Seabed space through the lens of deep-sea mining

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Abstract

The Anthropocene ocean is characterised by intense human activity, enacted through a network of exploration, delimitation, extraction and pollution which extends to the furthest reaches of the deep seabed. Growing state and private interest in seabed mining (SBM) is accompanied by accelerating scientific study of the deep seabed, which aims to understand the geology and distribution of mineral resources and to characterise deep-sea ecosystems. Meanwhile, the legal regime that governs activities in the Area encapsulates the diverging interests of actors and entities working in relation to SBM. The deep seabed is an interesting subject for conceptual consideration, as the focus of widespread attention centred around SBM, and host to the conflicting narratives of extraction and conservation that dominate SBM discourse. A broad literature review of deep seabed technologies, geology and biogeochemistry is followed by a more focussed examination of SBM resources, impacts and regulations. By examining the 'natural' processes and components of the deep seabed environment, the technology used to explore, observe, map and visualise it, and the legal instruments applied to regulate SBM, this thesis aims to shed some light on its epistemological construction and the implications for effective regulation. In turn, these findings inform more critical perspectives on the deep seabed, based on its multiscalar, dynamic materiality, and continuous mediation between life and matter.

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List of Acronyms

APEI	Area of particular environmental interest
AUV	Autonomous underwater vehicle
BBL	Benthic boundary layer
CCZ	Clarion–Clipperton Zone
CHM	Common heritage of mankind
CRC	Cobalt-rich crust
DEA	DISCOL experimental area
DISCOL	**Dis**turbance and re**col**onization experiment
DOOS	Deep Ocean Observing Strategy
EEZ	Exclusive economic zone
EIA	Environmental impact assessment
GOOS	Global Ocean Observing Strategy
IMMS	International Marine Minerals Society
ISA	International Seabed Authority
LOSC	Law of the Sea Convention
LTC	Legal and Technical Commission
MOR	Mid-ocean ridge
MPA	Marine protected area
OM	Organic matter
OMZ	Oxygen minimum zone
PSV	Production support vessel
REEs	Rare earth elements
ROV	Remotely operated vehicle
SBM	Seabed mining
SMS	Seafloor massive sulphides
UNCLOS	United Nations Convention on the Law of the Sea
VR	Virtual reality

List of Instruments

United Nations Convention on the Law of the Sea, 1982

Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, 1994

Convention on Biological Diversity, 1992

Draft text of an agreement under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (draft version January 2020)

Mining Code, International Seabed Authority:

> Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, 2000/2013 (ISBA/19/C/17 and ISBA/19/A/9)
>
> Regulations on Prospecting and Exploration for Polymetallic Sulphides in the Area, 2010 (ISBA/16/A/12/Rev.1)
>
> Regulations on Prospecting and Exploration for Cobalt-Rich Crusts, 2012
>
> Draft regulations on the exploitation of mineral resources in the Area
>
> Recommendations for the guidance of contractors for the assessment of the possible environmental impacts arising from exploration for marine minerals in the Area, 2013 (ISBA/19/LTC/8)

Code for Environmental Management of Marine Mining (2001, revised 2011), International Marine Minerals Society

1. Introduction

The upcoming UN Decade of Ocean Science for Sustainable Development (2021–2030) is just one global initiative reflecting growing awareness of the vital functions performed by the ocean that sustain life on Earth (Ryabinin et al., 2019). UN Sustainable Development Goal 14 also recognises the fundamental roles of the ocean in driving and regulating global cycles, and the need for effective oceans management. As scientific studies and findings on ocean environments proliferate, knowledge is also growing on the economic potential of ocean resources. The concept of the Blue Economy suggests that significant benefits can be gained from sustainable exploitation of these resources, which include mineral deposits, hydrocarbons and marine genetic resources. Debates around the Blue Economy focus on the limited state of scientific knowledge in many marine environments that host resources, with arguments that biodiversity, ecosystem resilience and carbon dynamics, among other factors, are not sufficiently understood to guarantee sustainable exploitation. The legal framework regulating the oceans is presided over by international law in the form of the United Nations Convention on the Law of the Sea (UNCLOS), which was finalised in 1982, and dedicated regulations for SBM are still being developed. As such, technological breakthroughs and advancing access to ever more distant parts of the ocean are not yet accounted for in legal measures to protect the marine environment. The result is a tenuous moment for extractive activities at sea, where the will to conserve the marine environment is met by motivations to commence extraction at a commercial scale.

