMS particles in the water masses) is derived by defining a set of potential consequences (C') (e.g. damage to the ecosystem's flora and fauna) and will be evaluated and categorised by utilising related background knowledge and uncertainty descriptions (K' and Q').

Environmental risk assessment is an essential appliance used to evaluate the human impact on the potential mineral extraction of the deep sea (Kaikkonen et al., 2018). ISA or the Norwegian authorities consider the risk assessment results to decide whether a planned project can edge forward and how possible ecological consequences can be reduced (Weaver et al., 2018). Because of the expected severity of industrial exploitation on the deep seabed, it is recommended to rely the environmental risk assessment on in situ experiments (Ahnert & Borowski, 2000). Ahnert and Borowski suggest in this initial article that it would be wise to commence simulation of less considerable impacts and increase the severity toward full-scale industrial exploitation while monitoring closely and evaluating possible impacts on each step.

Environmental management is a practice with an aim to minimise human-induced damage to the surrounding environment while maximising the human benefits of resource utilisation (Jones et al., 2018). Environmental management involves the identification and surveillance of the projected/actual environmental alterations throughout the project's period and the time after. This is done to enable informed decisions or potential interventions aimed at mitigating adverse effects (Billett et al., 2019).

Having a baseline is a part of the knowledge basis of risk. By knowing how the effect or the baseline is, one can compare it with other baselines and perhaps predict possible consequences. Because of this, it is crucial to consider time as a significant factor in risk analysis and management, particularly in a complex system with long-term consequences (Logan et al., 2021).

However, from complex systems like the deep-sea, it is especially challenging, or even impossible, to model and predict the effect in practice. By monitoring areas for potential changes, we can describe, predict, measure, and control risks (ISO, 2018). This helps to mitigate the limitations of risk prediction and outcomes. Although the foundation for risk assessment is not yet fully developed, my data can contribute to the knowledge base and enable the development of better risk assessment practices.

There are several widely recognised approaches for evaluating risks that have been approved by established standards and guidelines, the fields of risk assessment and risk management require further clarification on many of their fundamental scientific principles (Aven et Zio, 2014).

1.4 Mining in Norwegian waters

The Norwegian government has opened up for deep-sea mining on the continental shelf; this includes evaluating what mineral resources may be in the deep ocean within the exclusive economic zone, for example, on the Mohns Ridge 71 °N to 73 °N (Juliani & Ellefmo, 2018). The Norwegian Petroleum Directorate is in charge of the metal resource evaluation, whilst external exploration companies are preparing for the possible exploitation by gaining knowledge and researching various technologies for extraction (Norwegian Petroleum Directorate, 2023a). In July 2019, the “Law of Mineral Activities on the Continental Shelf” was approved in Norway, signifying that mining activity can eventually be opened on the Norwegian continental shelf (Seabed Mineral Law, 2019). However, the law states that environmental impact assessments must be executed before mining activity begins in the area in question. Nevertheless, Norway has started the opening process, marking a possible beginning of the first exploration phase in Norwegian waters in the spring of 2023 (Olje- og energidepartementet, 2022).

Seabed minerals that have been detected in Norwegian waters are, e.g. zinc, copper, lead, manganese, iron, silver, gold, cobalt, titanium, cobalt, zirconium, cerium and rare earth elements (Norwegian Petroleum Directorate, 2023b). The extraction of these minerals can be a new and valuable industry in Norway (Olje- og Energidepartementet, 2022). The technology for extracting minerals from the seabed at great depths is still in the development stages and is distinguished from conventional land-based mineral extraction practices. Due to the unique marine environment, distinct environmental considerations must be taken into account. As of the present time, no countries have ongoing deep-sea mining projects (Akvaplan NIVA, 2022).

1.5 Thesis aim

The expansion of human activities into the deep-sea poses new environmental threats that still need to be assessed. On the Norwegian continental shelf, there is an emerging interest from the industry in exploring seabed mineral deposits that co-exist with these still largely pristine ecosystems.

The Eco-Safe Ridge Mining research project seeks to address important knowledge gaps, evaluate environmental hazards, and determine suitable measures for minimising the impact of deep-sea mining. The main goal of this thesis is to contribute to the characterisation of the benthic community structure at the Fåvne Hydrothermal vent field and contribute with data for environmental risk assessment from seabed mining activities on the Arctic Mid Ocean Ridge. The outcome of this project will contribute to inform management and conservation policies, given the ongoing process that can lead to opening the Norwegian continental shelf to mining activities in the near future. I performed seafloor image analysis of high-resolution video transects recorded with ROV Ægir using manual annotation and the software Papara(zz)i to examine spatial patterns and structure using appropriate statistical methods. This research was used to discuss the environmental risk assessment of potential mining operations in the vicinity of the Fåvne hydrothermal vent field. With this knowledge base, the question if risks to the benthic megafauna resulting from exploration and (possible) extraction on the seabed be justified on the basis of contributing to the green shift, was situated.

Method

2.1 Data collection

2.1.1 The Arctic Mid-Ocean Ridge

Mid-ocean ridges are long underwater mountain ranges with activity connected to the formation of oceanic crust and host more than 80 % of Earth's volcanoes (Pedersen et al., 2021). The Arctic Mid-Ocean Ridge (AMOR) ranges from the northern parts of Iceland to the Siberian Shelf, with a span of more than 4000 km (Baumberger et al., 2016), and is separated from the Mid-Atlantic Ridge by Iceland. This separation works as a barrier for the migration and dispersal between the different systems (Sweetman et al., 2013). Considerable parts of AMOR are located in Norwegian waters and are potential mining sites for seabed minerals, especially seafloor massive sulphide deposits, which are most likely to have the most prominent financial gain in these areas (Pedersen & Bjerkgård, 2016).

2.1.2 Study area

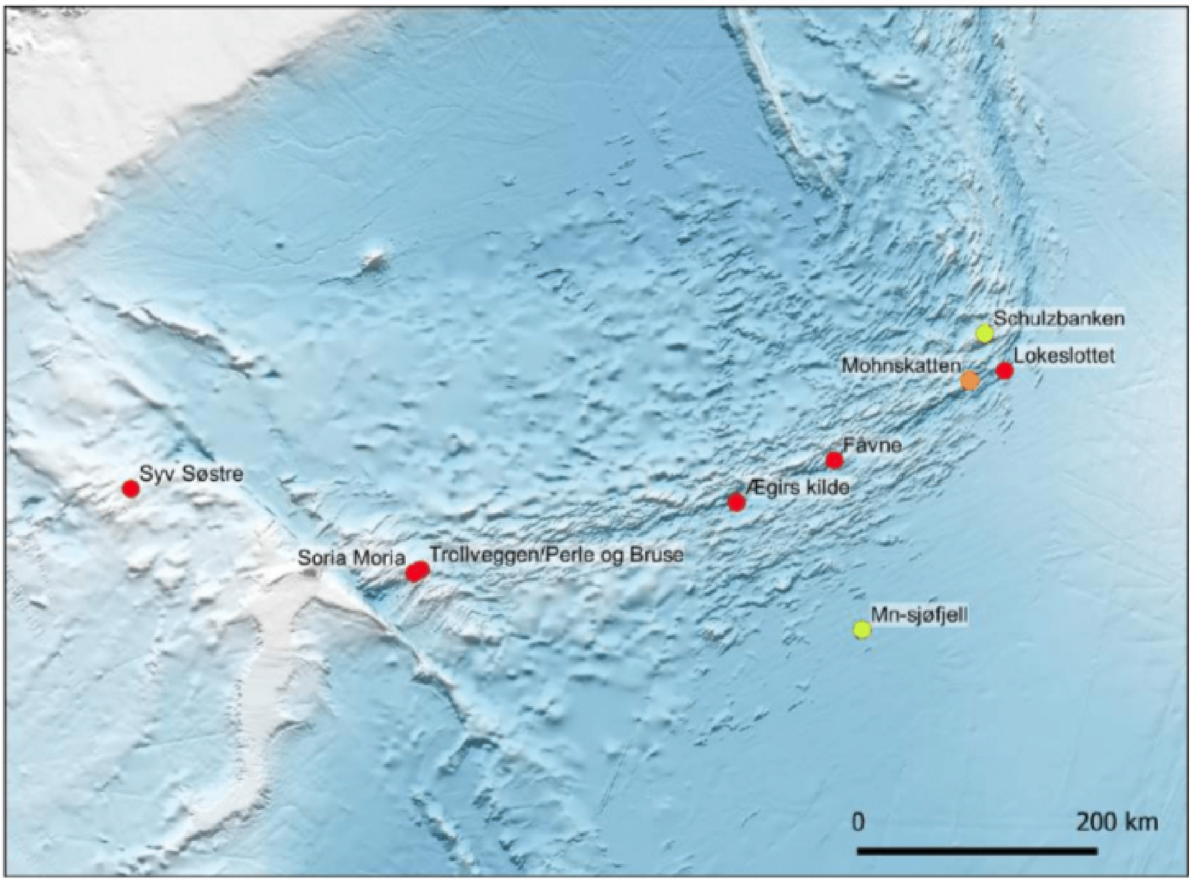


Figure 5. "Central locations in the research area. Red circle indicates active vent fields, orange circle indicates vent field with low activity level, and yellow circle indicates seamountain." Gathered from Pedersen et al., accessed 21. November 2022, https://www.regjeringen.no/contentassets/dbf5144d0fbc42b5a4db5fc7eb4fa312/vedlegg-3.-senter-for-dyphavsforskning-uib.-landskapstrekk-naturtyper-og-bentiske-okosystemer.pdf

There are eight known hydrothermal vent fields along the Norwegian part of AMOR; one of these is Fåvne, 72.8°N, 4.2°E at 3000 metres depth (Pedersen et al., 2021). The study site for this thesis is the Fåvne hydrothermal vent field located between Ægirs Kilde and Lokeslottet on the Norwegian part of the AMOR (Figure 5). Fåvne was discovered in 2018 and it consists of chimneys with black deposits as well as inactive chimneys (Pedersen et al., 2021). However, because of the recent detection of Fåvne, the material collected in 2019 at the site has yet to be processed, and the scientific knowledge about this site is restricted.

The Center for Deep Sea Research at the University of Bergen has an annual summer cruise to the Norwegian-Greenland Sea to map and conduct research on the volcanic sea floor, explore new hydrothermal vents and collect samples from the ecosystems and organisms.

The benthic community contains many different habitats, and data collection methods can vary and be complicated. The most important tool when researching along the AMOR is an ROV (Remotely Operated Vehicle). The ROV Ægir 6000 was used during the dives at Fåvne and can be submerged down to 6000 metres. It is rigged with different equipment for samplings, such as telemetry sensors, ATLAS manipulators, thrusters, a suction sampler, a scoop, a probe, a biosyringe, one HD camera and one 4K camera.

Using ROVs in deep-sea research is efficient for multiple reasons, e.g. they are often more cost-effective, it can be time-saving and they do not put human lives at risk. The harsh environment and extreme pressure in the deep sea make manned missions dangerous. ROVs can, in addition to this, be beneficial when sampling. Because it is often non-invasive and gentle to the environment, which is particularly important in the deep sea, where delicate ecosystems and rare species can easily be impaired. In the case of investigating the deep-sea with video transect (my study), there is a complete absence of any discernible footprint. With a ROV, you will get the precise location, and it has several video cameras which collect data to be used in quantitative studies and video analysis, including this thesis (Pedersen et al., 2021).

The ROV drove close to the seafloor and the hydrothermal vents at a slow speed during the transects to get high-resolution seafloor video of the environment with accurate positioning. My data was collected during the ROV578 dive, which was a 20-hour long dive, with an extensive visual survey over the vent field and the surroundings. During the transect, the ROV was flying at a speed of less than 0.25 knots at an altitude of 1-2 metres above the seafloor.

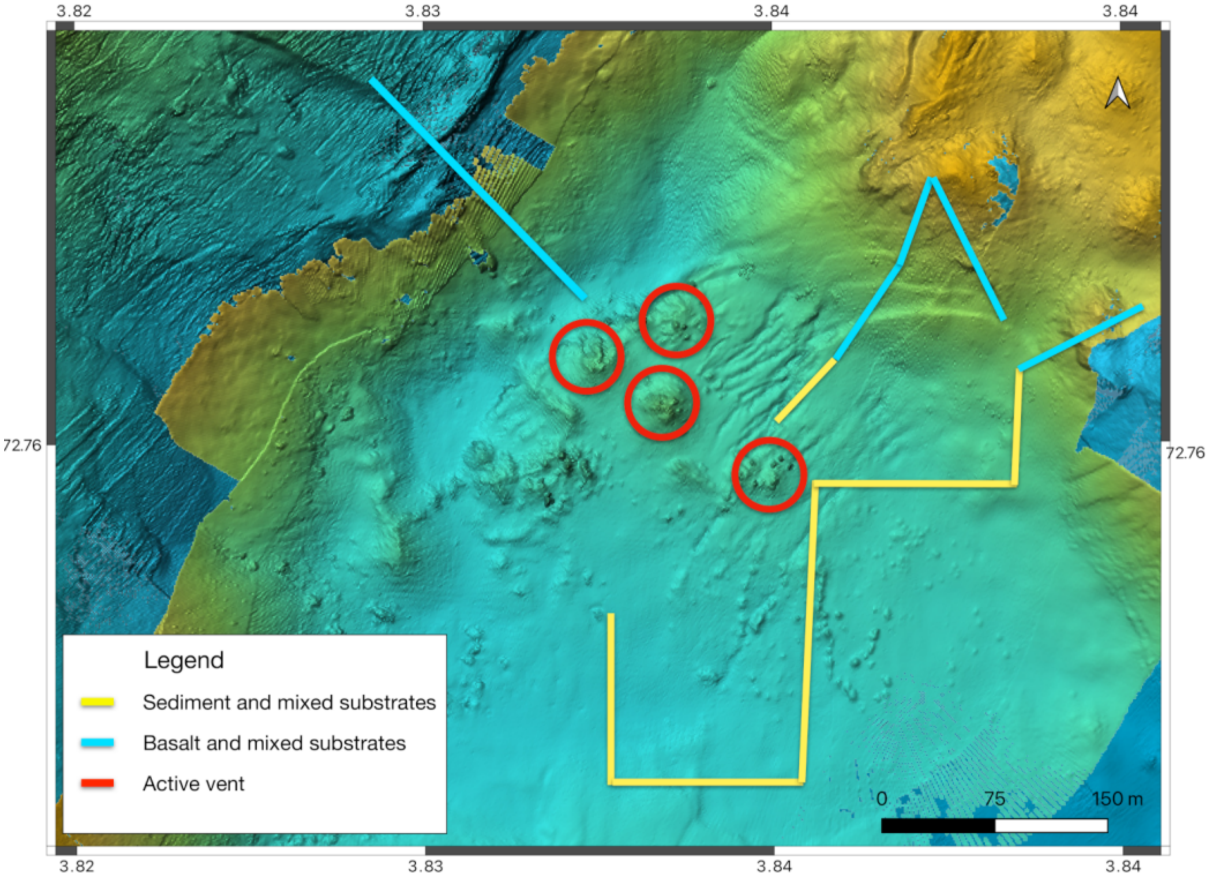


Figure 6. Bathymetric map of the Fåvne vent field showing the ROV track along which video transects were performed for this study, with indication of the habitat types found. Transects within the red circles were performed vertically along the active vents. .

