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Chapter 2
Interdisciplinary Approach to Deep-Sea Mining—With an Emphasis on the Water Column

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Abstract Deep sea mining refers to the mining of valuable mineral resources from the deep ocean floor. Given the complex and fragile nature of deep-sea ecosystems, adopting an interdisciplinary and holistic approach is crucial to ensure the sustainable and responsible development of deep-sea mining (DSM) operations. This includes work related to the assessment of potential environmental impacts where physical, chemical, and biological characteristics of the target area are studied along with potential short-term and long-term effects on the surrounding ecosystems. These effects will be mining system dependent. Stakeholder engagement is essential. There are however knowledge gaps related to the deep-sea ecosystems and their interconnectedness, biodiversity, ecosystem dynamics and both the potential impacts from a single operation and cumulative impacts of the mining activities, as well as the mining systems themselves and the characteristics of the deposits. Collaboration between marine biologists, oceanographers, geologists, engineers and other relevant disciplines is essential to gain comprehensive insights. Closing these gaps would enable the development and implementation of a robust regulatory framework at both national and international levels to govern potential deep-sea mining operations. Monitoring and enforcement mechanisms must also be put in place to ensure compliance with the not-yet-developed set of standards. Multiscale adaptive management approaches where different temporal- and spatial scales are taken into consideration and where scientific knowledge, stakeholder engagement, robust regulations, and responsible practices are integrated, are the prerequisite for future responsible extraction of mineral resources from the ocean floor. This chapter gives an overview of topics relevant and needed for a proper multiscale marine

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mineral management. Its focus on the water column is restricted to vertical transportation and the impact of plume resettlement on biogeochemical processes.

Keywords Adaptive management · Responsible mining · Holistic marine mineral resource management · Vertical transportation · Biogeochemical processes

1 Introduction

1.1 Setting the Scene

Recently, large potentials of deep-sea minerals, such as three-dimentional seafloor massive sulphides and the laterally extensive manganese-rich crusts, have been documented on the extended Norwegian continental shelf (OD, 2023). The Norwegian government has completed a regional environmental impact assessment (OED, 2022) and has suggested to open portions of the extended Norwegian continental shelf for "mining activities" (OED, 2023). Cook Island has recently presented its first JORC-compliant (JORC, 2012) estimate and classification of the nodule resources inside its national jurisdiction (Tay et al., 2023). In a similar situation, having signed 31 contracts for different seabed mineral deposits in the "Area,", that is, areas beyond the national jurisdictions or the international waters, the International Seabed Authority (ISA) has decided to accept submission of applications for deep-sea mining (DSM) (DW, 2023). However, this does not automatically mean that exploitation permits will be given and that mining operations can start. There will be decision gates that are tailored to ensure that the mining will be done responsibly. There are several questions that still need to be taken into consideration by the respective regulating agencies (either national or international), the contractors as well as different stakeholders. Examples of such questions are: What is responsible mining? What is sustainable mining and what does mining *for sustainable development* mean? What is and how can serious harm be defined? What is adaptive management and what are the spatial and temporal scales that adaptive management should act on? What parameters must or should be monitored to assess "serious harm"? How often and where should we monitor with what technology at what temporal- and spatial scales? Do we need deep-sea mining? Do we need minerals at all, or can recycling meet the future demand? What is really the life-cycle cost of some potential future deep-sea mining operation vs. some onshore mining operation?

Exploration activities around the world oceans have shown that the resource potential of deep-sea minerals is significant. It is argued that more research is required to close knowledge gaps associated with exploiting these deposits. Moreover, the issue of climate change is critical, and international consensus states that human activity has contributed to this change (EU, 2023; United Nations, 2023). Mining of minerals and metals from the deep sea may constitute a part of the solution along with onshore mining, more recycling, designs that enable repairing and environmental restoration and arguably a global change in the consumption pattern. One thing to consider is whether it is most responsible to allow for publicly funded scientists to make a first evaluation on whether deep-sea mining can be performed responsibly, or whether we should allow for public–private joint ventures to accelerate data collection and analysis to find necessary solutions. In this context, it is important to note that the interdisciplinary nature of deep-sea mining requires scientists across disciplines to cooperate. The impact is dependent on both the mining system and the ecosystem.

This chapter deals with parameters and approaches for assessment of environmental impact of deep-sea mining in the water column in a holistic marine mineral resource management perspective.

1.2 Scope, Aim and Rationale

This contribution aims to present the interdisciplinary activities performed at the Norwegian University of Science and Technology (NTNU) within the broad field of deep-sea mining with an emphasis on activities associated with the water column. This includes (1) vertical transportation and, specifically, vortex-induced vibrations and the simulation and the modelling thereof and (2) environmental impact from a sediment plume and the biogeochemical processes at the sediment-water interface. The part on vertical transportation is a review of Thorsen et al. (2019). This interdisciplinary approach is needed to properly elucidate the abovementioned questions and thereby assess the future of deep-sea mining. Saying a “yes”or “no” to deep-sea mining is not a matter of technology alone, but also of the challenges associated with formal, natural and social sciences.[1] In this context, the deep-sea mining pilot programme was established at NTNU in 2015, and the vision was “*to develop new solutions for evaluation, exploration and extraction of deep-sea minerals under societal responsibility for the environment and the international heritage of mankind*”.