This paradigm is exemplified in the case of seabed mining (SBM), which refers to the extraction of mineral-hosting deposits from the seabed that contain valuable metals. Commercial SBM has been mooted since the 1960s, but since the turn of the century it has attracted growing attention from private mining companies, governments, policymakers and researchers. SBM appears increasingly attractive from an economic point of view, due to depleting terrestrial reserves of high-grade mineral and metal deposits, unreliable global mineral supplies, and growing demand for metals and rare earth elements (REEs) to produce batteries, smartphones and other ‘green’ and high-tech applications (Hein et al., 2013). Mineral deposits at the seabed are estimated to substantially exceed continental reserves, and proponents of SBM argue that the environmental impacts of mining at the seabed are lower than those of mining onshore (Childs, 2019). Furthermore, advances in marine technology are enabling access to deeper parts of the ocean to facilitate exploration and exploitation. No commercial production on the deep seabed has yet taken place, as private companies and governments are currently at various stages of R&D, funding, planning and applying for SBM activities throughout the world’s oceans.[1]

[1] See tracking of vessels involved in SBM and designated mining areas at: deepseaminingwatch.msi.ucsb.edu

Seabed mineral resources are situated both within and beyond areas of national jurisdiction. This thesis focuses on SBM at the deep seabed beyond national jurisdiction, known as 'the Area'. Although the seabed below 200 m water depth constitutes 63% of Earth's surface area (Ingels et al., 2016), it is often described as the most poorly understood environment on the planet, and has been observed at very low spatial and temporal resolution (Levin et al., 2019). The majority of species at the deep seabed are thought to be undiscovered, while the role of the deep seabed in the carbon cycle and in regulating ocean-wide conditions and global climate remains unclear. As a result, the long-term effects of large-scale disturbances to the seabed are also unknown. As such, many scientists advocate a moratorium on SBM due to the lack of knowledge on the deep seabed environment, which, they argue, limits the ability of mining operations to predict, assess or avoid irreversible environmental damage (Thompson et al., 2018).

The conflicting interests found among mining operators, the marine scientific community and ISA representatives are reflected in the entangled epistemologies of science, technology and law. The distinct processes and fauna of the deep seabed (Ramirez-Llodra et al., 2010) and the unique governance structures that apply to it come together at the topic of SBM, making this an ideal topic to focus the thesis.

As the actors associated with SBM narratives continue to spar over their intentions for the seabed, the seabed itself remains a site that sits unmoving and unliving in the imagination. Its role is largely expressed as: 1) an inert medium that hosts valuable and potentially extractable minerals; and 2) the habitat for deep-sea life forms and forms of life. In fact, as this thesis will argue, the fundamental component of any SBM operation or deep-sea environment is the seabed itself. What is on first glance an inert, static surface in reality hosts highly complex and specific ecosystems, biogeochemical cycles and geological features which extend above and below the plane of the seabed as it is currently characterised legally. This perspective offers avenues to consider the deep seabed and SBM critically.

The past two decades have seen a wider movement based in social science and political geography to consider the 'geo' within the 'geopolitical'; that is, to take into account the geographic properties of territory in order to study its intersections with the social and political (Dalby, 2007; Clark, 2013). This aim has been manifested in studies on the challenges of governing three-dimensional territory, particularly following Elden (2013) (e.g. Bridge, 2013; Grundy-Warr et al., 2015), and verticality has been examined in the context of onshore mining, offshore hydrocarbon production and pipeline infrastructure (Bridge, 2013; Valdivia, 2015). Scholars have also argued for new appreciation of materiality and the elemental in characterising landscapes and environments (Bennett, 2004; Barry and Gambino, 2020). Critical ocean studies have emerged in tandem to explore concepts of the fluid, mobile territory of ocean space (Steinberg, 2013; Steinberg and Peters, 2015), through to legal delimitations of ocean space, and the inability of spatial ordering by international law to capture what the sea ‘actually’ is (Allott, 1992; Jones, 2016; Jay, 2018).

With the prospect of SBM at the deep seabed seemingly fast approaching, the seabed increasingly becomes a geopolitical arena. In the words of Jones (2016), ‘as the use of a space changes, the understanding of the space changes, and, ultimately, the way that space is ordered’. Accordingly, as commercial extraction threatens the deep seabed, its complex processes and dimensionality must be more deeply understood to facilitate its integration into regulations in a way that reflects its scales and properties. Critical ocean literature offers the chance to advance analysis of the seabed, following the studies of Childs (2018) on issues of volume and temporality surrounding SBM, and Hessler (2019), who treats SBM critically from the perspective of artistic works and theory. Much of the aforementioned research draws on knowledge typically produced in scientific studies, especially geoscience and oceanography. Therefore, analysing research on the seabed from various marine scientific disciplines, particularly benthic studies, should provide a holistic view of the current state of understanding. In turn, this can be applied to evaluate SBM governance, and finally to explore a new perception of seabed space by considering themes of volume and materiality.

1.1 Problem statement and research questions

In view of the above, a research gap can be identified: there is a need to explore the mining landscape and legal characterisation of the deep seabed, but conceptual and critical considerations of SBM from an interdisciplinary viewpoint are lacking. Three research questions are defined to structure this thesis:

(1) What is the nature of SBM deposits at the deep seabed?

Reviewing the literature on the main mineral deposits will enable key findings and research gaps to be collated, to present a comprehensive picture of their setting, formation and associated ecosystems.

(2) How does the regulatory framework account for impacts of SBM on the deep seabed?