2.2 Image Analysis

The image analysis work was divided into three parts:

1. Development of a morphospecies catalogue.
2. Detailed annotation of visual transects from ROV578.
3. Quantitative data analysis.

2.2.1 Morphospecies Catalogue

Before handling the data, it was necessary to set a baseline for the benthic community at Fåvne.

A species catalogue provides a comprehensive record of the biodiversity present in the area, which is crucial for monitoring changes in the ecosystem over time. Such catalogues can also serve as a reference for future studies on the area's flora and fauna, aiding in the identification of new species and the determination of their ecological roles. In the deep-sea there are only faunal catalogues. Cataloguing the species present in a recently discovered location is an essential aspect of biological exploration and comprehension and a fundamental step towards development of environmental conservation strategies. It provides a foundation for scientific research, facilitates the development of conservation strategies, and enhances our overall understanding of the natural environment (Limolino et al., 2017).

Morphospecies, also known as morphological species, is a taxonomic concept to define a group of organisms based on their physical characteristics. This approach of species classification is used when molecular data is difficult, unavailable or impractical, or when access to the physical specimen for adequate taxonomical examination is not possible.

Although only dive ROV578 was used for quantitative image analysis in the context of this thesis, screenshots of all morphospecies seen on videos from the ROV573, ROV577 and ROV578 dives were taken and sorted in taxonomic rank in a faunal catalogue. The organisms were morphologically identified by eye from images. The process of identifying these species involved an in-depth examination of their unique physical characteristics and behaviours. Nonetheless, species identification through images is difficult, and it is in many cases impossible. To address this known limitation, morphospecies names not identified to species level followed the terminology proposed by Horton et al. (2021) for the standardisation of open taxonomic nomenclature for image-based identifications. All the morphospecies not identified to species level were given a standardised name for other researchers to use the data and ensure that different studies are comparable. Whenever needed, voucher specimens were collected with the ROV for taxonomy and DNA barcoding studies by other researchers to compare with the morphological species identification.

2.2.2 Annotation

From the ROV578 dive, I chose clips relevant to our study. Videos containing sampling, inadequate lighting or visibility, footage from when the vehicle travelled to new locations, etc., were excluded. The transects going at a slow speed (less than 0.2 knots) near the bottom (1-2 m altitude) when the camera was facing the ground and the benthic fauna was visible were chosen and cut into shorter clips, which were the foundation for the faunal annotation. The clips were split into still images to make annotation easier. To avoid overlapping the pictures, frames were extracted every 20 seconds in each clip, and for this, I used the program FFmpeg, Fast Forward Moving Picture Experts Group (https://www.FFmpeg.org). For any given video clip, the extracted frames were saved with a specific name with the code (example):

```
./ffmpeg -i Favne_ROV578_clip36.mov -r 0.05 ROV578_frames_clip36-%03d.png
```

Additional quality control of the still images was performed to eliminate bad quality ones.

A total of 687 photographs of the seabed were obtained from the video footage, from which 572 (covering 1295.6 m^2 of seafloor) were used in the analysis. Information including dive number, time UTC, geographical coordinates, altitude above the seafloor, substrate type, any lebensspuren, tracks and morphospecies occurrences were registered for each image in an Excel sheet.

2.3 Statistical analysis

After all information per image was annotated, I narrowed all the data concerning habitat type (substrate) and morphospecies (abundance) for comparison of species in different habitats. Comparing different species across different habitats in a biological analysis of the deep sea is important for several reasons. First, the deep-sea is one of the most understudied and inaccessible ecosystems on our planet, and therefore, the discovery and understanding of species distribution and diversity can provide valuable insights into the functioning of deep-sea ecosystems.

Second, comparing different species across different habitats can help us understand how deep-sea organisms adapt to different environmental conditions, such as pressure, temperature, and chemical gradients. Variations in habitat are a crucial aspect of understanding different ecological aspects in a community. Studying the differences in habitat utilisation among species can give insight into the interaction among species in an ecosystem and is key to understanding the complex web of coexistence between species in an environment. This can provide crucial information about the physiological and ecological characteristics of these organisms, as well as their potential for adaptation to future changes in their environment.

Moreover, comparing species in different habitats can be helpful in the identification of key drivers in community structures and the general biodiversity in the deep sea. By analysing the distribution and abundance of species in these habitats, we may be able to identify ecological processes that contribute to forming communities in the deep sea. In addition to this, discovering the differences in species between habitats can be helpful in the prioritisation of conservation policies and in classifying which areas that should be categorised as high conservation policies.

Given that it is impossible to keep the ROV at a steady altitude at all times over rough seabed, images will vary in area of seafloor covered. The varying area displayed in each image may lead to a potential misrepresentation of species density. To address this issue, I used a software called PAPARA(ZZ)I to determine the size of the area depicted in each image. PAPARA(ZZ)I is a custom-built program used for annotating marine images and immediate analysis. The ROV is equipped with two laser points spaced at a 10 cm distance. I set the scale bar to 0.1 metres for all images and outlined the area of seafloor annotated in each image. Based on this, PAPARA(ZZ)I was able to calculate the useful area of each image, which is necessary for analysing and comparing species density instead of abundance.
After adding all information in the spreadsheet gathered from the program, including width pixels, height pixels, width (metre), height (metre), scale pixels and scale metres are used and image area in square metres, I calculated the organism density for each observation: Density = counts individuals) / Area (m^2). This method is not

perfect due to the tilt of the ROV camera; however, the consistency in the angle across all the images makes them more amenable to comparative analysis.

For the rest of my analysis, I used the R package *Vegan 2.6-4* (Oksanen et al., 2022), which is a community ecology package. The software incorporates a variety of analytical tools for analyses of diversity patterns in biological communities.
Firstly, assemblage diversity was assessed by estimating taxa richness (S), the inverse Simpson diversity index (1/D) and Pielou's evenness index (J=H/ln(S).
These are numerical measures used to describe the variety and abundance of species. I calculated how many species were in the different types of substrates that were identified. These indices help to quantify species diversity and complexity in an ecosystem and are an important tool to track alterations in biodiversity or compare different ecosystems. It is also relevant for measuring the health of the ecosystem, identifying areas of high conservation value and informing management and conservation strategies. Statistical testing of differences between diversity indices among habitat types was performed using Kruskal-Wallis tests.These were chosen instead of ANOVA because the data had a non-normal distribution and non-homogeneity of variance (tested first with Shapiro-Wilk tests and Levene's tests). Pairwise differences in diversity indices between habitats were performed through a post-hoc Dunn's test using the R package *dunn.test*.

I also conducted a multivariate analysis to identify patterns in the data set. Multivariate analysis is a statistical approach used to analyse data containing multiple variables at the same time and makes it possible to investigate connections and patterns and to understand how they influence each other. Variation in morphospecies composition was investigated with non-metric multidimensional scaling (nMDS) analysis, a multivariate statistical method commonly used to explore complex patterns of similarity or dissimilarity and make it into a matrix, using the R package *vegan*. The nMDS analysis was based on a Bray-Curtis dissimilarity matrix between each pair of photographs, calculated from faunal densities with prior Wisconsin and square root transformation of the data (it is done to reduce variability in the data and make it more suitable for statistical analysis). The *metaMDS* function in *vegan* was run with three dimensions, 999 maximum iterations and 500 maximum numbers of random starts.

To compare similarities in the data set, I conducted an ANOSIM, an analysis of similarities. This is an analysis of the groupings of nMDS and is used to investigate if there is a significant difference between two or more groups of samples. It is a common analysis used in community ecology to compare the different species' diversity and community structures and can provide insights into the factors driving these differences. The results after ANOSIM ranges from -1 to 1, where a negative value indicates more similarity than what can be expected by chance, 0 is no separation, and 1 indicates a complete separation between the testing groups.

To identify the contributions of each morphospecies to the observed clustering pattern, I did a SIMPER analysis (similarity percentage analysis), a multivariate statistical method, in *vegan*. It is common to use SIMPER in ecological research to investigate the composition and abundance of species in different habitats. It is done by calculating the percentage contribution of each factor to the dissimilarity between the groups of samples. SIMPER calculates the average dissimilarity between pairs of samples both within and between the groups and then assigns the dissimilarities to specific variables or factors. It was used to determine the morphospecies contributing the most to the dissimilarity of epifaunal assemblage composition among habitat types. SIMPER analysis is used to, e.g. identify key environmental factors reliable for the differences in communities in different habitats. When the important factors have been identified, researchers understand more of the ecological processes affecting and making these habitats and, in that way, help to inform management and conservation.

Results

3.1 Image analysis

A total of 687 images were annotated for fauna and seabed characteristics. Of these, 120 contained no visible fauna and were therefore removed from the data set before the multivariate analysis because you can not compare two images that have nothing to compare as it is technically impossible to compare 0 with 0.

The image data covered six distinct habitat types defined according to the type of substrate or the presence of visible hydrothermal activity (Table 1). These were: Active vent (206 images, 216.1 m²), basalt (88 images, 266.4 m²), inactive sulphide (14 images, 26.9 m²), mixed substrate I (mix of soft sediment and inactive sulphide) (47 images, 142.3 m²), mixed substrate II (soft sediment and inactive basalt) (138 images, 291.6 m²) and soft sediment (194 images, 541.2 m²) making 687 images with a total of 1484.5 m² surveyed (Table 1). After discarding unsuitable images, there were 572 images with a total of 1295.6 m² to be used in the analysis.

Table 1. The total number of images on each habitat/substrate and total area of seafloor surveyed.

Habitat/substrate	**Number of images**	**Area of seafloor surveyed (m²)**
Active vent	206	216.1
Basalt	88	266.4
Inactive sulphide	14	26.9
Mixed substrate I	47	142.3
Mixed substrate II	138	291.6
Soft sediments	194	541.2
Sum	**687**	**1484.5**