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[1] With *formal science* it is meant knowledge that deals with abstract concepts, logical reasoning and mathematical principles rather than direct observations of nature and natural processes. Unlike *natural sciences* (such as geology, physics or biology) that investigate the physical universe or *social sciences* (such as psychology or sociology) that study human behaviour and the societies they live in, formal sciences focus on theoretical frameworks and formal models that are independent of specific empirical observations but play an important role in practical applications, like mining.

1.3 Components of Deep-Sea Mining

The deep-sea mining value chain consists of a series of working processes including ore evaluation and assessment, prospecting and exploration, ore development, ore production on the deep ocean floor including thorough and extensive environmental monitoring, vertical transportation, dewatering, loading and transport, off-loading of ore at shore, mineral processing, refinement and, finally, sales and logistics of data, equipment and personnel to name a few. The value chain as it is presented here is technology focused, but equally important for a responsible sourcing of minerals are disciplines within the natural, social, and formal sciences. There is a demand for minerals and metals in society, where electrification and reduction of poverty, as well as reducing carbon footprint, are a few of the important driving forces. With the activities defined in the *deep-sea mining pilot programme*, connected with associated projects like the EU-funded projects Blue Mining and Blue Nodules and MarMine (Ludvigsen et al., 2016), supported by the Norwegian Research Council, and the NTNU-funded TripleDeep project (Ingulstad, 2023), NTNU has attempted to address challenges related to mining minerals from the deep sea by including ethical, social and environmental aspects.

The pilot programme was initially organized and established standing on six pillars to address the challenges: (1) mineral exploration, (2) resource geology, (3) ethics and environment, (4) historical and legal aspects, (5) platform development and (6) subsea systems and processes (Fig. 2.1).

Based on these pillars, the pilot programme has since its beginning, in addition to the activities presented in sections 2 and 3 of this chapter, completed projects on exploration and resource geology (Dumais & Brönner, 2020; Juliani, 2019; Juliani & Ellefmo, 2018a, b; Lim et al., 2019; Pryadunenko et al., 2022; Ryan, 2023; Ryan et al., 2023; Snook et al., 2018; Sture et al., 2019), on exploitation (Sevillano & Sangesland, 2022; Knudsen et al., 2016; Lesage et al., 2018; Lesage, 2020; Perera et al., 2022; Perera & Nilsen, 2022; Fard & Tedeschi, 2017, 2018; Eidsvik & Schjølberg, 2016a, b), on logistics and mineral processing (Kowalczuk et al., 2018, 2019; Solheim et al., 2020, 2022) and within the humanities and social sciences (Stabell & Steel, 2018; Meyer, 2018; Stabell, 2020, 2021; Nilsen, 2020).

2 Vertical Transportation

2.1 Aspects of Structural Dynamics Relevant for Hydraulic Lift Risers

There are several uncertainties and challenges related to the commercialization of deep-sea mining, where environmental issues resulting from the extraction of the targeted resources may become critical (Miller et al., 2018). The technical challenges include mineral processing, energy supply, extraction and vertical

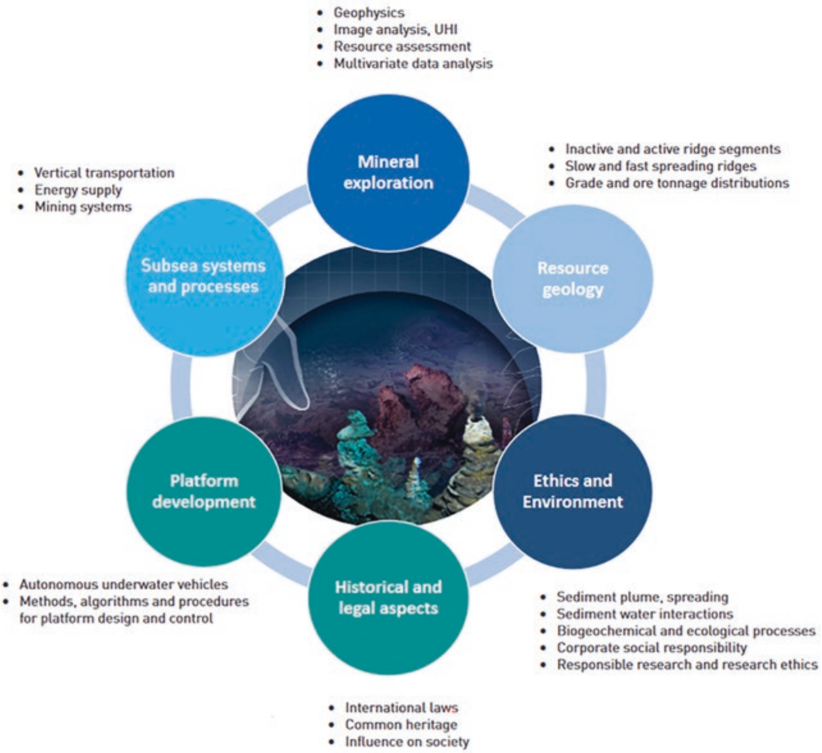

Fig. 2.1 The six original pillars of the Deep-Sea Mining Pilot programme at NTNU (Dumke et al., 2018)

transportation. With respect to the latter, suggested alternatives include mechanical bucket systems, container lifting and hydraulic lifting using slurry pumps (Laugesen et al., 2021), the latter eventually combined with airlift obtained by injecting compressed air into the liquid/solid mixture (Schulte, 2013). The hydraulic lift methods require a vertical pipe, that is, a riser, to transport the ore/water mixture. The riser will be exposed to current and wave loads that can cause fatigue failure. To avoid such failures in risers, which are extensively used in the offshore industry for transportation of oil and gas, much research has been carried out regarding their dynamic response (Patel & Seyed, 1995).