Reviewing impact studies on SBM operations, and the current status of SBM regulations, will clarify the context and effectiveness of the legal framework.

(3) How can seabed space be re-imagined in the context of SBM?

With understanding of scientific and legal factors that form perspectives on SBM, this information can be interpreted critically to generate new ideas on seabed space, which may impact future perspectives on its relation to ocean space and earth systems.

1.2 Methodology

The research problem was identified from reading critical geography literature, and the intention is to conduct a wide-ranging literature review based in various fields of marine science, to synthesise the findings, and to transport them into a different context to generate new meaning from the results. As such, this thesis is interdisciplinary, and its methodology is unlike the traditional approach taken by a thesis based in either marine sciences or geography.

Due to the exploratory nature of the research, as reflected in the open-ended problem statement, research questions have been defined to guide the research process. A hypothesis has not been formulated, to allow the direction of study to develop organically. Furthermore, qualitative methods are used, since synthesis and interpretation of textual content are applied to produce findings. The possibility of research bias and subjectivity is present in such a flexible, open-ended research process, so certain measures have been taken to enhance the validity and reliability of findings. Now follows a detailed account of the research design.

Data collection took place through a wide-ranging literature search. The examined literature includes primary sources, such as scientific studies and legal text, and secondary sources, such as critical studies, review papers and books. The broad nature of the literature review poses the danger of missing or neglecting key subjects. To combat this, review papers and books were consulted for each subtopic to ensure effective coverage and improve content validity, as detailed in Table 1.

Table 1 *– Sources used to initiate citation and snowball searching*

Section	Sources
2.1–2.3 Ocean basins, deep-sea sediments and fauna	**Seibold and Berger, 2017**: 'The sea floor: an introduction to marine geology' (textbook); **Ramirez-Llodra et al., 2010**: 'Deep, diverse and definitely different: unique attributes of the world's largest ecosystem' (review paper); **Lessin et al., 2018**: 'Modelling marine sediment biogeochemistry: Current knowledge gaps, challenges, and some methodological advice for advancement' (review paper)
2.4 Technology	**Levin et al., 2019**: 'Global observing needs in the deep ocean' (review paper)
3.1 SBM types and settings	**Miller et al., 2018**: 'An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps' (review paper)
3.2 SBM impacts	**Levin et al., 2016**: 'Defining "serious harm" to the marine environment in the context of deep-seabed mining' (research paper) **Middelburg et al. (eds), 2018**: 'Assessing environmental impacts of deep-sea mining – revisiting decade-old benthic disturbances in Pacific nodule areas', Biogeosciences journal, special issue
3.3 Regulatory framework	**Thompson et al., 2018**: 'Seabed mining and approaches to governance of the deep seabed' (review paper); **Rothwell and Stephens, 2016**: 'The International Law of the Sea' (textbook)

The choice of literature to include was made based on assessment of relevance, which could be subject to researcher bias. Therefore, certain measures were taken to select literature methodically, to enhance the validity of the study. A ‘snowball’ approach to identifying pertinent literature was applied, whereby research begins with a small number of sources, and further sources are identified from their reference lists or bibliographies, thus allowing the thread of research to be followed. However, this technique rapidly increases the number of identified sources, which can lead to an overwhelming amount of literature. The research design aimed to mitigate this issue by drawing on the overview sources mentioned above and breaking the subject down into key topics. The focus on SBM also concentrated the study and narrowed down the amount of relevant information to be considered.

Citation searching was also applied, whereby Google Scholar was used to consult the list of works citing a source, from which relevant articles were then chosen. This was an important component, as the subject of critical ocean studies is relatively new and it was important to identify new papers, and scientific findings on SBM are being published at a rapid rate. This combination of snowball and citation searching allowed a full timeline of literature to be consulted, from earliest sources on the subject to preprints, so that the most up-to-date methods are considered in the context of their development. This allowed a thorough mapping of key concepts and research gaps.

Common themes running through the literature were then identified and synthesised, before interpretation and discussion in the context of critical ocean studies. Post-humanist approaches of human geography have recently taken a ‘material turn’, that is, an approach to studying the intersection of human experience with ‘earthly features’ of the world in an elemental sense (Anderson and Wylie, 2009; Peters, 2017). This approach has been applied to studies of the ocean based in critical geography, which consider its ‘meaning’ as a space when its materiality is taken into account. Such work has drawn on post-structuralist theory and science and technology studies (Murdoch, 2005) to examine space and place, time and temporality, and movement and mobility – core concepts of geography (Peters, 2017).

In applying aspects of this critical approach to broad findings of a study informed by geoscience, this thesis hopes to make a valuable and original contribution through extending the empirical findings of scientific studies to explore perceptions and constructions of the deep seabed.