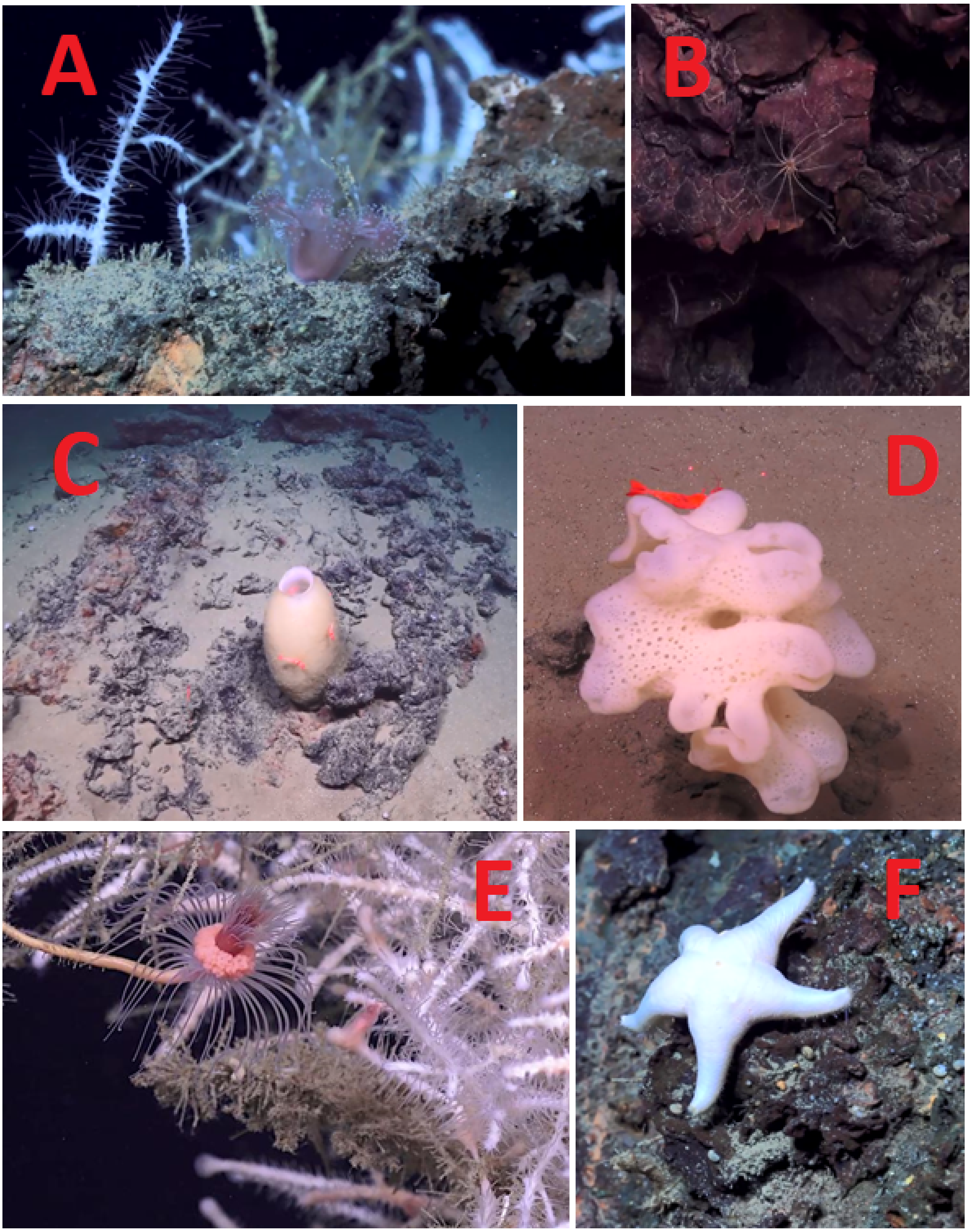


Figure 7. Examples of fauna found on Fåvne. A - Stauromedusae sp. indet, Isopoda sp. indet., *Cladoriza gelida*. and small gastropods. B - *Poliometra prolixa*. C - *Asconema megaatrialia*, anemones and Caridea gen. indet. D - *Caulophacus arcticus*, Bythocaris sp. indet. and Foraminifera shells. E - Hydrozoa gen. indet 1 and *Cladorhiza gelida*. F - *Tylaster willei* and small Gastropoda sp. indet.

Upon conducting a meticulous analysis of the selected images, a total of 17,950 individual faunal observations belonging to 34 morphospecies distributed across seven phyla were annotated from the images (Appendix 1). One morphospecies (*Crossota* sp. indet.) is pelagic, it was therefore removed from the analysis due to its high mobility. Other mobile taxa, including shrimps and fish, were kept in the analysis due to their benthic or demersal nature. Some of the morphospecies in the faunal catalogue were not observed in the analysed images and thus were not used in the analysis.

This information provides valuable insight into the biodiversity and complexity of the ecosystem in which these species coexist. Figure 7 shows a few examples that showcase the remarkable diversity of fauna that can be found on the Fåvne hydrothermal vent field. These offer a glimpse into the vast array of animal life that exists between various species.

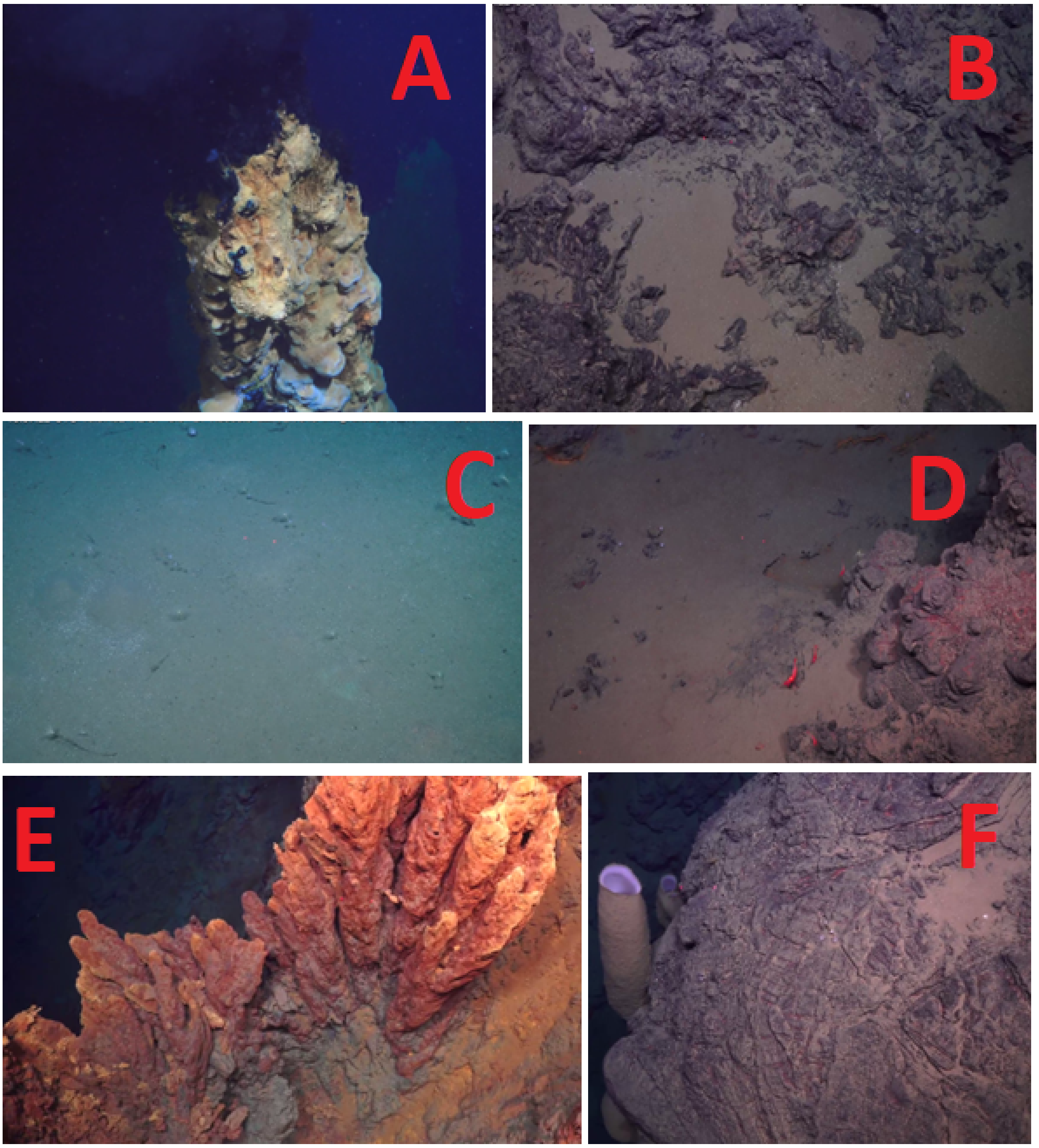


Figure 8. Examples of different habitat types at Fåvne hydrothermal vent field. A - Active sulphide, black smoker. B - Mixed substrate I, a mix of soft sediment inactive and sulphide inactive. C - Soft sediment inactive. D - Mixed substrate II, a mix of soft sediment inactive and basalt. E - Sulphide inactive. F - Basalt.

There is a disparity in habitats at Fåvne. Habitats were divided into six different types; (1) soft sediments, (2) inactive sulphides (sulphide seafloor with no visible sign of venting), (3) basalt, (4) a mix between soft sediment and inactive sulphide, a mix between soft sediment and basalt, a mix between soft sediment and active sulphide, and active vent. The different substrates near the hydrothermal vent field provide a range of microhabitats for organisms to colonise and contribute to high biodiversity in these extreme environments.

3.2 Species and habitat relationship

Figure 9 shows that a significant degree of species diversity exists between different phyla across a majority of the habitats. Specifically, all seven phyla were observed in five out of the seven habitats (mixed substrate I, basalt, mixed substrate II and soft sediment). Notably, the highest levels of faunal density were observed in proximity to active vents due to the geochemical conditions supporting the growth of chemosynthetic bacterias that are primary producers.
Figure 9 shows a difference in community composition between habitats. It shows a clear contrast between the species distribution in different areas, which indicates that certain species are better adapted to particular environmental conditions. The graphs highlights the importance of understanding how species are distributed in different environments.

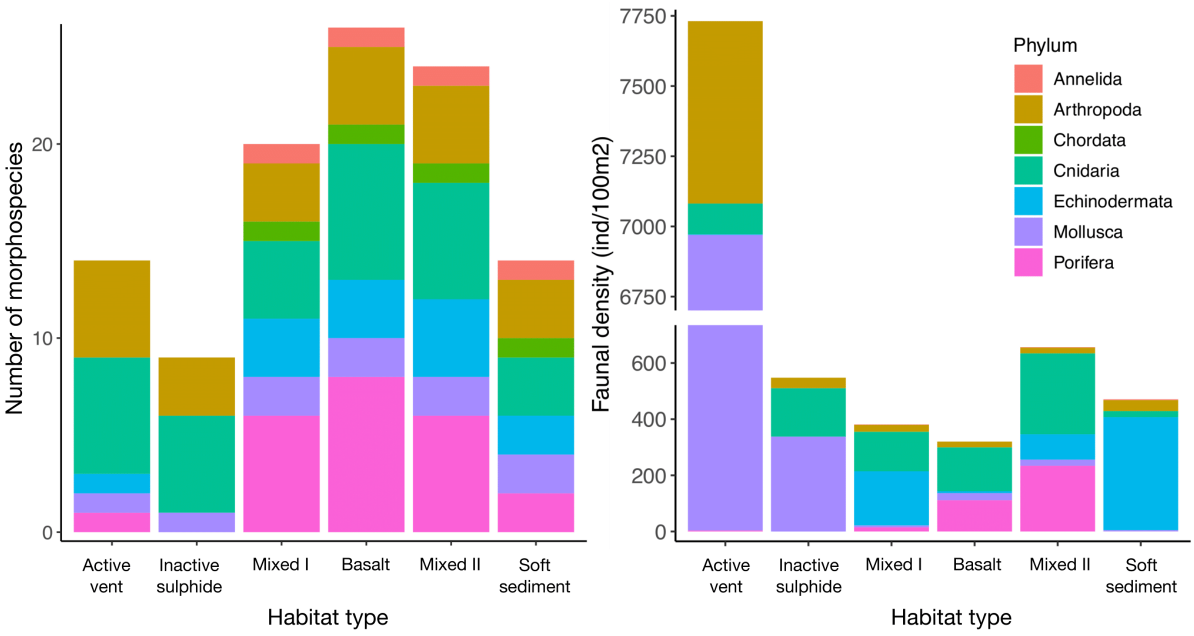
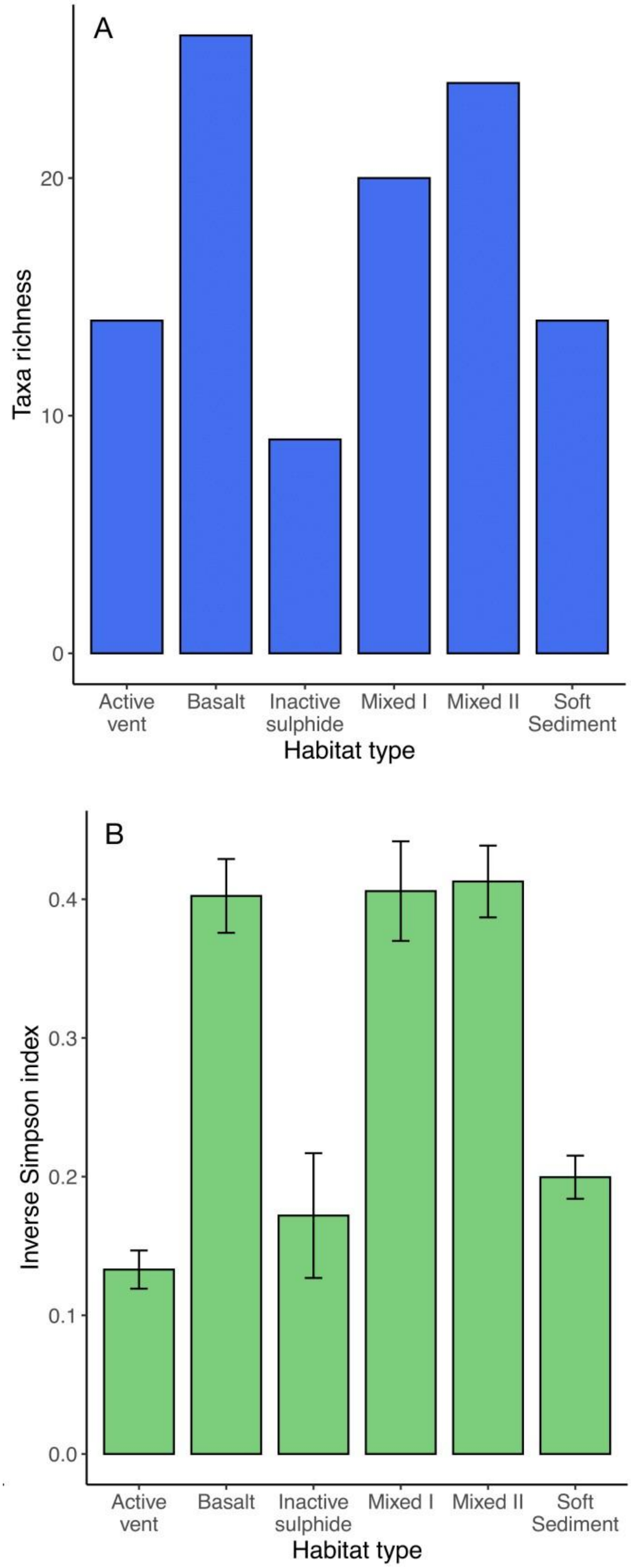


Figure 9. Benthic epifauna recorded in the analysed images at Fåvne. Left: Number of morphospecies per phylum. Right: Faunal densities normalised to individuals per 100 m² (on the right).