The response related to vortex-induced vibrations (VIV) is known to be associated with large uncertainties, representing a safety risk and a major design issue. VIV occurs due to the oscillating fluid forces caused by flow separation and shedding of vortices in the wake of the cylinder when the riser is exposed to current. The research on VIV has been considerable, as reflected by several reviews (Bearman, 1984; Williamson & Govardhan, 2004; Wu et al., 2012). The basic vortex shedding process for stationary cylinders is reasonably well understood (Sumer & Fredsøe, 1997); however, the complexity increases as the cylinder is allowed to oscillate, which may lead to unsteady and chaotic response that may be detrimental to the fatigue life (Modarres-Sadeghi et al., 2010, 2011). A flexible cylinder will in general oscillate with a moderate amplitude both in the crossflow (CF) and in-line (IL) directions. However, the fatigue damage may be significant due to high modes of vibration at a relatively high frequency (Baarholm et al., 2006). Prediction of fatigue damage caused by VIV is an important part of riser design where the current state of art applied by the offshore industry relies on empirical models such as SHEAR7, VIVA and VIVANA (Larsen et al., 2005; Triantafyllou et al., 1999; Vandiver & Li, 2005). These tools operate in the frequency domain, which means that non-linear effects such as time-varying mass and stiffness are not considered. To deal with these effects, the solution must be carried out in the time domain, using a step-by-step integration scheme. Several empirical time domain methods have been proposed, such as the wake-oscillator models (Kurushina et al., 2018), the artificial neural network approach (Mainçon, 2011) and the phase-coupled synchronization model (Thorsen & Sævik, 2017). A common challenge with all empirical models is to find suitable parameters for different flow regimes and real-life riser configurations.

Although most of the knowledge about VIV from the offshore industry can be directly applied to deep-sea mining, an important difference is related to the internal flow, which may include heavy particles and density variations (van Wijk et al., 2016). It is, therefore, of interest to study how such variations affect riser VIV and fatigue.

The published literature on VIV response in deep-sea mining risers is limited. Wang et al. (2018) studied vessel motion-induced VIV of a free-hanging riser, however, excluding the effects from internal flow or density variations. Verichev et al. (2011) discussed various excitation mechanisms relevant for mining risers, however, focusing on the instability that occurs when the slurry velocity exceeds the critical value. Boomsma and Blanken (2014) describe recent developments in vertical transportation models; however, no quantitative results were presented. Knudsen et al. (2016) carried out numerical simulations of riser VIV, accounting for the time-varying inertia and centrifugal forces caused by an internal flow of water and solids, demonstrating that the internal flow can change the maximum curvature of the riser. Fatigue was not part of the investigation. Thorsen and Sævik (2018) assumed a sinusoidal density variation and used a simplified analytical model to predict the wavelength that would give the largest disturbance on VIV; however, the model is not capable of quantifying the effect on fatigue life from the internal density wave.

As part of the Centre for Research–based Innovation MOVE, financially supported by the Norwegian Research Council and the consortium partners, Thorsen et al. (2019) presented a framework for non-linear time-domain dynamic analysis of deep-sea mining riser systems including both VIV and flow loads. The framework is based on a full two-way coupling between the structural and flow models, that is, the effect from both riser motion and flow dynamics can be fully accounted for in one analysis. This means that phenomena related to flow transients (e.g., start/stop of flow) and non-linear structure behaviour when exposed to combined loads from currents, waves and floater motions can be accounted for in a single analysis.

Here, a brief description of the models developed and reported in Thorsen et al. (2019) is given and some key results are commented upon with a focus on how the flow may influence the VIV response and fatigue behaviour of riser systems relevant for deep sea mining.

2.2 *Numerical Models*

2.2.1 Riser Dynamics and Hydrodynamic Loads

The structural analysis is based on the finite element programme RIFLEX (Fylling et al., 1995) for dynamic analysis of slender marine structures. The riser is modelled by beam elements, formulated using a co-rotated reference frame to account for large displacements and rotations in 3D space. The non-linear dynamic analysis is based on the incremental form of the dynamic equilibrium equation, which is solved by the Newmark-β method and a Newton-Raphson iteration procedure. The external hydrodynamic loads (per unit length) at any point along the riser are calculated as:

$$\begin{aligned}\mathbf{f} = C_M \rho \frac{\pi D^2}{4} \dot{\mathbf{u}}_n - \left(C_M - 1\right) \rho \frac{\pi D^2}{4} \ddot{\mathbf{x}}_n + \frac{1}{2} \rho D\ C_D \left|\mathbf{v}_n\right| \mathbf{v}_n \\ + \frac{1}{2} \rho D\ C_{v,y} \left|\mathbf{v}_n\right| \left(\mathbf{j}_3 \times \mathbf{v}_n\right) \cos \phi_{\text{exc}}\end{aligned} \tag{2.1}$$