Interdisciplinary research

It has been recognised that problems posed in the marine realm require new combinations of knowledge and viewpoints to find solutions (Turner et al., 2017). This thesis aims to integrate knowledge from different disciplines for the following purposes, according to Knutsson (2006): to *broaden*, by taking multiple perspectives into account with recognition of their underlying principles; to *reconfigure*, by transporting established knowledge into new, integrative contexts; and to *synthesise*, by combining knowledge from separate disciplines to form new, integrated forms of knowledge.

The main original offering is the synthesis of knowledge from multiple disciplines, and the transporting of these findings into a critical context. As such, this thesis aims to achieve interdisciplinary knowledge integration as it is defined by Turner et al. (2017), by 'focusing and blending' aspects of different disciplines and linking common issues to gain new understanding. By integrating theory, rather than methodology, the hope is to make connections between the epistemological frameworks and ontologies of multiple disciplines of marine science, and branches of critical geography. It has been recognised that interdisciplinary work based in the natural and social sciences may bring challenges, in terms of the different styles of discipline-specific language, methodology, cognition and even thesis structure, in addition to vagueness of research objectives (Turner et al., 2017; MacLeod, 2018). However, while approaching a topic from multiple angles doubtless limits the depth and breadth of study that could be covered with one discipline, findings drawn from multiple disciplines may produce original perspectives.

Chapter 2 now reviews the current understanding of the seafloor at various spatial and temporal scales with reference to these fields, to situate the starting point of this study within a scientific context. This first part of the thesis assembles a current picture of the scientific characterisation and study of the seabed, including its context in the broader discipline of marine sciences, and state-of-the art techniques. This section is regarded as a purely factual review that draws data from empirical literature.

On this basis, **Chapter 3** goes on to present the geological characteristics, settings and distribution of the three main targets of SBM, before outlining the main findings of SBM impact studies. Again, this part is largely factual. It then moves on to detail the legal framework currently applied to the deep seabed to govern SBM and its interpretation by other researchers.

Finally, the data gathered in the previous sections is interpreted through the perspective of a different discipline, as **Chapter 4** brings together the scientific and legal depictions of the deep seabed and its resources explored in prior chapters to analyse its representation in a theoretical and material sense. **Chapter 5** concludes with implications and limitations.

2. Background: The seabed

Throughout the 20th century, advancing scientific knowledge about the deep seabed was linked to major breakthroughs in tectonics, and ocean and climate cycles. As well as a vital component of earth systems, its varying physical, geological and geochemical properties make the deep seabed a unique environment that is distinct from all other marine and coastal ecosystems (Ramirez-Llodra et al., 2010).

Production of the first global-scale bathymetric maps, particularly by Tharp and Heezen in 1977, revealed the oceans' submerged topography and provided the final proof of Wegener's 1912 plate tectonics theory. Likewise, studies of alternating magnetic anomalies present in oceanic crust confirmed the concept of seafloor spreading (Vine and Matthews, 1963), while more complex models of mid-ocean ridges (MORs) and subduction zones furthered understanding of ophiolite sequences onland (Dilek, 2003). More recently, discoveries of hydrothermal vents and their associated biota and ecosystems have shed light on the organisation and origins of life forms (Martin et al., 2008), while the use of molecular methods to examine deep-sea microbes is inviting increasing attention to the possibilities and applications of genetic resources (Ferrer et al., 2009).

Links between the deep seabed environment and scientific understanding of the planet have evolved with technology that enables multiple disciplines to pursue specific lines of enquiry into the seabed. An established international community of deep-sea researchers now cooperates through national and international programmes. To provide a broad background to the thesis, this chapter explains the formation and destruction of the seabed, followed by a closer look at deep seabed sediments and benthic biogeochemistry. Typical habitats and characteristics of deep seabed fauna are explored, before a description of technologies used for exploration, sampling, mapping and visualisation. The chapter concludes with a review of human activities. First, modes of classifying the seabed are discussed.

Delimiting the seabed

Various classification schemes have been devised to delimit seabed areas. The 'deep' sea(bed) is commonly defined as being below 200 m water depth, on the basis that:

> *…changes in light, food supply, and the physical environment lead to altered animal taxonomic composition, morphologies, and lifestyles that are collectively understood to represent the deep sea both within the water column and at the seafloor. (Levin et al., 2019; Pörtner et al., 2019)*

The deep sea is further split into the bathyal zone (200–3,000 m), characterised by varied geomorphology and features such as canyons, seamounts and ridges; the abyssal zone (3,000–6,000 m), dominated by abyssal plains; and the Hadal zone, from 6,000 m and deeper, largely comprising Pacific trenches. Hereby, bathymetry, ecology and physical oceanographic properties are considered together to identify distinct horizontal provinces (Figure 2.1a).

These integrated definitions are situated alongside a classification typically applied in the marine sciences that is based on bathymetry, namely seabed slope angle, which is essentially an idealised transect of a passive continental margin (Figure 2.1b). Here the continental shelf becomes the continental slope, which transitions through the continental rise into the abyssal plain.