3.2.1 Diversity indices

Taxonomic richness and diversity were substantially higher on basalt and mixed substrate areas compared to the other habitat types (Figure 10). The Kruskal-Wallis test revealed significant differences in the inverse Simpson diversity index (1/D) and Pielou’s evenness ($p < 0 .001$ in both cases). Specifically, epifaunal assemblages at active vents showed significantly lower diversity compared to the other habitats (Dunn test: $p < 0.01$) except for inactive sulphide areas ($p > 0.05$). Epifaunal diversity on soft sediment was higher than that on active vents ($p < 0.01$), despite the much larger survey area. On the other hand, there was no significant variation in epifauna diversity among basalt and mixed substrate habitat types.

Evenness was significantly lower on assemblages inhabiting active vents and, to a lesser degree, soft sediments (Dunn test: $p < 0.001$ for all pairwise comparisons). This result is consistent with comparatively lower species diversity at these habitats and high abundance of a few dominant species: vent-endemic gastropods and amphipods on vents, Bathycrinus carpenterion soft sediment areas. The highest evenness values were found on basalt assemblages, which also shows the highest species diversity but no particularly dominant species.


A
Taxa richness
0
10
20
Active vent
Basalt
Inactive sulphide
Mixed I
Mixed II
Soft Sediment
Habitat type
B
Inverse Simpson index
0.0
0.1
0.2
0.3
0.4
Active vent
Basalt
Inactive sulphide
Mixed I
Mixed II
Soft Sediment
Habitat type

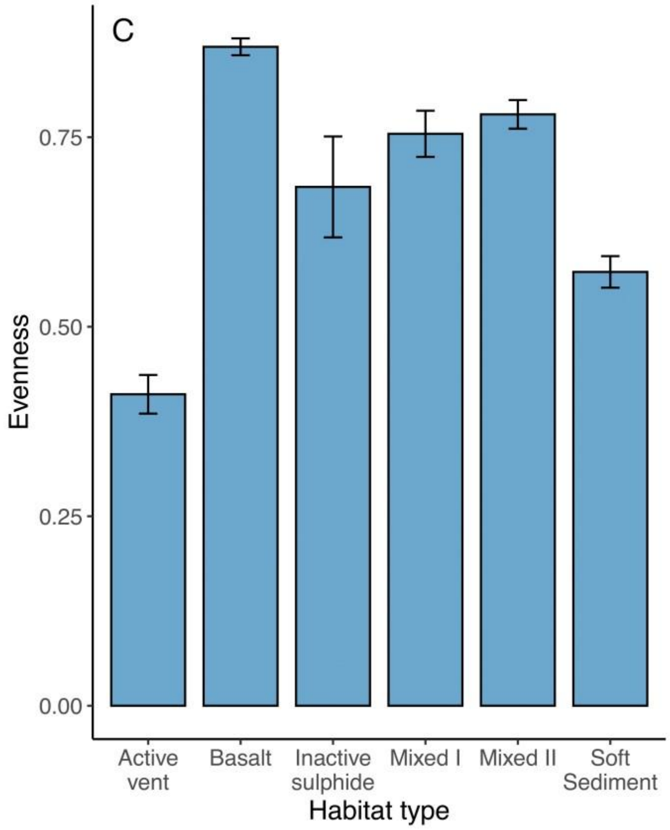


Figure 10. Variation among habitat types in morphospecies richness S **(A)**, inverse of Simpson's diversity index 1/D **(B)** and Pielou's evenness J **(C)**. Plots B and C show mean values across seabed images, error bars indicate 95% confidence intervals.

3.2.2 Community patterns

nMDS ordination

Figure 11 is a two-dimensional nMDS plot representing the dissimilarities of the faunal composition, the assemblage of each image. The scattering of points shows that individual images have a considerable amount of differences between them. Points (representing individual images) are coded by habitat type and we can see that the same habitat type is closer together. Active vents are clearly different from the other habitat types, and the scattering within this habitat is possibly due to the difference between the mound and the active chimney where species compositions are different. There is a clear transition from the active vent (red) to the periphery of inactive sulphide (green) and other background habitats. There was a significant scattering of data points in the ordination space, indicating large variability in morphospecies composition between images, even those within similar habitats. This large variability is also expressed in the fact that the vast majority of pairwise dissimilarities were 1 (Figure 12).

Clustering of groups based on habitat type revealed clear differentiation between assemblages on active vents and the background (basalt, sediment and intermediate habitats). There was some overlapping between active vents and inactive sulphides, but also between inactive sulphides and basalt habitats. This may indicate undetected hydrothermal activity in the areas classified as inactive.

The stress factor for this analysis is 0.14. Stress value of less than 0.05 is an excellent fit, stress less than 0.20 is considered as good or acceptable fit, meaning that it is acceptable and can be interpreted with confidence. This is a data set with a large amount of points which makes the stress higher. If the analysis were only between active vents and basalt there would have been less points and the stress would have been lower. The ellipses have confidence intervals of 50% or more. If higher confidence intervals would have been used, the intersection between groups would have been lost because of the scatterings of the points.
Analysis of similarities (ANOSIM) revealed statistically significant differences in morphospecies composition among habitat types (R=0.411; p=0.001).

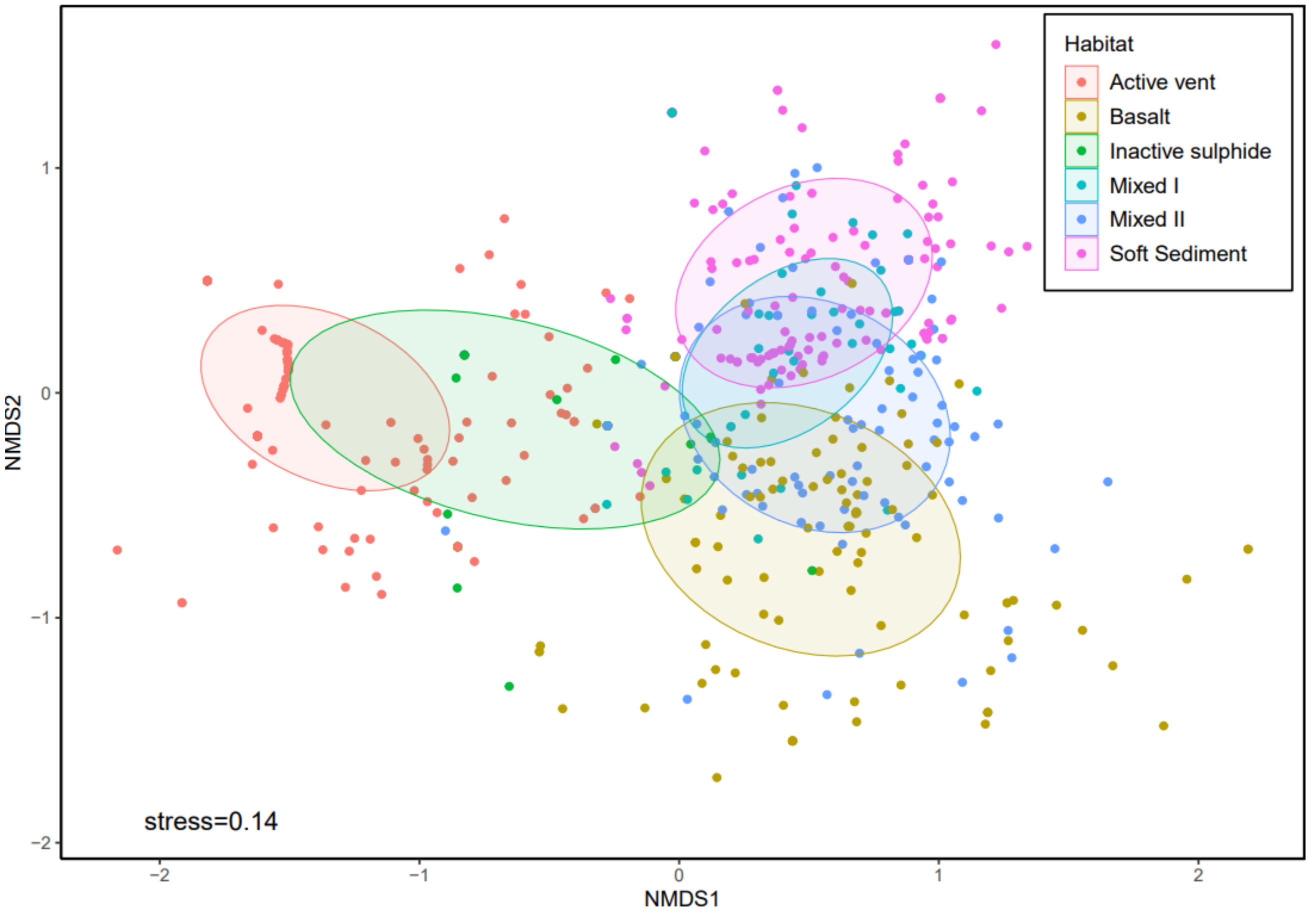


Figure 11. Non-metric multidimensional scaling (nMDS) plot showing variation in epibenthic fauna assemblage composition between habitat types at Fåvne. Points represent individual images, ellipses represent 50% confidence intervals. The analysis was based on pairwise Bray-Curtis dissimilarity calculated from square-root transformed faunal densities (ind./m2).

Figure 12 shows that the pairwise Bray-Curtis dissimilarities are mostly 1. A value of 1 indicates that the images do not have any morphospecies in common, while a value of 0 indicates that the images have identical morphospecies composition. As most of the values are 1, this indicates that the community composition is highly dissimilar and the images have unique morphospecies compositions. This could be due to the relatively small area covered by each individual image and the patchy nature of benthic faunal distribution in the area.

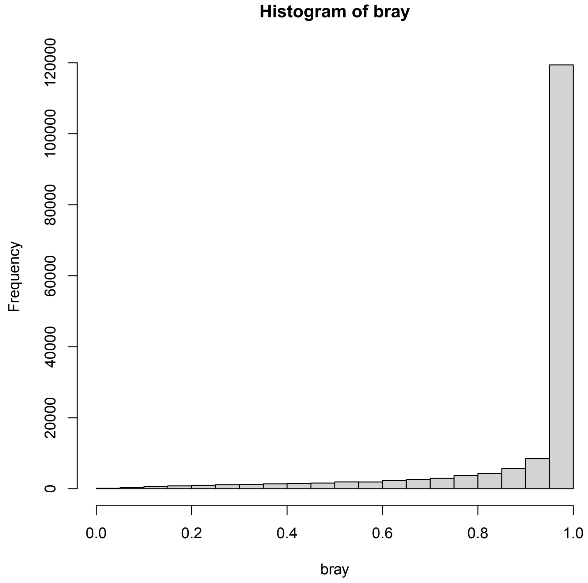


Figure 12. Histogram of pairwise Bray-Curtis dissimilarities. The Y axis shows the frequency of pairwise comparisons, the x axis shows the value of Bray-Curtis dissimilarity ranging from 0 to 1.

Simper

Table 2 shows selected results of the SIMPER analysis, which involved 15 comparisons between habitat types altogether. From table 2 it is indicated that *Bathycrinus carpenteri* is the species contributing the most to dissimilarity between soft sediment and basalt, *Bathyphellia margaritacea* for inactive sulphide and basalt, and Amphipoda sp. indet is the species contributing the most dissimilarity between both soft sediment and active vent, basalt and active vent and inactive sulphide and active vent. These findings can indicate that Amphipoda sp. indet and Gastropoda sp. indet. are indicator species for active sites.

Table 2. Selected results of similarity percentage (SIMPER) analysis, showing the morphospecies contributing the most to dissimilarity of faunal assemblage composition between habitat types at Fåvne (the complete table can be found in Appendix). Average morphospecies contribution to average between-group dissimilarity; SD: standard deviation of contribution; Ratio: Average/SD; Av.A and Av.B: average abundances per group; Cum. Sum: ordered cumulative contribution (summing up to 1).