The three first terms make up Morison’s equation (Faltinsen, 1999), while the final term represents the oscillating force due to vortex shedding, as proposed by Thorsen and Sævik (2017). C_M and C_D are the inertia and drag coefficients, while $C_{v,y}$ determines the strength of the vortex shedding force. Furthermore, $\dot{\mathbf{u}}_n$ is the normal component (i.e., perpendicular to the cylinder axis) of the fluid particle acceleration, $\mathbf{x}_n$ is the normal component of the cylinder acceleration and $\mathbf{v}_n$ is the normal component of the relative fluid velocity. The relative flow velocity is given as $\mathbf{u}_n - \dot{\mathbf{x}}_n$, where $\boldsymbol{u}_n$ is the incoming flow velocity and $\dot{\mathbf{x}}_n$ is the velocity of the cylinder cross-section. ρ is the seawater density and D is the outer diameter of the cross-section. $\boldsymbol{j}_3$ is a unit vector pointing in the direction of the cylinder axis, which means that the cross product in Eq. (2.1) ensures that the vortex shedding force is acting perpendicular to the instantaneous relative velocity. There will also be vortex shedding forces in the flow direction, causing in-line VIV. Therefore, an in-line excitation term was later added to Eq. (2.1) by Ulveseter et al. (2018), which was further improved by Kim et al. (2021). However, in the present study, only the crossflow term was considered as described in some detail.

The oscillations of the vortex shedding force are described through the time-varying excitation force phase ϕ_{exc}, where the evolution in time is given by Eqs. (2.2) and (2.3):

$$\frac{d\phi_{\text{exc}}}{dt} = 2\pi \frac{\hat{f}_{\text{exc}} \left|\mathbf{v}_n\right|}{D} \tag{2.2}$$

$$\hat{f}_{\text{exc}} = \begin{cases} \hat{f}_0 + \left(\hat{f}_{\max} - \hat{f}_0\right)\sin\left(\phi_{\dot{y}_{\text{rel}}} - \phi_{\text{exc}}\right), \left(\phi_{\dot{y}_{\text{rel}}} - \phi_{\text{exc}}\right) \geq 0 \\ \hat{f}_0 + \left(\hat{f}_0 - \hat{f}_{\min}\right)\sin\left(\phi_{\dot{y}_{\text{rel}}} - \phi_{\text{exc}}\right), \left(\phi_{\dot{y}_{\text{rel}}} - \phi_{\text{exc}}\right) < 0 \end{cases} \tag{2.3}$$

This makes it possible for the vortex shedding force to vary its instantaneous (dimensionless) frequency between $f_{\min}$ and $f_{\max}$, upon watching the phase difference $\phi_{\dot{y}} - \phi_{\text{exc}}$ between the structural velocity and VIV load and by that locking on to the frequency of vibration. For more details, see Thorsen and Sævik (2017).

2.2.2 Internal Flow Loads

The internal flow model adopted is a one-dimensional two-fluid model originally developed for gas-liquid two-phase flows, which is based on a finite volume Lagrangian slug tracking model concept first tested by Nydal (2012) and later extended and modified (Smith, 2017). In the model, solid particles and water phases are treated as a part of the liquid mixture.

The effect of the internal flow on the structural dynamics is presented in the following. First, the weight of the internal fluid will contribute to the effective submerged weight, w_s of the pipe:

$$w_s = w_d + w_f - \rho g A_e \tag{2.4}$$

where w_d is the dry weight of the empty pipe, w_f is the weight of fluid inside (including water and particles), and the last term is the buoyancy.

Due to the VIV response, the riser will be exposed to curvature deformation that changes over time, forcing the inside fluid/particles to follow a time-varying curve path. To illustrate this, consider the deformed beam element in Fig. 2.2.

By assuming that the pipe deformations are small in the co-rotated reference frame, the time-dependent position of an internal fluid particle can be expressed as:

$$\mathbf{r}_f\left(t\right) = Vt\mathbf{j}_3 + u\mathbf{j}_1 + v\mathbf{j}_2 \tag{2.5}$$

where V is the internal slurry velocity, while u and v are the lateral displacements of the beam in the local x- and y-directions, respectively. $\boldsymbol{j}_1$,$\boldsymbol{j}_2$ and $\boldsymbol{j}_3$ are orthogonal unit vectors as shown in Fig. 2.2, and t is some arbitrary instant of time. The velocity of a fluid particle is found as the material derivative of the position:

$$\mathbf{v}_f = \frac{D\mathbf{r}_f}{Dt} = \frac{\partial \mathbf{r}_f}{\partial t} + V\frac{\partial \mathbf{r}_f}{\partial z} = \left(\frac{\partial u}{\partial t} + V\frac{\partial u}{\partial z}\right)\mathbf{j}_1 + \left(\frac{\partial v}{\partial t} + V\frac{\partial v}{\partial z}\right)\mathbf{j}_2 + V\mathbf{j}_3 \tag{2.6}$$

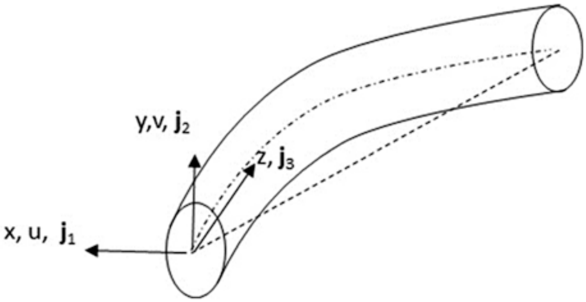

Fig. 2.2 The riser is curved during vortex-induced vibrations and the deformation changes over time forcing the inside particles to follow a time-varying curve path. This is illustrated considering a beam element in a deformed state