An alternative frame of reference used to spatially define ocean space and the seabed is the hypsographic curve (Figure 2.2), essentially a histogram which plots the elevation of the seabed alongside the land in relation to sea level, the average land height, and the average ocean depth, as a function of the cumulative area of Earth's surface that it occupies. Bathymetric zones are loosely assigned based on slope angle, although this scheme is data-led and uses theoretical horizons as anchors.

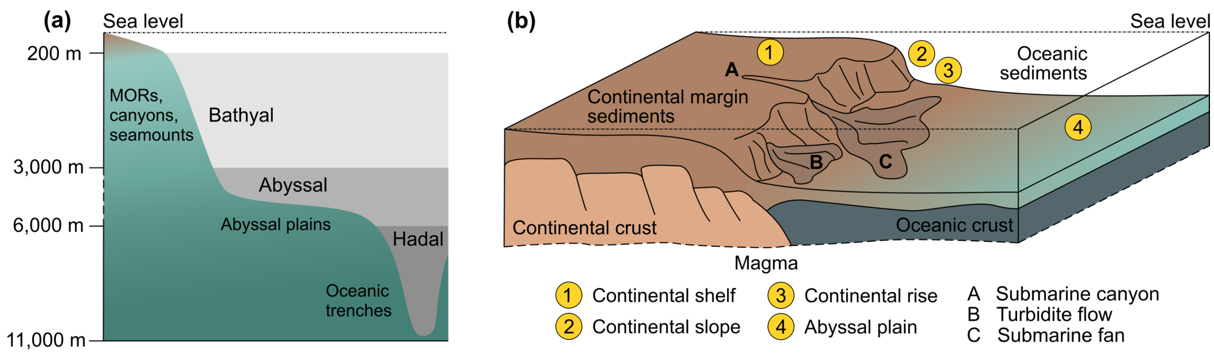

Figure 2.1 *– Typical seabed classification scheme according to (a) depth of deep-sea provinces and (b) slope angle*

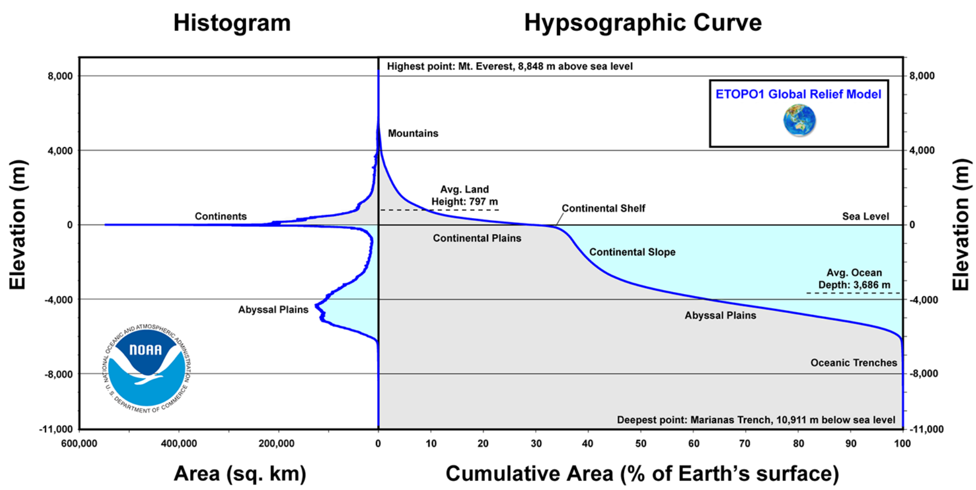

Figure 2.2 *– Global histogram (left) and hypsographic curve (right) of Earth's surface (Eakins and Sharman, 2012)*

The use of a theoretical reference level is also seen in the case of the geoid, the equipotential surface that corresponds to the ocean surface as it would lie if influenced only by the rotation and gravitation of Earth, with the ability to flow through continents (Figure 2.3). The influence of waves, tides and currents are negated in the geoid, as it represents the ocean 'at rest' (Zheng et al., 2018). The geoid thus provides a universal frame of reference for height measurements which accounts for gravity variations across Earth's surface that occur as a result of uneven mass distribution, i.e., topography and bathymetry. Hence, the physical seafloor is intimately related to the theoretical geoid.

The seabed is also divided into legal zones according to the LOSC, as discussed in section 3.3.