Morphospecies	Average	SD	Ratio	Average A	Average B	Cum. Sum
Soft sediment vs Basalt						
Bathycrinus carpenteri	0.1632	0.1469	1.1108	0.4586	0.0014	0.1739
Bythocaris sp. indet.	0.1140	0.1353	0.8427	0.2465	0.1766	0.2954
Pantopoda gen. indet.	0.0837	0.1399	0.5979	0.2144	0.0218	0.3846
Bathyphellia margaritacea	0.0759	0.1081	0.7022	0.0486	0.1983	0.4655
Asconema megaatrialia	0.0586	0.1115	0.5263	0.0000	0.1698	0.5280
Soft sediment vs Active vent						
Amphipoda sp. indet.	0.1792	0.1639	1.0930	0.0000	0.4596	0.1839
Bathycrinus carpenteri	0.1729	0.1541	1.1220	0.4586	0.0000	0.3614
Gastropoda sp. indet.	0.1370	0.1430	0.9588	0.0000	0.3516	0.5021
Bythocaris sp. indet.	0.1030	0.1387	0.7429	0.2465	0.0642	0.6079
Pantopoda gen. indet.	0.0943	0.1489	0.6330	0.2144	0.0526	0.7047
Basalt vs Active vent						
Amphipoda sp. indet.	0.1704	0.1570	1.0850	0.1840	0.4596	0.1763
Gastropoda sp. indet.	0.1300	0.1366	0.9514	0.0000	0.3516	0.3109
Bythocaris sp. indet.	0.0775	0.1275	0.6079	0.1766	0.0642	0.3912
Bathyphellia margaritacea	0.0742	0.1123	0.6608	0.1983	0.0230	0.4680
Caridea gen. indet.	0.0674	0.1264	0.5328	0.0654	0.1447	0.5378

Inactive sulphide vs Active vent						
Amphipoda sp. indet.	0.1943	0.1744	1.1138	0.1000	0.4596	0.2251
Gastropoda sp. indet.	0.1629	0.1560	1.0443	0.1697	0.3516	0.4138
Bathyphellia margaritacea	0.1069	0.1546	0.6914	0.2595	0.0230	0.5377
Caridea gen. indet.	0.1068	0.1625	0.6571	0.1769	0.1447	0.6613
Bythocaris sp. indet.	0.0871	0.1413	0.6163	0.1849	0.0642	0.7622
Inactive sulphide vs Basalt						
Bathyphellia margaritacea	0.1274	0.1428	0.8921	0.2595	0.1983	0.1407
Bythocaris sp. indet.	0.1078	0.1436	0.7506	0.1849	0.1766	0.2597
Caridea gen. indet.	0.0835	0.1488	0.5612	0.1769	0.0654	0.3520
Anthosactis janmayeni	0.0724	0.1392	0.5201	0.0465	0.1551	0.4320
Actiniaria sp. indet. 4	0.0707	0.1448	0.4882	0.1498	0.0422	0.5101

Discussion

4.2 Community structure

Mapping different habitats in the deep is important for several reasons. Firstly, it is crucial for understanding and protecting these unique and valuable ecosystems. By mapping habitats, it becomes possible to identify areas with high biodiversity and pinpoint hotspots that require conservation and protection measures. The mapping and comprehension of habitats can be valuable for scientific progress, as it may lead to new discoveries and scientific advancements. Due to volcanic activity, habitats within a small area can vary significantly, resulting in an environment that differs from the surrounding waters. This variation is evident at the seafloor as well, as shown in figure 8. The physical and chemical differences in these habitats supports a diverse range of life.

The research on community structure at Fåvne hydrothermal vent field has revealed several interesting findings. Firstly, the research area exhibits a relatively high species diversity with a total of 34 annotated megabenthic morphospecies and 45 catalogued species within 11 phyla. This result is most certainly an underestimate due to the reasons explained under the Limitations section. Figure 9 illustrates a contrast in species diversity at distinct substrates, where, e.g. *Bathycrinus carpenteri*, a deep-sea crinoid (feather star), is the most prevalent species at the soft substrate and exerts significant dominance in the area. Several locations of soft sediment were heavily inhabited by this species. Deep-sea crinoid aggregations are considered vulnerable marine ecosystems (VMEs) (Ramirez-Llodra et al., 2020). VME is a rare or unusual deep-sea ecosystem particularly fragile and sensitive to disturbance. It has several indicator species or key species that can be used to identify and monitor the systems. In this case, when *Bathycrinus carpenteri* is present, it implies that the recovery of the ecosystem following alteration can pose considerable challenges, be timely and sometimes not possible (Watling & Auster, 2021).

Even at small spatial scales, we can find different habitats with different fauna. It is this kind of characterisation that we need to understand the risks of deep-sea mining and establish spatial management plans.

Video transects in inactive sulphide areas show a low species diversity and a generally low abundance of organisms. Research backs up this observation and explains it with the fact that the temperature is lower than at the active vents and lacks chemosynthetic activity, the primary producers (Levin et al., 2009). Nevertheless, inactive sulphide habitats still support a diversity of species and are of scientific interest. However, there is a clear difference in sampling quantity at different habitats. Table 1 shows the limited sampling from inactive sulphide compared to other habitats. The study area covering inactive sulphide was only 26.9 m² compared to study areas of e.g., soft sediments covering 540.2 m². The consequence of this underrepresentation of data from a habitat is that the number of morphospecies is lower since more analysed images leads to the detection of more species until we reach a representative level of sampling. Because of this, the sampling of inactive sulphide is not sufficient and future research needs an increasing sampling effort and surveying of inactive sulphide habitats.

At one point, every hydrothermal vent will cease and stop venting, it will become hydrothermally inactive and eventually extinct. It is commonly believed that deep-sea mining will happen at inactive vents due to the cooler and less toxic surroundings; this means it is essential to classify the difference between active, inactive and extinct vents. Defining a separate hydrothermal vent or a whole field as active can be somewhat easy due to the visual signs of smoke or shimmering seawater emerging from the vents. They can also be categorised as active from the adjacent vent-endemic fauna. The more complicated mapping is to differentiate inactive from extinct vents, and it is essential to obtain specific criteria to distinguish the vents. Some indicators for hydrothermal inactivity are collapsed chimneys as inactive vents are likely to collapse after more than 1000 years. In addition to this, extensive oxidation of sulphide minerals, the absence of chemosynthetic fauna and a presence of slow-growing sessile species such as sponges and deep-sea corals are also indicators of inactive vents (Jamieson and Gartman, 2020). The comprehensiveness of hydrothermal cells beneath the seafloor is not yet entirely grasped, thereby making it intricate to define active, inactive, and extinct vents.

All areas of my surveys are inside an active vent field which gives us no reason to believe any hydrothermal vents are extinct. This is the reason why we refer to inactive vents as not extinct in this project because they can be reactivated. It is important to understand the extensive geological connectivity within a hydrothermal vent field and its complexity and dynamic systems, and it is crucial for managing the potential impacts of deep-sea mining on the surrounding ecosystems and for identifying areas that are particularly important for conservation and management efforts.

4.1 Limitations

Identifying and understanding the sources of errors is crucial for any research project. In this section, I will identify and discuss some of the most common sources of error and limitations of my methods and their potential impacts on study outcomes.

Some mobile organisms may be attracted or repelled by the noise and light from the ROV and may alter their natural behaviour patterns in the deep-sea. This can be a disturbance and a limitation of a research project like this one, where the aim is to study organisms in their natural state in their habitat. It can alter my data collection by attracting organisms that were not supposed to be in the investigated habitat, and because of their mobility, it is possible they have been counted multiple times or avoided the lighting and therefore avoided the cameras, thereby distorting the data. In the case of my study, it is unlikely that the ROV has attracted any fauna, but on the other hand some fish may have remained undetected by avoiding the vehicle.

Despite carefully studying the video transect and screenshots, there are limiting factors associated with this way of species identification. The angles and quality of the images may not capture a good view of the organisms making it difficult to accurately identify certain characteristics that are important for species identification. The technical limitations can make the image quality poor due to inadequate lighting, wrong focus, far distances or unfavourable angle of the habitat. Additionally, fauna that is too small for the image resolution cannot be annotated. The way to address this technical limitation is to carry out a thorough quality control and keep only good images, which is what I did in my thesis.

The lack of sufficient images can make it difficult to accurately identify certain characteristics of a species, and because some species look very similar to each other, it can be difficult to differentiate them based on their morphological characteristics alone. An important factor in morphologically identifying organisms, especially in an under-explored ecosystem, is the lack of knowledge in relation to intraspecific variation. Not only can different species look similar, but there may also be significant variation within a species, making it difficult to identify individuals belonging to the same species based on their morphology. Limitations in species identification through seabed images were addressed by adopting guidelines proposed among the international scientific community for image-based identifications.

Accurately identifying species based on morphology alone can be a challenging task requiring specialised expertise, knowledge and equipment. Possible subtle differences may be hard to detect without extensive training in taxonomy. In addition, identifying based on the morphology of certain species may require taxonomic methods and equipment such as a microscope or dissecting tools to see the striking differences, or even molecular analysis. However, there are in addition taxonomic uncertainties due to the substantial portion of the fauna at these remote locations of the animal kingdom that has yet to be formally described.

Some species in the deep sea are difficult to identify through visual observation alone, such as Gastropoda sp. indet., which can be classified as a cryptic species complex - morphologically they are hard to distinguish, but are genetically distinct (Van Dover, 2011). Gastropoda sp. indet. Is therefore too complex to be identified without DNA analysis in a lab. While we know that there are multiple species of gastropoda, this study treats them as one due to the difficulty of species identification. As a result, the calculation of species diversity may be underestimated, especially for active vents where Gastropoda sp. indet. is abundant. If all gastropods and amphipods were correctly identified to the species level, taxa richness from active vents and Simpson's index would likely be higher. In figure 10, evenness analysis suggests that gastropods and amphipods dominate the faunal assemblage, while mixed substrates have high diversity without any one particular species dominating, which is expressed in the higher values for evenness.

Cryptic species make it difficult to comprehend the species diversity and understand the distribution of vent species. Overall, these limitations in species identification highlight the importance of advanced techniques, such as DNA analysis, in accurately characterising biodiversity in the deep sea.

4.3 Future mineral demand

The demand for minerals and metals may become higher as the demand for technology increases. The critical role of minerals and metals in modern society raises concerns regarding meeting the high demand; as such, it has opened up a discussion if we need more minerals for the future society. As mentioned in the introduction, an increase in technology solutions is essential for the green transition. However, there is also a need for responsible mineral use and sourcing. Therefore, we need to aim for a circular economy model rather than a linear economy for the minerals and metals to be held in society over a more extended period of time and reused in new products and technologies.

According to a new report by SINTEF (Simas et al., 2022), the future demand for minerals is largely dependent on the choice of technology. The report concludes that the transition to technologies using less critical minerals makes it possible to decrease the demand for cobalt, nickel, lithium, copper, platinum and rare earth elements by 30%. In addition, the report concludes that replacing lithium-ion batteries and changing the electric vehicle chemistry can reduce the demand for nickel, manganese and cobalt by 40 - 50%. To reduce the request for rare earth elements, we can expand the use of electric traction motors and turbine generators that contain a small amount or no rare earth elements, leading to a reduction of 20% in demand for these minerals (Simas et al., 2022).

It is difficult to estimate the mineral demand in the future due to the high acceleration of technological progress and development. The calculation on mineral demand a decade ago presented a completely different number than what is measured today and most likely what will be estimated a decade from now as well. Several state-of-the-art low-carbon technologies that are only in an early stage now show great potential to reduce the future demand for critical minerals substantially. Several manufacturers have shown promising results in reducing critical minerals in their products in relation to electric vehicles and wind turbines (Simas et al., 2022). These auspicious results in new technology can be the start of a change in the future mineral demand.

Minerals and metals have been, and still are, beneficial for society and increase humans' quality of life. The demand for minerals will persist even if it diminishes due to advancements in technology. It is crucial to recycle minerals to contribute to sustainable development; however, it is important to note that recycling minerals do not necessarily decrease the demand for primary minerals rather than a substitute for primary mineral production (Graedel et al., 2011). Minerals that have been recycled are often used in lower technical specifications, e.g. materials used in construction and packaging, while the primary minerals are used in electrical devices or aerospace components that require high purity. In addition, it is vital to understand that the rate of metal recycling is highly dependent on the metal in question, what specific recycling process is used and in what region of the world it is performed (Graedel et al., 2011).

Simas et al. (2022) conclude that the total mineral demand can be reduced by 50% by 2050, and it can be supplied by 20% through recycling. Based on this report, the need for future minerals may be considerably less than previously assumed. According to the report, one may argue that deep-sea mining might be uneconomical, unnecessary and irresponsible. While the future mineral demand is still uncertain, it is crucial to examine how mining activities will not only affect the ecosystem, but how the ecosystem services conducted by natural systems will be affected.

The deep-sea provides many ecosystem services other than the economically beneficial ones affiliated with fisheries, energy and minerals. The deep ocean is a potential source of new pharmaceuticals, biomaterials and genetic resources (Levin et al., 2019). It supports essential services of habitat, food and shelter and maintains biodiversity (Buhl-Mortensen et al., 2010) and possibly the genetic adaptation capacity that may contain the key for ecosystems and species to adapt. There is a widespread belief that the deep-sea acts as a repository of genetic adaptive potential, meaning it can facilitate the capacity of ecosystems and species to adapt to future environmental conditions. Moreover, it is thought that the genetic resources found in the deep sea can provide solutions for future problems humans may encounter (Ramirez-Llodra et al., 2010). The diversity of life near hydrothermal vents provides valuable insights into the origin and limits of life on Earth.

Furthermore, there are non-monetary services, such as cultural services, that can be affected by deep-sea mining. Cultural services, e.g. preservation of cultural heritage and traditional fishing practices, can be significantly affected by deep-sea mining.

4.4 Post-normal Science and Deep Sea Mining: Uncertainty and Ethics

Post-normal science is a concept that was introduced by Silvio Funtowicz and Jerome Ravetz in the 1990s to describe a new type of scientific practice that emerges when decision-making is faced with high complexity, uncertainty, and values in dispute (Funtowicz and Ravetz, 2020). The concept of post-normal science is relevant to the issue of deep sea mining because it raises important questions about the scientific uncertainty and complexity surrounding this emerging industry. Firstly, the deep sea is a complex and poorly understood environment, with many uncertainties and knowledge gaps that require a post-normal science approach to address. For example, the deep sea is home to many unique and poorly studied species, and there is a limited understanding of the ecological and biogeochemical processes that occur in these environments. Deep-sea mining has potential environmental and social impacts that are not yet understood.

Secondly, exploring and studying the deep sea requires a collaborative and interdisciplinary approach that is consistent with the principles of post-normal science. Deep-sea research is highly interdisciplinary and involves experts from many different fields, including biology, chemistry, geology, physics, and engineering, as well as stakeholders such as policymakers, resource managers, and local communities. Effective deep-sea mining also requires a recognition of the social and cultural contexts in which it takes place and the interests and values of different actors involved.