The fluid particle acceleration is found through similar differentiation of the velocity:

$$\mathbf{a}_f = \frac{D\mathbf{v}_f}{Dt} = \frac{\partial \mathbf{v}_f}{\partial t} + V\frac{\partial \mathbf{v}_f}{\partial z} = \left(\frac{\partial^2 u}{\partial t^2} + 2V\frac{\partial^2 u}{\partial t \partial z} + V^2\frac{\partial^2 u}{\partial z^2}\right)\mathbf{j}_1 + \left(\frac{\partial^2 v}{\partial t^2} + 2V\frac{\partial^2 v}{\partial t \partial z} + V^2\frac{\partial^2 v}{\partial z^2}\right)\mathbf{j}_2 \tag{2.7}$$

Hence, the following three force components will act on the pipe because of the internal fluid (Païdoussis & Li, 1993):

$$\mathbf{f}_{\text{inertia}} = -m_f\left(\frac{\partial^2 u}{\partial t^2}\mathbf{j}_1 + \frac{\partial^2 v}{\partial t^2}\mathbf{j}_2\right) \tag{2.8}$$

$$\mathbf{f}_{\text{Coriolis}} = -2m_f V\left(\frac{\partial^2 u}{\partial t \partial z}\mathbf{j}_1 + \frac{\partial^2 v}{\partial t \partial z}\mathbf{j}_2\right) \tag{2.9}$$

$$\mathbf{f}_{\text{centrifugal}} = -m_f V^2\left(\frac{\partial^2 u}{\partial z^2}\mathbf{j}_1 + \frac{\partial^2 v}{\partial z^2}\mathbf{j}_2\right) \tag{2.10}$$

where m_f is the internal slurry mass per unit length. The inertia term is independent of the internal flow velocity and is accounted for in the numerical model by adding the mass, m_f, to the element mass matrix, whereas the Coriolis- and centrifugal forces are added to the element load vector.

2.2.3 Effect of Internal Flow on Structural Dynamics of a Mining Riser

The numerical model described above was used to study the VIV and fatigue of an example mining riser at a water depth of 2350 m corresponding approximately to the depth at Loki's Castle, which is an active hydrothermal vent field located along the Arctic Mid-Atlantic Ridge (see Thorsen et al., 2019 for details). Compared to traditional oil and gas risers, the essential difference is the internal flow where a hydraulic lift method was assumed consisting of water and ore particles. Focus was on density variations in the internal slurry flow and the effects this may have on riser fatigue, which has previously received little attention. A case study was carried out, where the example riser was subjected to VIV caused by a steady current, along with different types of internal slurry flows. The internal flows considered were a steady state flow with a constant mixture density and time-varying flows generated by turning the inflow of particles on and off with periods ranging from 10 to 100 s. The time-varying flows were associated with density waves of different wavelengths moving up the riser. A sheared current profile was further assumed as the basis for studying displacements, stresses and fatigue along the riser.

The study confirmed that internal density waves in the conveyed slurry may influence VIV of deep-sea mining risers, in terms of both increasing and decreasing riser fatigue depending on the wavelength of density variations versus the VIV mode number excited for a given environmental condition. It is, therefore, difficult to give general guidelines other than performing numerical simulations supported by experiments on a case-to-case basis.

3 The Potential Impact of Plume Resettling on Biogeochemical Processes at Sediment–Water Interface

3.1 Background

Most of the expected environmental impact of DSM due to plume development, transport and resettling on the surface sediment in marine environments are based on conjectures extracted from limited knowledge and data. Those data and knowledge are insufficient to reduce the existing epistemological uncertainties. Besides the lack of data, heterogeneity of seabed and biota adjacent to potential DSM zones in seafloor massive sulphides (SMS), manganese nodules and cobalt crusts regions make the challenge even more prominent.

There is still a great deal of uncertainty among researchers and decision-makers in identifying essential variables needed in models to predict, to evaluate the potential severity of DSM activities and to mitigate the effects of the proposed operation on the marine environment and ecosystem (Beaulieu et al., 2017; MIDAS, 2016).

When we consider the inevitable limitation of resources for monitoring and acting in deep-sea environments, the recommended adaptive strategy for environmental management with a prioritized hierarchy for the mitigation measures (Durden et al., 2017) reveals the necessity of prioritizing also to study impacts according to the expected severity of the effects that may occur during DSM activities.

Regarding the priority, it is tempting to evaluate and discuss whether the primary focus of studying the potential impact of DSM should be on the sediment–water interface or water column. Undoubtedly, the water column will be affected directly and indirectly through disruption of benthic-pelagic coupling; therefore, some baseline parameters, such as oxygen, sulphide, turbidity, bio-essential and toxic elements and zooplankton migration (Collins et al., 2013), must be studied. In addition, coagulation/flocculation of natural particles exported from the epipelagic zone and their fluxes (i.e., part of the process of carbon export from the surface to the deep ocean and seafloor) should be studied. However, since most of the suspended particles are expected to settle rapidly to the vicinity of DSM zones, and the remaining suspended particles be carried away to adjacent regions for a more extended period near the seafloor, it is hard to believe that water with excess density due to resuspended sediment from any mining activity on the seafloor and plume from dewatering will move vertically up (Bashir et al., 2012) and create significant impact in the upper water column. The plumes usually affect the sediment-water interface and a portion of the low-lying water column just 25–50 m above the seabed where the excess water and sediment are discharged (Muñoz-Royo et al., 2022). Since sustained plumes become more dilute in the water column with increasing distance from the area where they form (Van Zyl et al., 2002), the impact of particles on the water column would be less than that on the sediment–water interface in the adjacent zones of DSM activities. The effect of DSM on the water column biogeochemistry and biota might be more pronounced due to the disruption of elemental fluxes between the sediment surface and overlying water column, which is central for benthic–pelagic coupling, and makes the sediment–water interface more critical.