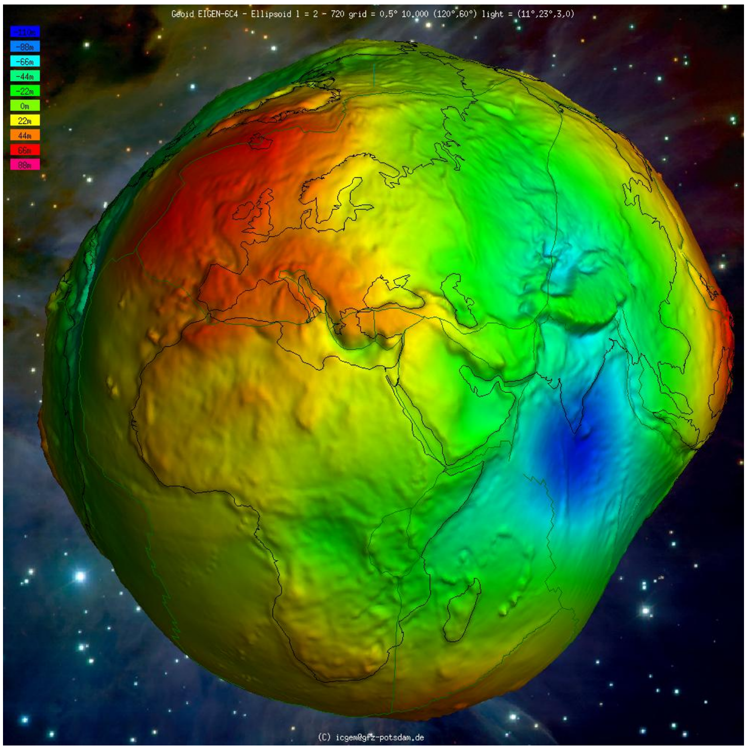

***Figure 2.3** – The Geoid. Undulations are multiplied with a 'boost' factor to enhance visibility (Ince et al., 2019)*

2.1 Overview of ocean basins

At the broadest scale, the oceans are underlain by large structural depressions formed from dense basaltic oceanic crust, upon which are superimposed bathymetry controlled by volcanism and sedimentation. These features comprise an oceanic basin, as summarised in Figure 2.4, which are controlled at the largest scale by the movement of oceanic and continental plates across the Earth at 1–10 cm year^{-1}.

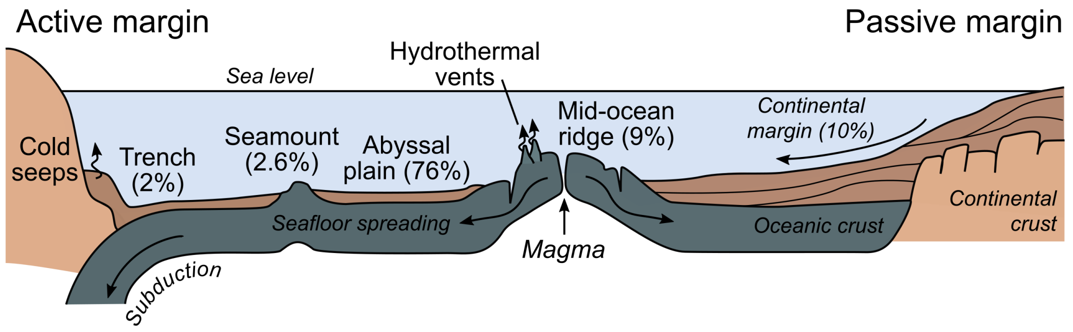

Figure 2.4 *– Schematic summary of ocean basin features and processes, indicating percentage cover of seafloor (percentages from Ramirez-Llodra et al., 2010)*

At MORs, upwelling magma erupts through the seabed and forms new oceanic crust, which is subsequently pushed away. This process, known as seafloor spreading, is associated with intense tectonic activity along the main MORs and at transform faults, which offset ridges laterally. Cold seawater percolates into the crust at the fractured flanks of MORs, where it is heated at depth, leaches metals from the surrounding basalt, and rises to emerge at the seabed, where hydrothermal vents are formed by the precipitation of leached components.

Chains of volcanoes are formed at rising magma hotspots, or at convergent oceanic boundaries. Underwater volcanoes may not grow to reach the sea surface, in which case they are known as seamounts, or may have been previously emergent and eroded to form a flat top, in which case they are known as guyots. Seamounts and guyots are pervasive features of the seafloor; they are estimated to comprise 4.7% of its surface (Miller et al., 2018) and there are over 14,500 structures higher than 1 km and over 30,000 in total (Watts, 2019).

The subduction and melting of dense, basaltic oceanic crust beneath lighter, granitic continental crust at active margins compensates for the creation of new seafloor at MORs. As a result, the oldest known oceanic crust is just 180–200 Myr, although a portion possibly aged ~340 Myr has been identified in the eastern Mediterranean Sea (Granot, 2016). Meanwhile, at passive margins, continental sediments eroded from land are transported into the oceans to form the low-angled continental slope. Canyons incising the continental slope act as conduits for this material. Instability resulting from this buildup of sediments produces massive flows of material into the deeper ocean, known as turbidites, which ultimately deposit a smooth, flat layer of sediment that blankets the underlying basement. This layer forms the abyssal plains, which dominate the deep seabed – as can be seen in the hypsographic curve (Figure 2.2). A continuous rain of largely biogenic sediment originating from pelagic marine organisms also contributes to the buildup of deep-sea sediments, which are mostly terrigenous clays and calcareous ooze, and typically build up over 10–100s millions of years at slow rates of 0–10 m Myr^{-1} (Olson et al., 2016) while undergoing compaction and lithification. As a result, extensive, often continuous marine sedimentary sequences are preserved in the geologic record (Seibold and Berger, 2017).