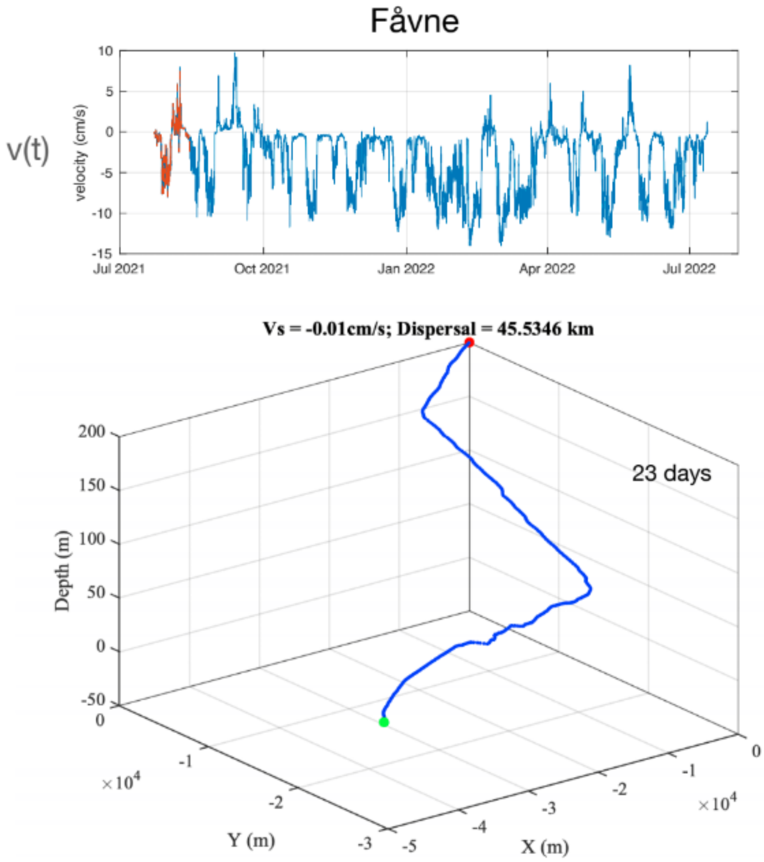
Finally, the ethical and political dimensions of deep-sea mineral exploration and exploitation require a post-normal science approach that takes into account the values, interests, and power relations of different actors. Deep-sea mining raises questions about the equitable distribution of benefits and risks, as well as the potential impacts on local communities and ecosystems. A post-normal science approach to deep-sea mining would require engaging with these questions and involving stakeholders in decision-making processes.

In the context of deep-sea mining, post-normal science could also involve acknowledging and addressing the uncertainties and ambiguities surrounding the potential environmental and social impacts of this industry. This could include adopting a precautionary approach that prioritises the protection of the marine environment, as well as investing in long-term monitoring and research to understand the impacts of deep-sea mining better. The precautionary principle is imaginable even more critical in the deep sea than in other ecosystems due to the low resilience, slow recovery potential and lack of basic scientific knowledge. Therefore, limiting the initial damage to this extraordinary environment is essential, which can lead to a more sustainable and economically beneficial outcome (Huvenne et al., 2016).

Overall, post-normal science can help to ensure that deep sea mining decisions are made in a transparent, inclusive, and socially responsible way that takes into account the uncertainties and values that are inherent in this complex issue.

4.5 Re-establishment of the ecosystem

According to the consultation document (høringsdokument) concerning the impact assessment of the consequences of seabed mineral extraction on the continental shelf, state that the most significant environmental ramifications will be associated with nearby benthic habitats (Olje- og energidepartementet, 2022). The document asserts that the consequences of the activity will be limited to the extraction area of 0.2-0.5 square kilometres in the case of sulphides and 20 square kilometres for the extraction of crusts. Figure 6 depicts the area of my studies at a specified scale, illustrating the relatively small expanse of the region and the diverse array of habitats in the limited area. Preliminary dispersal modelling studies of plume particles with ocean currents indicate that plumes can spread over large areas, and that the affected areas depend on variability of ocean currents (Figure 13), which can lead to a much larger zone of affected habitats.


Fåvne
v(t)
velocity (cm/s)
10
5
0
-5
-10
-15
Jul 2021
Oct 2021
Jan 2022
Apr 2022
Jul 2022
Vs = -0.01cm/s; Dispersal = 45.5346 km
23 days
Depth (m)
200
150
100
50
0
-50
Y (m)
$\times 10^4$
0
-1
-2
-3
X (m)
$\times 10^4$
-5
-4
-3
-2
-1
0

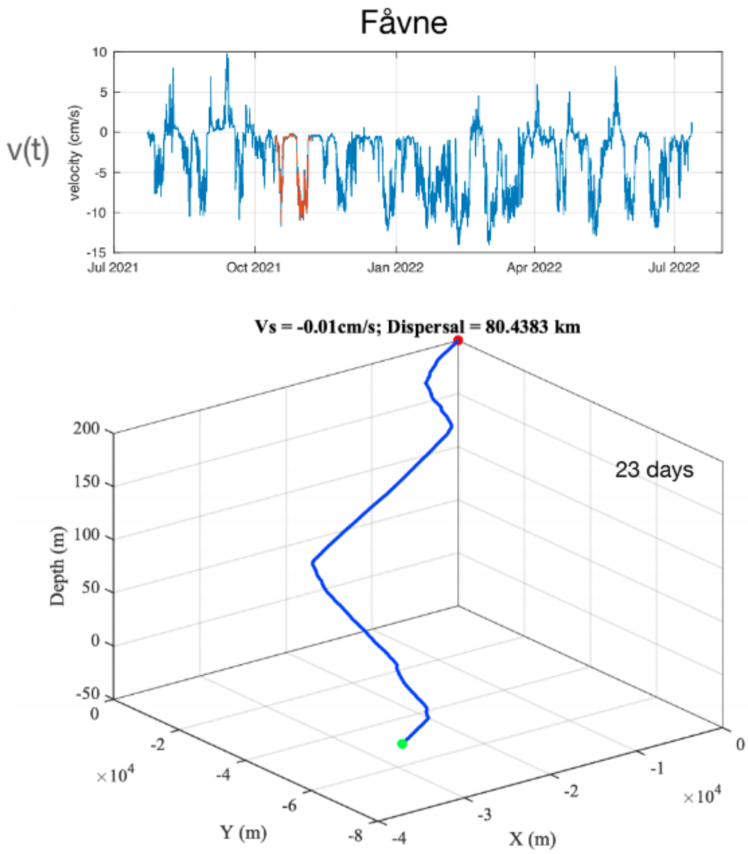

Fåvne
v(t)
velocity (cm/s)
10
5
0
-5
-10
-15
Jul 2021
Oct 2021
Jan 2022
Apr 2022
Jul 2022
Vs = -0.01cm/s; Dispersal = 80.4383 km
23 days
Depth (m)
200
150
100
50
0
-50
Y (m)
$\times 10^4$
0
-2
-4
-6
-8
X (m)
$\times 10^4$
-4
-3
-2
-1
0

Figure 13. Particle motion function: 3D dispersal. Variation in particle dispersal at Fåvne in 23 days at different depths and with seasonal variation.
The top figures show the bottom current data (speed) in blue over time and the data used for modelling the particle motion in orange. The bottom figures show the motion of a settling particle (15-20 um) inside a flow field (constrained by bottom currents) from when it is released (red dot) to when it settles on the seafloor (green dot). Gathered from Thibaut Laurent Gilbert Barreyre, 2023 (Barreyre/Eco-Safe (unpublished)).

According to preliminary results conducted by Thibaut Barreyre, there are several factors that influence particle dispersal. He collected Ocean Bottom Current data at several locations on the Mohn's Ridge, including at Fåvne, where he collected 354 days of data. Figure (13) This statement suggests that the dispersion of particles from mining activities is highly influenced by seasonal variations, indicating that the impact of extraction activities may fluctuate throughout the year. Additionally, the far-reaching effects of extraction consequences demonstrate that mining activities can have a significant impact beyond the immediate vicinity of the mine site. Both of these observations emphasise the importance of carefully assessing the potential impacts of mining operations and implementing effective mitigation strategies to minimise their negative effects on surrounding environments.

The level of uncertainty of species recovery after disturbance or destruction is substantial. Firstly, many deep-sea organisms can live for thousands of years, e.g. corals and sponges (Roark et al., 2009). Organisms belonging to these long-lived taxa are characterised by slow growth, delayed maturation and low reproductive capacity, and some of the species are rare. These traits render them vulnerable to environmental change and ultimately make a recovery demanding, if not unattainable, within the human timescale (Levin, 2019).

It is stated in the consultation document that the possibility of re-establishment for benthic communities is different based on the seafloor substrate. According to them, the presence of underlying hard substrate on seamounts containing manganese

crust areas makes a basis for re-establishes of fauna, a claim that lacks any empirical basis (Olje- og energidepartementet, 2022). The document also stated that after the extraction of metals and minerals at active sulphide, a new chimney would be created through time and make a foundation for the re-establishment of benthic fauna. Firstly, mining active chimneys is both dangerous due to the high temperature and toxicity, posing risks as well as the possibility of a collapse of chimneys and landslides, leading to safety implications and exposing the ecosystem to uncertain consequences (Van Dover et al., 2018).
Secondly, most of the species found on active hydrothermal vents are endemic, meaning they are not found anywhere else, putting these exclusive species at risk from extraction mining methods leading to their extinction (Van Dover, 2011). In addition, disturbing one vent field can have wider consequences due to reduced connectivity along the ridge. Lastly, the statement in question seems to be insufficient as it is missing some relevant factors. Yes, chimneys can potentially continue growing after extracting. However, the growth rate of hydrothermal vent chimneys depends on various factors such as fluid chemistry, temperature, surroundings and pressure, and these factors are not fully studied and are based on limited data. This means that this is also just speculation.

Arguments towards the re-establishment of hydrothermal chimneys and local fauna have been presented. One of the main ones is the recovery of vent communities after volcanic eruptions after a few decades, as documented on the East Pacific Rise (Shank et al., 1998) and disturbance at Mariana Arc with an even shorter recovery time (Chadwick et al., 2010). However, these examples used as evidence for vent community recovery after natural disturbance cannot be compared with the vent sites at slow-spreading mid-ocean ridges such as the Mohn Ridge where one can find a significant abundance of mineral resources without frequent ecological disruption (Van Dover et al., 2018). In addition, we do not know about the resilience of the vent-endemic species on vents on these slow-spreading ridges, how many species have the ability to re-colonise, the impact of new species interactions or the duration required for the ecosystem to be restored.

To learn about recovery time at vent sites after disturbance, it is essential to understand the connectivity between sites. Connectivity in marine ecosystems refers to the flow of organisms and genetic information between populations, habitats or ecosystems. When the connectivity is high, it means that the genetic diversity is high, which promotes more resilient populations and ecosystems. However, when the connectivity is low, the genetics are more isolated, and the ecosystem is more vulnerable to environmental disturbances (With et al., 1997). Higher isolation also means a smaller chance for a disturbed area to be recolonized by larvae dispersing from other populations. Understanding connectivity in the deep sea can be helpful in identifying habitats or areas that are vulnerable to deep-sea mining and, therefore, creating strategies to enforce a healthy ecosystem with minimised impacts of potential activities. Deep-sea ecosystems are often highly interconnected, which means that organisms are dependent on each other for resources. By disrupting the ecosystem through mining activities, it could have potential consequences for a large part of the ecosystem and the disruption may extend beyond the immediate area of mining, impacting a significant portion of the ecosystem as well as adjacent ecosystems. For example where two areas of the seafloor are connected through a migration route used by a specific species. Mining these areas can disrupt the migration of the species and cause negative consequences for the population (Gary et al., 2020).

Biodiversity loss in the deep sea can have a great impact on other ecosystems and biotas. Microorganisms in the deep sea contribute significantly to the provision of several ecosystem services, including playing an important role in nutrient cycling and carbon fixation (Thurber et al., 2014). Apart from their crucial function in facilitating primary production via chemosynthesis, several microbes found in hydrothermal ecosystems perform indispensable roles for a variety of species by emitting signals that guide the settling of larvae (Orcutt et al., 2020). In summary, mining activity on active hydrothermal vent sites can disrupt microbial life, the primary foundation of the food web in these ecosystems, which can potentially lead to the compromising abundance and diversity of life and production (Van Dover et al., 2018).

4.6 Moratorium in relation to deep-sea mining

By now, it is clear that the deep sea is a complex ecosystem that plays crucial roles for several species, other ecosystems and possibly hosts the answer to questions researchers hope to uncover, such as what are the limits of life and the origin of life on Earth. It is largely unexplored and not fully understood, which is the reason for an ongoing debate about whether a moratorium should be imposed on human activities in this environment. Firstly, a moratorium on deep-sea mining activities should happen because it is home to a diverse range of species where several have never been researched and are unique. A moratorium could provide protection for these species until we comprehend a better understanding of the ecosystem and its fauna. It would also prevent habitat destruction through significant damage to habitats, which often have slow recovery rates. Contradicting arguments are economic benefits through job creation and revenue generation. Advances in technology make it possible to explore and possibly exploit the deep sea in ways that previously were not possible. A moratorium could impede progress in these areas. It is suggested that rather than imposing a moratorium, we should improve regulation, laws and oversight of deep-sea mining to minimise the impact of human activities. The problem with this is that we do not know about the severity or impact of human activities, and there are great uncertainties. Our understanding of the deep sea and the influence of human activities is limited, the uncertainties are great, and the risks are high. Implementing a moratorium could allow for additional research to be carried out prior to any irreversible damage being inflicted.

The decision about whether or not to impose a moratorium on deep-sea activities is dependent on several factors, including the social, economic and environmental effects of the activities in question. The consideration of valuable alternatives to deep-sea mining also plays an important role in the determination of the implementation of a moratorium.