Even though the plume production by resuspension of sediment from dredging and excavation and sediment–water discharge after preliminary (subsea) separation process of potential DSM activity are the major concerns for environmental impact, there are still very few research activities focusing on the effects of resettling of resuspended sediment on crucial biogeochemical processes at the sediment–water interface on the adjacent seabed zones of prospected DSM regions, probably due to logistical difficulties.

This section aims to focus on the aspects and parameters related to plume dispersion and resettling in sediment–water interface, factors affecting how far the plume will spread over both proximal and distal zones from DSM areas, to enhance the spreading zones and to identify essential variables and the knowledge gaps for understanding the potential environmental impacts on vital processes at the sediment–water interface. All the aspects and parameters listed and discussed below should be evaluated when developing models of sediment dispersion and consequent resettling, blanketing and their impact on biogeochemical processes at the sediment–water interface. This could be eventually used to decide which variables should be prioritized and introduced to the model to examine the plume dispersion and consecutive effects on the biogeochemical process at the sediment–water interface.

3.2 Physical, Chemical Characterization of Suspended Sediment and Physical Oceanographic Data

Size, structure, porosity and elemental composition of resuspended materials are important information for understanding the impacts and developing models of sediment dispersion and resettling and its effects on marine biogeochemistry and ecosystem. To predict the impacts, it is crucial to evaluate parameters such as the plume direction and longevity, the strength, direction of bottom current and water stability, as well as the physical character of resuspended particles (Bashir et al., 2012). Besides these, the condition of turbidity current developments such as sudden density changes in the water column and topography of the seabed are critical factors that affect dispersion of the plume. A recent study (Muñoz-Royo et al., 2022) suggests that turbidity current dynamics were overlooked in previous modelling attempts. Turbidity currents (or seafloor sediment flows) are among the volumetrically most important yet least documented sediment transport processes in oceanic systems (Paull et al., 2018). The topography of the different potential deep-sea mining regions varies greatly. Sites with sharp slopes may have contributed to the formation of turbidity currents (Birney et al., 2006). Experiments in the deep seabed polymetallic nodule zone, which is a relatively flat seabed, showed that a disturbance might create a low-lying, laterally spreading turbidity current (Muñoz-Royo et al., 2022). If DSM sites have higher elevations relative to the surrounding area, as in the case of ferromanganese crusts and hydrothermal sulphides, which are located on seamounts and ridges, the potential of triggering turbidity current because of the plume formation will be greater and the extent of dispersal of such plumes might be increased.

It is known that sediment carried by turbidity flows can create completely new habitats in the deep sea by removing existing communities, uncovering or triggering new resources and transforming aerobic communities into anaerobic ones (Bigham et al., 2020). Formation of turbidity current due to plumes of DSM activities may jeopardize the recommended buffer zone in the vicinity to facilitate recolonization after the mining operation (Birney et al., 2006). Therefore, the assessment of the potential impacts of plumes by modelling should have a risk analysis of the plume initiating a turbidity current downslope.

3.3 Sedimentation Rate

Most of the zones which might experience resettling of sediment from the plume produced by DSM activities are expected to be in the deep-sea region. Natural sedimentation rate of these areas varies from 0,0001 to 0,03 mm year^{-1}(Lyle, 2015), which are very low. Even relatively higher sedimentation rates in proximal active hydrothermal zones and hemipelagic surface sediment are between 0,8- and 1-mm year^{-1} (Lyle, 2015). In the case of DSM activity, sedimentation rate due to resettling of plume materials in the adjacent zone will be much higher than the background sedimentation flux. This extreme sedimentation will affect some critical biogeochemical processes such as oxygen penetration and connected redox chemistry, nutrient flux, organic and inorganic carbon fluxes and coupled activity of microbial fauna.

Decomposing of organic matter and inorganic C assimilation by heterotrophic and autotropic bacterial activity, respectively, and C sequestration in the sediment will be affected by resettling of resuspended materials on the surface sediment carried by plumes. Besides this, transporting excessive sediment may have harmful effect on sessile organisms due to its clogging effects and its toxic elemental content.

In one of the few on-site tests, a dredge was pulled over the seabed in the Clarion Clipperton Zone, showing that the sediment redeposition thickness can reach up to 9 mm directly next to the dredging tracks and 0.07 mm in about 300 m away from the dredging centre (Purkiani et al., 2021) during the test period. These sedimentation rates are almost >100–1000 times higher than the background annual sedimentation rates in deep-sea environment. These tests were however conducted with a dredge, which, in a technical sense, is not comparable to any likely mining equipment. Bed disturbance and flow conditions around the source would be different, effectively making a comparison for such near-field scale challenging. Another test has been conducted with a nodule collector system in Malaga Bight (300 meters water depth), sediment traps installed at 50- and 250 m distance from the trajectory followed by the nodule collector. Sedimentation rates of 200–800 $mg/m^2/h$ were observed at 2.5 metre above (sea-) bed (mab), which was the lowest altitude at which the sediment traps could be installed (Haalboom et al., 2023).