Active and passive continental margin sediments are another important feature of the seafloor, and often host large quantities of mineral resources. However, this thesis focuses on the deep seabed, so continental sediments are not discussed further.

2.2 Deep-sea sediments and biogeochemistry

Lessin et al. (2018) mention the three main roles of the benthic (seabed) environment within marine systems: as the 'transfer zone between the biosphere and geosphere'; as a habitat for diverse organisms; and as a modulating component in marine cycles of carbon, nutrients and trace elements. These cycles are complex, with many unknowns.

In a typical model, the deep seabed mostly receives organic matter (OM) vertically from exported photosynthetic biomass originating in the photic zone, much of which is carbonate skeletal material or packaged in faecal pellets, particle aggregates and faunal carcasses. Smaller quantities of OM are transported laterally from the continental margins. Due to efficient recycling and consumption of OM by heterotrophs in the water column, a minimal proportion reaches the deep seafloor (~5%). Due to low accumulation rates of biogenic and lithogenic organic material, and corresponding long oxygen exposure times, the majority of deposited OM is remineralised, so that only ~0.1% is buried and preserved within deep-sea sediments. Remineralisation of OM releases nutrients into the water column, making them available to pelagic fauna, while OM burial effectively sequesters carbon originating from the atmosphere into deep-sea sediments; in this way, the deep seabed acts as a carbon source and sink.

At abyssal zones, the deep seabed environment is highly sensitive to the vertical supply of particulate OM, and thus to phytoplankton activity at the surface ocean. Sinking aggregates of OM can reach the deep seabed rapidly, even within 6 weeks (Thiel et al., 2001), where the supply can reflect seasonal patterns of surface primary production. The availability of food for organisms at the deep seabed was previously thought to be perpetually limited, based on the quantity of OM measured at the seabed; it receives just 1 g carbon per m^2 per year from sedimentation. However, molecular studies have revealed that a higher fraction of OM in deep sea environments is in a digestible form, compared to this fraction in coastal environments (Danovaro et al., 2014). Life is also sustained at the deep seabed in reducing environments by chemical energy sources, which provides an important carbon fixation mechanism. However, the overall proportion of OM from sources other than the photic zone is unknown.

Benthic fluxes

The fields of sedimentary biogeochemistry focus more closely on benthic fluxes at the sediment–water interface, that is, the mass transport of solutes, fluids and particulate matter through the porous seabed. According to Lessin et al. (2018):

> *The benthic–pelagic boundary is often simplistically regarded as a discontinuity, the interface between a completely fluid, dynamic water column and a rigid, porous benthic system. The reality is a spatially and temporally varying dynamic bottom boundary layer characterised by strong physico-chemical gradients.*

This bottom boundary layer (BBL) is characterised by the presence of reactive OM and constant mixing, and is usually defined as the upmost metre (Jørgensen and Boetius, 2007). Deep ocean waters, which are typically oxic, are mixed into the BBL by burrowing animals in the seabed. The oxygen present in this upper layer is then reduced in microbially catalysed reactions that degrade OM. As a result, nutrients are made available to the microbial community, which in turn supports meio- and macrobenthos at the seabed. Below the mixing depth, as depleted oxygen is not replaced, nitrate, oxidised manganese and iron, then sulphate, and bicarbonate are successively used as electron acceptors at increasing depth in the anoxic zone.

Aller (2014) explains how early conceptual models of benthic reaction and transport devised in the 1950s adopted a one-dimensional approach, with deposits 'modelled as laterally homogeneous bodies, diffusively and advectively open to exchange of solutes and particles… and accreting upward in the vertical dimension' (Figure 2.5(a)). However, models must also take into account disturbance by burrowing benthic fauna, which rework and irrigate solid particles (bioturbation) and solutes (bioirrigation) generally in the upper 10–50 cm of sediment, but occasionally to depths of several metres (Figure 2.5(b)), and episodic lateral transport of sediments by turbidites (Figure 2.5(c)). These processes introduce significant heterogeneity into the sediment and necessitate two- or three-dimensional modelling, as burrows increase surface area within the seabed, across which solute exchange and reaction may take place. As such, underestimating the effects of burrowing has a significant effect on global flux estimates.

These sensitive flux processes typically occur at scales of micro-to-millimetres and seconds to minutes, within the top few metres of sediment. This presents a great challenge to researchers to observe and measure benthic reactions in situ or to recreate them in the laboratory. As a result, benthic systems are under-represented in biogeochemical and ecosystem modelling, despite their powerful influence on benthic fluxes through structuring and circulating components through the seabed.