At this point in time, only 41 (8%) deep-sea hydrothermal vent fields have been incorporated into marine protected areas (MPAs) (Beaulieu et al., 2013). Since 2010, 34 Marine Protected Areas (MPAs) covering deep-sea areas have been established. These areas include crucial topographic features of deep-sea habitats, such as mid-ocean ridges, fracture zones, and four hydrothermal vent fields. Compared to other European countries and the EU, Norway is falling behind in the protection of deep-sea environments. By creating MPAs before the beginning of any deep-sea activities, Norway can minimise the negative impacts on these ecosystems and secure their long-term health and productivity.

Concluding remarks

A total of 1484.5 m² of seafloor was visually surveyed with help from cameras on an ROV. Analysis reveals significant differences in species composition in different habitats in Fåvne hydrothermal vent. The community composition is highly dissimilar showing that the morphospecies vary between habitats. Species diversities were highest on basalt habitats, while the species densities were highest on active vents due to the primary production from chemosynthetic bacteria supporting organisms. Surveys on inactive sulphide habitats were not sufficient enough and results from this habitat may therefore not be representative.

A recent report from SINTEF highlights that the expansion of mining to the deep-sea is not necessary for facilitating the green transition. Rather, the reports recommend that focus should be moved to reducing the mineral demand by implementing a circular economy, increased recycling efforts and promoting the development of new technologies.

Given the significant knowledge gaps, a precautionary approach is imperative when facing deep-sea mining activities. The potential impact of mining activities on organisms, connectivity between habitats and how ecosystems will recover after possible extraction remains uncertain. Given the uncertainty surrounding deep-sea activities and the potential significance of these ecosystems, the establishment of additional Marine Protected Areas (MPAs) in hydrothermal vent fields could be beneficial. The existing uncertainties need to be further investigated and continued research on the topic needs to be conducted to fully calculate the consequences and to strengthen our understanding.

References

Ahnert, A., & Borowski, C. (2000). Environmental risk assessment of anthropogenic activity in the deep sea. *Journal of Aquatic Ecosystem Stress and Recovery*, *7*(4), 299–315. https://doi.org/10.1023/A:1009963912171

Akvaplan-niva. (2022). Virkninger for naturforhold, miljø og annen næringsvirksomhet relatert til konsekvensutredning for åpning av norsk sokkel for havbunnsmineralvirksomhet. https://www.regjeringen.no/contentassets/dbf5144d0fbc42b5a4db5fc7eb4fa312/vedlegg-8.-akvaplan-niva.-virkninger-for-naturforhold-miljo-og-annen-naringsvirksomhet.pdf

Amon, D. J., Gollner, S., Morato, T., Smith, C. R., Chen, C., Christiansen, S., Currie, B., Drazen, J., Fukushima, T., Gianni, M., Gjerde, K., Gooday, A, Grillo, G., Heackel, M., Joyini, T., Ju, S., Levin, L., Metaxas, A., Mianowicz, K., Molodtsova, T., Narberhaus, I., Orcutt, B., Swaddling, A., Tuhumwire, J., Palacio, P., Walker, M., Weaver, P., Xu, X., Mullap, C., Edwards, P., Pickens, C. (2022). Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. *Marine Policy*, *138*. https://doi.org/10.1016/j.marpol.2022.105006

Amon, D. J., Ziegler, A. F., Dahlgren, T. G., Glover, A. G., Goineau, A., Gooday, A. J., Wiklund, H., Smith, C. R. (2016). Insights into the abundance and diversity of abyssal megafauna in a polymetallic-nodule region in the eastern Clarion-Clipperton Zone. *Scientific Reports*, *6*. https://doi.org/10.1038/srep30492

Anderson, T. R., & Rice, T. (2006). Deserts on the sea floor: Edward Forbes and his azoic hypothesis for a lifeless deep ocean. *Endeavour*. https://doi.org/10.1016/j.endeavour.2006.10.003

Aven, T., & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*, *12*(1), 1–11. https://doi.org/10.1080/13669870802488883

Aven, T. (2014). *Risk, Surprises and Black Swans: Fundamental ideas and concepts in risk assessment and risk management*. *Risk, Surprises and Black Swans: Fundamental ideas and concepts in risk assessment and risk management* (pp. 1–262). CRC Press. https://doi.org/10.4324/9781315755175

Aven, T., & Zio, E. (2014). Foundational Issues in Risk Assessment and Risk Management. *Risk Analysis*, *34*(7), 1164–1172. https://doi.org/10.1111/risa.12132

Aven, T. (2023). Is the definition of risk still contested? *Proceedings of the Institution of Mechanical Engineers*, Part O: Journal of Risk and Reliability. 237(1):3-3. doi:10.1177/1748006X221125865

Bang, R. N., Trellevik, L. K. L. (2022). Perspectives on exploration and extraction of seafloor massive sulfide deposits in Norwegian waters. *Miner Econ*. https://doi.org/10.1007/s13563-022-00346-y

Baumberger, T., Früh-Green, G. L., Thorseth, I. H., Lilley, M. D., Hamelin, C., Bernasconi, S. M., Okland, I., Pedersen, R. B. (2016). Fluid composition of the sediment-influenced Loki's Castle vent field at the ultra-slow spreading Arctic Mid-Ocean Ridge. *Geochimica et Cosmochimica Acta*, *187*, 156–178. https://doi.org/10.1016/j.gca.2016.05.017

Beaulieu, S. E., Baker, E. T., German, C. R., & Maffei, A. (2013). An authoritative global database for active submarine hydrothermal vent fields. *Geochemistry, Geophysics, Geosystems*, *14*(11), 4892–4905. https://doi.org/10.1002/2013GC00499

Billett, D. S. M., Jones, D. O. B., & Weaver, P. P. E. (2019). Improving Environmental Management Practices in Deep-Sea Mining. In *Environmental Issues of Deep-Sea Mining* (pp. 403–446). Springer International Publishing. https://doi.org/10.1007/978-3-030-12696-4_15

Boetius, A., & Haeckel, M. (2018). Mind the seafloor. *Science*, *359*(6371), 34-36. https://doi.org/10.1126/science.aap7301

Boschen, R. E., Rowden, A. A., Clark, M. R., & Gardner, J. P. A. (2013, November). Mining of deep-sea seafloor massive sulfides: A review of the deposits, their benthic communities, impacts from mining, regulatory frameworks and management strategies. *Ocean and Coastal Management*. https://doi.org/10.1016/j.ocecoaman.2013.07.005

Buhl-Mortensen, L., Vanreusel, A., Gooday, A. J., Levin, L. A., Priede, I. G., Buhl-Mortensen, P., Gheerardyn, H., King, N., Raes, M. (2010). Biological structures as a source of habitat heterogeneity and biodiversity on the deep ocean margins. *Marine Ecology*, *31*(1), 21–50. https://doi.org/10.1111/j.1439-0485.2010.00359.x

Chadwick, W. W., Embley, R. W., Baker, E. T., Resing, J. A., Lupton, J. E., Cashman, K. V., Dziak, R., Tunnicliffe, V., Butterfield, D., Tamura, Y. (2010). Spotlight 10: Northwest Rota-1 seamount. *Oceanography*, *23*(1), 182–183. https://doi.org/10.5670/oceanog.2010.82

Collins, P. C., Croot, P., Carlsson, J., Colaço, A., Grehan, A., Hyeong, K., Kennedy, R., Mohn, C., Smith, C., Yamamoto, H., Rowden, A. (2013). A primer for the Environmental Impact Assessment of mining at seafloor massive sulfide deposits. *Marine Policy*, *42*, 198–209. https://doi.org/10.1016/j.marpol.2013.01.020

Danovaro, R., Snelgrove, P. V. R., & Tyler, P. (2014). Challenging the paradigms of deep-sea ecology. *Trends in Ecology and Evolution*. Elsevier Ltd. https://doi.org/10.1016/j.tree.2014.06.002

Danovaro, R., Aguzzi, J., Fanelli, E., Billett, D., Gjerde, K., Jamieson, A., Ramirez-Llodra, E., Smith, C., Snelgrove, P., Thomsen, L., Van Dover, C. L. (2017, February 3). An ecosystem-based deep-ocean strategy. *Science*. American Association for the Advancement of Science. https://doi.org/10.1126/science.aah7178

Funtowicz, S., & Ravetz, J. (2020). Post-Normal Science. In *Science for Policy Handbook* (pp. 14–18). Elsevier. https://doi.org/10.1016/B978-0-12-822596-7.00002-4

Gary, S. F., Fox, A. D., Biastoch, A., Roberts, J. M., & Cunningham, S. A. (2020). Larval behaviour, dispersal and population connectivity in the deep sea. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-67503-7

Godet, L., Zelnios, K. A., & Van Dover, C. L. (2011). Scientists as Stakeholders in Conservation of Hydrothermal Vents. *Conservation Biology*, no-no. https://doi.org/10.1111/j.1523-1739.2010.01642.x

Gollner, S., Kaiser, S., Menzel, L., Jones, D. O. B., Brown, A., Mestre, N. C., van Oevelen, D., Menot, L., Colaco, A., Canals, M., Cuvelier, D., Durden, J., Gebruk, A., Egho, G., Haeckel, M., Marcon, Y., Mevenkamp., L., Morato, T., Pham, C., Purser, A., Sanchez-Vidal, A., Vanreusel A., Vink, A., Martinez Arbizu, P. (2017). Resilience of benthic deep-sea fauna to mining activities. *Marine Environmental Research*. Elsevier Ltd. https://doi.org/10.1016/j.marenvres.2017.04.010

Graedel, T. E., Allwood, J., Birat, J. P., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S., Sonnemann, G. (2011). What do we know about metal recycling rates? *Journal of Industrial Ecology*, *15*(3), 355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x

Hannington, M., Jamieson, J., Monecke, T., Petersen, S., & Beaulieu, S. (2011). The abundance of seafloor massive sulfide deposits. *Geology*, *39*(12), 1155–1158. https://doi.org/10.1130/G32468.1

Hannington, M. D., De Ronde, C. E. J., & Petersen, S. (2019). Sea-Floor Tectonics and Submarine Hydrothermal Systems. In *One Hundredth Anniversary Volume*. Society of Economic Geologists. https://doi.org/10.5382/av100.06

Horton, T., Marsh, L., Bett, B. J., Gates, A. R., Jones, D. O. B., Benoist, N. M. A., Pfeifer, S., Simon-Lledo, E., Durden, J., Vandepitte, L., Appeltans, W. (2021). Recommendations for the Standardisation of Open Taxonomic Nomenclature for Image-Based Identifications. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.620702

Hund, K., La Porta, D., Fabregas, T., Laing, T., & Drexhage, J. (2020). Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. *World Bank Publications*, 110. Retrieved from www.worldbank.org http://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf

Huvenne, V. A. I., Bett, B. J., Masson, D. G., Le Bas, T. P., & Wheeler, A. J. (2016). Effectiveness of a deep-sea cold-water coral Marine Protected Area, following eight years of fisheries closure. *Biological Conservation*, *200*, 60–69. https://doi.org/10.1016/j.biocon.2016.05.030

ISO. (2018). ISO 31000:2018 - Risk Management - Guidelines. *Organización Internacional de Normalización*. International Organisation for Standardization. Retrieved from https://www.iso.org/obp/ui/#iso:std:iso:31000:ed-2:v1:en

Jamieson, J. W., & Gartman, A. (2020). Defining active, inactive, and extinct seafloor massive sulfide deposits. *Marine Policy*, *117*. https://doi.org/10.1016/j.marpol.2020.103926

Jones, D. O. B., Kaiser, S., Sweetman, A. K., Smith, C. R., Menot, L., Vink, A., Trueblood, D., Billet, D., Arbizu, P., Radziejewska, T., Singh, R., Ingole, B., Stratmann, T., Simon-Lledo, E., Durden, J., Clark, M. R. (2017). Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. *PLoS ONE*, *12*(2). https://doi.org/10.1371/journal.pone.0171750

Jones, D. O. B., Amon, D. J., & Chapman, A. S. A. (2018). Mining deep-ocean mineral deposits: What are the ecological risks? *Elements*, *14*(5), 325–330. https://doi.org/10.2138/gselements.14.5.325

Juliani, C., & Ellefmo, S. L. (2018). Resource assessment of undiscovered seafloor massive sulfide deposits on an Arctic mid-ocean ridge: Application of grade and tonnage models. *Ore Geology Reviews*, *102*, 818–828. https://doi.org/10.1016/j.oregeorev.2018.10.002

Jun, W., Mughal, N., Zhao, J., Shabbir, M. S., Niedbała, G., Jain, V., & Anwar, A. (2021). Does globalization matter for environmental degradation? Nexus among energy consumption, economic growth, and carbon dioxide emission. *Energy Policy*, p. *153*. https://doi.org/10.1016/j.enpol.2021.112230

Kaikkonen, L., Venesjärvi, R., Nygård, H., & Kuikka, S. (2018). Assessing the impacts of seabed mineral extraction in the deep sea and coastal marine environments: Current methods and recommendations for environmental risk assessment. *Marine Pollution Bulletin*. Elsevier Ltd. https://doi.org/10.1016/j.marpolbul.2018.08.055

Kaiser, S., Smith, C. R., & Arbizu, P. M. (2017). Editorial: Biodiversity of the Clarion Clipperton Fracture Zone. *Marine Biodiversity*. Springer Verlag. https://doi.org/10.1007/s12526-017-0733-0

Kuhlman, T., & Farrington, J. (2010). What is sustainability? *Sustainability*. MDPI. https://doi.org/10.3390/su2113436

Laffoley, D., Baxter, J. M., Amon, D. J., Currie, D. E. J., Downs, C. A., Hall-Spencer, J. M., Harden-Davies, H., Page, R., Reid, C. P., Roberts, C. M., Rogers, A., Thiele, T., Sheppars, C. R. C., Sumaila, R. U., Woodall, L. C. (2020). Eight urgent, fundamental and simultaneous steps needed to restore ocean health, and the consequences for humanity and the planet of inaction or delay. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(1), 194–208. https://doi.org/10.1002/aqc.3182

Levin, L. A., Mendoza, G. F., Konotchick, T., & Lee, R. (2009). Macrobenthos community structure and trophic relationships within active and inactive Pacific hydrothermal sediments. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *56*(19–20), 1632–1648. https://doi.org/10.1016/j.dsr2.2009.05.010

Levin, L. A., & Bris, N. L. (2015). The deep ocean under climate change. *Science*. American Association for the Advancement of Science. https://doi.org/10.1126/science.aad0126

Levin, L. A. (2019). Sustainability in Deep Water: The Challenges of Climate Change, Human Pressures, and Biodiversity Conservation. *Oceanography*, *32*(2), 170–180. https://doi.org/10.5670/oceanog.2019.224

Levin, L.A., Amon, D.J. & Lily, H. (2020). Challenges to the sustainability of deep-seabed mining. *Nat Sustain* 3, 784–794. https://doi.org/10.1038/s41893-020-0558-x

Logan, T. M., Aven, T., Guikema, S., & Flage, R. (2021). The Role of Time in Risk and Risk Analysis: Implications for Resilience, Sustainability, and Management. *Risk Analysis*. John Wiley and Sons Inc. https://doi.org/10.1111/risa.13733

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-Being. Synthesis*. *World Health*. Washington, DC: Island Press.