Sessile organisms are part of the higher benthic trophic level in deep-sea sediment which being adapted to very low sedimentation rates would be killed by as little as a few millimetres of sediment burial (Bigham et al., 2020). In the deep-water ecosystem, semiochemicals are critical for ecological functions including defence and competition for resource; it is also possible that mining-related sediment resuspension and eventual blanketing could impact species or the function of semiochemicals and prevent future use of genetic resources (Levin et al., 2020) in deep-sea water column, especially in bathypelagic (1000–4000 m), abyssopelagic (>4000 m) zones and the deep-sea benthos.

3.4 Rate of Change in the Fluxes of Bio-Essential and Toxic Elements

Fluxes, production and consumption of dissolved and particulate organic carbon (DOC and POC), Dissolved and particulate inorganic carbon (DIC & PIC), nutrient, bio-essential and toxic elements at sediment–water interface are essential to define the ongoing biogeochemical conditions of sediment prior to any anthropogenic impact. These fluxes are expected to change simply due to sudden accumulation of resettled sediment from the plume from DSM activities.

Sulphide minerals contain potentially toxic elements such as Hg, Cd, As, Ni, etc. (Koski, 2012). To evaluate the impact of these contaminants on the biota living in the surface sediment, under the effect of resettlement of plumes, it is necessary to have information on (i) geochemical and ecological baselines (Collins et al., 2013; Koski, 2012), (ii) the natural variations in elemental concentrations in the surface environment prior to mining and (iii) transport and transformation process of the mobilized elements.

During resuspension of sediment, both redissolution and mobilization of some elements and/or removal of existing elements by adsorption on the surface of suspended oxyhydroxide particles will happen (Lyle, 2015). As bioavailability and potential toxicity are functions of the physical and chemical forms of elements (speciation), specific transportation and transformation pathways, such as adsorption on the suspended particles and ingestion of or bacterial colonization on particles, are equally important to follow.

3.5 Microbial Community Responses

Benthic microbial ecosystem plays a crucial role in carbon, nitrogen, phosphorous and other elemental cycles and ecosystem functioning. While benthic heterotopic bacteria decompose organic carbon, autotropic bacteria can convert dissolved inorganic carbon into biomass at rates that are as high as the bacterial assimilation of POC-DOC (Sweetman et al., 2018). Any changes in the flux of POC/DOC and DIC into sediment will affect bacterial activities and microbial community structure. How the deep-sea bacterial community will react to the sudden and extreme sedimentation rates and potential blanketing effects of resettling of suspended sediment is not yet clear. Changing the flux of essential elements for biological activities will affect microbial community structure and this change eventually will influence the redox condition of the sediment and in turn new biogeochemical settings will be established.

3.6 Redox Condition of Surface Sediment

Due to changes in redox condition after DSM activities resulting in plume transport and resettling of suspended sediment, the solubility and mobility of some redox-sensitive metals (such as Fe, Mn, Cr, etc.) might change. These changes will have critical effects on other particle reactive toxic metals (such as Hg and Pb) mobilities (Kohler et al., 2022) and toxicities. It is therefore necessary to monitor the oxidation-reduction conditions, and other redox condition proxies, such as organic matter, NO_3, NH_4, PO_4, Fe and Mn concentrations in surface sediment and on the sediment–water interface.

4 Multiscale Marine Mineral Resource Management Framework

Building on an established management framework (Durden et al., 2017), a future deep sea mining operation must be managed through a smart, integrated and holistic multilevel and multi-perspective mineral resource and environmental management system. Two perspectives must arguably be considered: (1) public governance and (2) business management. Both perspectives are linked to the regional environmental management plan (REMP) and the environmental management and monitoring plan (EMMP) in the sense that they are developed by the public regulatory body and put constraints on or limitations on how the mining operation can and should be executed. Modelling and prediction techniques are needed to model both passive and active biotic and abiotic substances at temporal and spatial resolutions of months to years and from hundreds of km and down to a few hundred metres, respectively. Relevant monitoring capacities for ground-truthing must also be able to work on these scales. For example, in the case of modelling of the larvae, the way the plume will affect the larvae dispersal and the interactions on the sediment–water interface should guide the temporal and spatial scale of the connectivity processes in the REMP and EMMP. There are, to the authors' knowledge, no models available that simultaneously perform adequately across all temporal and spatial scales. It is, therefore, essential that the near-field models in the future management systems are properly translated to relevant source terms in the large-scale models, based on a realistic description of the mining operation and the stressors it causes.

Given the international consensus that active hydrothermal sites should be avoided, areas beyond the active vent sites at different ridge settings must also be handled in a future system. A model must be established that quantifies how and to what extent a plume affects the dispersal of bathyal species. Monitoring activities must contribute to integrating chemical and textural (grain size and shape) modules to the plume. Further, it must model and simulate the plume at scales less than 200 m and down to the immediate surroundings of the mining tool, effectively describing the source term of a disturbance generated by the equipment, which can be excavation, separation processes or manoeuvring. The composition of the sediment brought into suspension, for example, sediment type, particle size and shape and extracellular polymeric substance (EPS), are of utmost importance. These properties influence the settling velocity and distribution of the sediment plume. Together with typical flow properties such as momentum, concentration, and the resulting mixture densities, they are relevant to enable appropriate modelling on the larger scales. Such multi-resolution modelling and simulation should cover a potential mining site and beyond. Predictive habitat modelling must combine existing cross-disciplinary data from biology, microbiology, geochemistry, geology and oceanography in an integrated spatial analysis of multidisciplinary and multiscale datasets. Predictive habitat mapping of physical and biogeochemical settings of biological communities and ecosystem functions should be integrated into the spatial management framework. This would guide science-based spatial planning and management of mining operations, EMMPs and REMPs and make sure that future monitoring actions are implemented to ensure that models are appropriate (e.g., having the right spatial scale) for the development of relevant policies.