Muñoz-Royo, C., Peacock, T., Alford, M. H., Smith, J. A., Le Boyer, A., Kulkarni, C. S., Haley Jr, P. J., Mirabito, C., Wang, D., Adams, E. E., Ouillon, R., Breugem, A., Decrop, B., Lanckriet, T., Supekar, R. B., Rzeznik, A. J., Gartman, A., Ju, S. J. (2021). Extent of impact of deep-sea nodule mining midwater plumes is influenced by sediment loading, turbulence and thresholds. *Communications Earth and Environment*, *2*(1). https://doi.org/10.1038/s43247-021-00213-8

Nakamura, K., Toki, T., Mochizuki, N., Asada, M., Ishibashi, J. I., Nogi, Y., Yoshikawa, S., Miyazaki, J., Okino, K. (2013). Discovery of a new hydrothermal vent based on an underwater, high-resolution geophysical survey. *Deep-Sea Research Part I: Oceanographic Research Papers*, *74*, 1–10. https://doi.org/10.1016/j.dsr.2012.12.003

Norwegian Petroleum Directorate. (2023a). Act relating to Mineral Activities on the Continental Shelf (Seabed Minerals Act). Retrieved from https://www.npd.no/en/regulations/acts/act-relating-to-mineral-activities-on-the-continental-shelf-seabed-minerals-act/

Norwegian Petroleum Directorate. (2023b). Ressursvurdering havbunnsmineraler. Retrieved from: Ressursvurdering havbunnsmineraler (npd.no)

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: A scientific synthesis. *PLoS ONE*, *9*(7). https://doi.org/10.1371/journal.pone.0101298

Oksanen, J., Gavin, S., Blanchet, F., Roeland, K., Pierre, L., Peter, M., O'Hara, R. B., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedwars, M, Bolker, B., Borcard,m D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Evangelista, H., Fitx, J. R., Friendly, M., Furneux, B., Hanninga, G., Hill, M. O., Lahti, L., McGlinn, D., Oulette, M. H., Ribeiro, C. E., Smith, T., Stier, A., Ter, B. C., Weedon, J. (2022). vegan: Community Ecology Package. R package version 2.6-4. *Community Ecology Package*, *2.6-4*, 1–297. [Software].
Available from https://cran.r-project.org/package=vegan

Olje- og energidepartementet. (2022). *Høring - Konsekvensutredning for mineralvirksomhet på norsk kontinentalsokkel og utkast til beslutning om åpning av område.*
https://www.regjeringen.no/no/dokumenter/horing-konsekvensutredning-pa-norsk-kontinentalsokkel/id2937810/?utm_source=www.regjeringen.no&utm_medium=rss&utm_campaign=RSS-2581966&expand=horingssvar

Orcutt, B. N., Bradley, J. A., Brazelton, W. J., Estes, E. R., Goordial, J. M., Huber, J. A., Jones, R., Mahmoudi, N., Marlow, J., Murdock, S., Pachiadaki, M. (2020). Impacts of deep-sea mining on microbial ecosystem services. *Limnology and Oceanography*. Wiley Blackwell. https://doi.org/10.1002/lno.11403

Paulikas, D., Katona, S., Ilves, E., Stone, G., & O'Sullivan, A. (2020). Where should metals for the green transition come from. *Comparing Environmental, Social, and*

Economic Impacts of Supplying Base Metals from Land Ores and Seafloor Polymetallic Nodules (DeepGreen, 2020).

Pedersen, R. B., Olsen, B. R., Barreyre, T., Bjerga, A. Denny, A., Eilertsen, M. H., Fer, I., Haflidason, H., Hestetun, J. T., Jørgensen, S., Ribeiro, P. A., Steen, I. H., Stubseid, H., Tandberg, A. H. S. & Thorseth, I. (2021). Fagutredning Mineralressurser i Norskehavet - Landskapstrekk, Naturtyper og Bentiske Økosystemer. Retrieved from https://www.npd.no/globalassets/1-npd/fakta/havbunnsmineraler/fagutredning-mineralressurser-norskehavet-naturforhold-uib.pdf Accessed 19.10.2022

Petersen, A. C. (2000). Philosophy of climate science. *Bulletin of the American Meteorological Society*, *81*(2), 265–271. https://doi.org/10.1175/1520-0477(2000)081<0265:POCS>2.3.CO;2

Petersen, S., Krätschell, A., Augustin, N., Jamieson, J., Hein, J. R., & Hannington, M. D. (2016). News from the seabed – Geological characteristics and resource potential of deep-sea mineral resources. *Marine Policy*, *70*, 175–187. https://doi.org/10.1016/j.marpol.2016.03.012

Ramirez-Llodra, E., Brandt, A., Danovaro, R., De Mol, B., Escobar, E., German, C. R., Levin, L., Martinez, A. P., Menot, L., Buhl-Mortensen, P., Narayanaswamy, B., Smith, C, Tittensor, D., Tyler, P., Vanreusel, A., Vecchione, M. (2010). Deep, diverse and definitely different: Unique attributes of the world’s largest ecosystem. *Biogeosciences*, *7*(9), 2851–2899. https://doi.org/10.5194/bg-7-2851-2010

Ramirez-Llodra, E., Hilario, A., Paulsen, E., Costa, C. V., Bakken, T., Johnsen, G., & Rapp, H. T. (2020). Benthic Communities on the Mohn’s Treasure Mound: Implications for Management of Seabed Mining in the Arctic Mid-Ocean Ridge. *Frontiers in Marine Science*, *7*. https://doi.org/10.3389/fmars.2020.00490

Rolinski, S., Segschneider, J., & Sündermann, J. (2001). Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *48*(17–18), 3469–3485. https://doi.org/10.1016/S0967-0645(01)00053-4

Russo, P., Del Bufalo, A., & Fini, M. (2015). Deep sea as a source of novel-anticancer drugs: Update on discovery and preclinical/clinical evaluation in a systems medicine perspective. *EXCLI Journal*. Leibniz Research Centre for Working Environment and Human Factors. https://doi.org/10.17179/excli2014-632

Shank, T. M., Fornari, D. J., Von Damm, K. L., Lilley, M. D., Haymon, R. M., & Lutz, R. A. (1998). Temporal and spatial patterns of biological community development at nascent deep-sea hydrothermal vents (9°50'N, East Pacific Rise). *Deep-Sea Research Part II: Topical Studies in Oceanography*, *45*(1–3), 465–515. https://doi.org/10.1016/S0967-0645(97)00089-1

Simas, M., Aponte, F., & Wiebe, K. (2022). The Future is Circular: Circular Economy and Critical Minerals for the Green Transition. Retrieved from https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/3032049/CircularEconomyAndCriticalMineralsReport.pdf?sequence=7&isAllowed=y

Society for Risk Analysis (2020). Glossary of Risk-Related Terms. Retrieved from https://www.sra.org/wp-content/uploads/2020/04/SRA-Glossary-FINAL.pdf

Sylvan, J. B., Toner, B. M., & Edwards, K. J. (2012). Life and death of deep-sea vents: Bacterial diversity and ecosystem succession on inactive hydrothermal sulfides. *MBio*, *3*(1), 1–10. https://doi.org/10.1128/mBio.00279-11

Sweetman, A. K., Levin, L. A., Rapp, H. T., & Schander, C. (2013). Faunal trophic structure at hydrothermal vents on the southern Mohn's ridge, arctic ocean. *Marine Ecology Progress Series*, *473*, 115–131. https://doi.org/10.3354/meps10050

Tao, C., Li, H., Jin, X., Zhou, J., Wu, T., He, Y., Deng, X., Gu, C., Zhang, G., Liu, W. (2014). Seafloor hydrothermal activity and polymetallic sulfide exploration on the southwest Indian ridge. *Chinese Science Bulletin*. Science in China Press. https://doi.org/10.1007/s11434-014-0182-0

Thurber, A. R., Sweetman, A. K., Narayanaswamy, B. E., Jones, D. O. B., Ingels, J., & Hansman, R. L. (2014). Ecosystem function and services provided by the deep sea. *Biogeosciences*, *11*(14), 3941–3963. https://doi.org/10.5194/bg-11-3941-2014

United Nations. (1992). A/CONF.151/26/Vol.I: Rio Declaration on Environment and Development. *Report of the United Nations Conference on Environment and Development*, *I*(August), 1–5. Retrieved from: http://www.un.org/documents/ga/conf151/aSaat ini, orang yang dimaksud adalah bank, yaitu suatu lembaga keuangan berupa perusahaan yang mewakili nasabah untuk melakukan:conf15126-1annex1.htm

U.S. Environmental Agency. (1998). *Guidelines for Ecological Risk Assessment.* https://www.epa.gov/sites/default/files/2014-11/documents/eco_risk_assessment1998.pdf

Van Der Sluijs, J. P., Petersen, A. C., Janssen, P. H. M., Risbey, J. S., & Ravetz, J. R. (2008). Exploring the quality of evidence for complex and contested policy decisions. *Environmental Research Letters*. Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/3/2/024008

Van Dover, C. L. (2011). Mining seafloor massive sulphides and biodiversity: What is at risk? *ICES Journal of Marine Science*. https://doi.org/10.1093/icesjms/fsq086

Van Dover, C. L., Arnaud-Haond, S., Gianni, M., Helmreich, S., Huber, J. A., Jaeckel, A. L., Metaxas, A., Pendleton, L., Petersen, S., Ramirez-Llodra, E., Steinberg, P., Tunnicliffe, V., Yamamoto, H. (2018). Scientific rationale and international obligations for protection of active hydrothermal vent ecosystems from deep-sea mining. *Marine Policy*, *90*, 20–28. https://doi.org/10.1016/j.marpol.2018.01.020

Van Dover, C. L. (2019). Inactive sulfide ecosystems in the deep sea: A review. *Frontiers in Marine Science*. Frontiers Media S.A. https://doi.org/10.3389/fmars.2019.00461

Vanreusel, A., Hilario, A., Ribeiro, P. A., Menot, L., & Arbizu, P. M. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. *Scientific Reports*, *6*. https://doi.org/10.1038/srep26808

Watling, L., & Auster, P. J. (2021). Vulnerable Marine Ecosystems, Communities, and Indicator Species: Confusing Concepts for Conservation of Seamounts. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.622586

Weaver, P. P. E., Billett, D. S. M., & Van Dover, C. L. (2018). Environmental Risks of Deep-sea Mining. In *Handbook on Marine Environment Protection* (pp. 215–245). Springer International Publishing. https://doi.org/10.1007/978-3-319-60156-4_11

Weaver, P. P. E., & Billett, D. (2019). Environmental Impacts of Nodule, Crust and Sulphide Mining: An Overview. In *Environmental Issues of Deep-Sea Mining* (pp. 27–62). Springer International Publishing. https://doi.org/10.1007/978-3-030-12696-4_3

Weaver, P. P. E., Aguzzi, J., Boschen-Rose, R. E., Colaço, A., de Stigter, H., Gollner, S., Heachel., M., Hauton, C., Helmons, R., Jones, D., Lily, H., Mestre, N., Mohn, C., Thomsen, L. (2022). Assessing plume impacts caused by polymetallic nodule mining vehicles. *Marine Policy*, *139*. https://doi.org/10.1016/j.marpol.2022.105011

Williams, R., Erbe, C., Duncan, A., Nielsen, K., Washburn, T., & Smith, C. (2022). Noise from deep-sea mining may span vast ocean areas. *Science*, *377*(6602), 157–158. https://doi.org/10.1126/science.abo2804

With, K. A., Gardner, R. H., & Turner, M. G. (1997). Landscape Connectivity and Population Distributions in Heterogeneous Environments. *Oikos*, *78*(1), 151. https://doi.org/10.2307/3545811

Wynne, B. (1992). Uncertainty and environmental learning. Reconceiving science and policy in the preventive paradigm. *Global Environmental Change*, *2*(2), 111–127. https://doi.org/10.1016/0959-3780(92)90017-2