As touched upon in Sect. 3, the assessment of ecotoxicological environmental hazards posed by sediment plumes is also of importance for any management system. Given a mineral resource and economic model, a preferred mining method, the REMP and the EMMP and the monitoring procedures and analysis methods and techniques, long- and short-term mine plans will have to be developed for each mining project. The monitoring procedures will contribute to maximize resource utilization or any other objective while minimizing the environmental impact. A thorough understanding of concepts such as "serious harm" constitutes a core in such developments.

Like in any extractive industry, any mined area will be significantly impacted if exploitation takes place. The generated environmental impact should be kept as localized as reasonably possible. Containing environmental effects closer to the mining site will leave larger unaffected areas that could serve as refugia (Wittmann, 2022) for the fauna and significantly reduce impacts outside of the contract area. It would also provide more options for locating Preservation Reference Zones (PRZs) and lead to less impacts on adjoining contract areas (Weaver et al., 2022).

The data collected during a mining operation must be fed back into both the development and the reconciliation and update of the mine plan, the EMMP and the REMP in an adaptive manner. Modules and procedures for such updates by developing multilevel and multi-perspective feedback loops are needed. Further, a link to thresholds and how to assess impact must be developed (Hitchin et al., 2023; Washburn et al., 2019; Weaver et al., 2022). In effect, modules and procedures in a future management system will define the interface between the public and the private governance perspective, and it will be an integrated part of an adaptive management system (Clark et al., 2022; Hyman et al., 2022) that constantly will be better at quantifying the link between environmental pressure and stressors and the environmental impact.

5 Discussion and Way Forward

A total of 31 exploration licenses have been issued by the International Seabed Authority in the Area. Nineteen of these licenses are for polymetallic nodules in the Clarion-Clipperton Fracture Zone, the Central Indian Ocean Basin and in the Western Pacific Ocean. Seven licenses are for polymetallic sulphides in the Southwest Indian Ridge, Central-Indian Ridge and Mid-Atlantic Ridge. The five remaining licenses are for cobalt-rich crusts in the Western Pacific Ocean. The global mineral resource potential on the deep ocean floor is huge (Mizell et al., 2022). International and national authorities are assessing the possibilities to open mining activities on the deep ocean floor.

Although the quantity is disputed (Moana et al., 2022), the green energy transition will increase the demand for minerals and metals (European Commission Joint Research Centre, 2023; IEA, 2021). Can and should the (deep) ocean floor be a part of the solution? There are many unanswered questions associated with this, including: (1) How can local consequences and global benefits be balanced? (2) How can we compare the impact of deep-sea versus terrestrial mining? (3) How can we proceed without complete knowledge in accordance with the precautionary principle? (4) Is it possible to extract without an environmental impact? (5) How should governments develop incentives in a world of uncertainty?[2]

Adaptive management is necessary and must be implemented. The environmental stressors described in Sect. 3 will have to be considered as a constraint in the development of future mine plans and iterative loops must be defined to ensure thorough and effective updates of the REMPs and the EMMPs. The effect of the bathymetry on the potential development of the turbidity flows should also be considered as a controlling factor in the mine plan development. Various technology concepts are under development, challenging the environmental performance of current technology. Whether these concepts are eventually viable options to reduce the environmental footprint needs to be seen. It is important that the industry is challenged to improve upon its environmental footprint, leading to stricter requirements on the permissible environmental impacts. Incorporation of new technology is only likely if the technology concept is robust and has been proven to work appropriately at higher technology readiness levels. Therefore, pilot testing to ground truth results from, for example, the simulation approach presented in Sect. 2, must be encouraged and permitted.

Data collection, data analysis and data management are part of the core in adaptive management. Data must be distributed and shared to ensure well-informed decisions both by national and international regulating and managerial bodies and commercial entities to questions such as: (1) How should the flow of data be set up to make sure that the right data arrive correctly at the receiving end? (2) How do we make sure that all relevant data are taken into consideration when optimizing the mine plan? (3) How can we convince the society that the published data are reliable? (4) Are we as human beings capable of understanding the complexity of these systems and the needed interdisciplinary nature? NTNU Oceans has aimed at an interdisciplinary approach on the topic as a part of the pilot programme on deep-sea mining. Over the years, many challenges have been resolved, but the more one knows, the more questions arise.

Our society needs minerals and metals. Interdisciplinary and holistic thinking is the key to making sound future decisions about undertaking deep-sea mining and making sure that the first deep-sea mining operation is not the last due to improper public and private environmental and resource management.

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[2] Some of these are addressed in the TripleDeep-project (Ingulstad, 2023).

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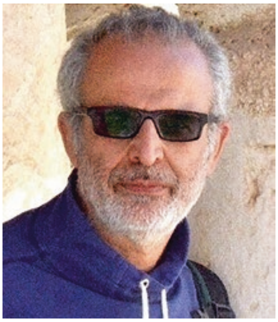

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