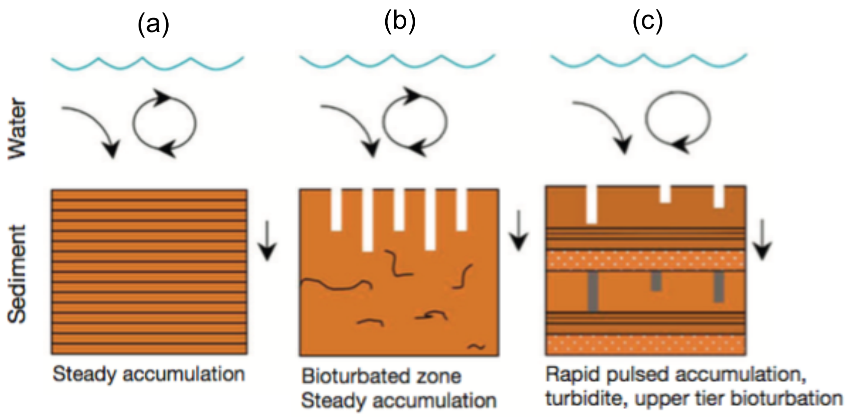

***Figure 2.5** – Benthic transport models. (a) Steady vertical accumulation; (b) steady vertical accumulation with bioturbated surface; (c) episodic sedimentation by turbidites, and stable bioturbation. From Aller (2014)*

However, new sampling technologies and computational techniques are facilitating higher-resolution models that take into account small-scale heterogeneity, biological transport (i.e. bioturbation and bioirrigation), episodic events, and dynamics of the benthic–pelagic boundary layer (Lessin et al., 2018).

2.3 Characteristics of benthic fauna

Below the taxonomic level of phyla, deep-sea faunal composition is distinct from that of the upper ocean (Ramirez-Llodra et al., 2010). Extreme conditions at the deep seabed, namely low temperature (-1–4°C), high pressure and a total lack of light, have traditionally been considered as environmental limitations that dictate the general characteristics of deep-sea fauna – that is, long-lived and slow-growing, with slow metabolisms; all factors that make them vulnerable to rapid environmental changes. However, due to its significant heterogeneity at all spatial scales, the deep seabed is now known to host high biodiversity, with specialised and often endemic faunal communities (Zeppilli et al., 2016). Although the majority of the seafloor experiences food limitation, bathymetric features such as MORs and seamounts represent sites of exchange with the geosphere and local disturbances to basin-scale oceanographic conditions, and therefore constitute hotspots of biodiversity.

Sediments cover the majority of the abyssal plains and provide soft substrate for organisms to dwell within (infauna) or on the surface (epifauna). Fauna are also classified as mega (cm–m), macro (cm), meio (mm) and micro (µm), and impact sedimentary systems at corresponding scales. Heterotrophic megafauna at the seabed are dominated by scavenging organisms, known as detritivores, which consume OM and larger animal carcasses that sink from the water column, as in the case of whale falls. In areas with hard surfaces, filter feeders consume particles swept past by currents. Meanwhile, symbiotic chemosynthesis constitutes an aphotic form of primary productivity at vents and cold seeps where abundant inorganic energy sources are available, mainly methane, hydrogen sulphide and iron.

Thriving microbial communities have been found in all sampled marine sediments, including at the deep seabed; cell counts in seabed sediments contain 10- to 10,000-fold more cells per unit volume than productive surface waters across the sediment–water interface (Jørgensen and Boetius, 2007). Bacteria and archaea orchestrate chemical cycling in deep-sea sediments, and microbial life has been observed to depths of 2.5 km below the seabed, in sediments up to 100 million years old. Extrapolations through the deep biosphere, using the upper theoretical temperature limits for microbial life (100°C) and the geothermal gradient (20–40°C km^{-1}), have calculated that microbial cells in the deep biosphere may account for over half of all microbial life in the ocean (Jørgensen and Marshall, 2016). However, the diversity and distribution of bacteria and archaea through the seabed are largely unknown.

Although wider scale patterns of deep-seabed biodiversity may be unresolved, studies focussing on particular ecosystems are beginning to elucidate their faunal dynamics (Ingels et al., 2016). For instance, hydrothermal vents are characterised by extreme conditions, even compared to standard deep-sea environments, reaching temperatures up to 400°C and pH 2–3. Although they are hotspots of biomass, diversity tends to be low, as a few highly specialised species dominate, most of which are endemic to vent environments. Large faunal communities are based on microbial chemoautotrophs, hosted symbiotically on larger benthic invertebrates such as tubeworms, mussels, clams and shrimp (Van Dover, 2014). These larger taxa form intricate 3D habitat structures, which offer shelter to microbes and juvenile invertebrates.

Seamounts also provide 'islands' of shallow seafloor in the open ocean, with exposed rock surfaces supplying habitats for attached benthic organisms. The physical presence of seamounts disrupts and redirects current flows, which causes mixing of water masses from the upper oxygen minimum zone (OMZ) with lower oxic water masses, resulting in oxidation and precipitation of nutrients. This is hypothesised to locally enhance biodiversity, resulting in higher primary productivity, endemism and species richness, according to the seamount oasis theory (Rowden et al., 2010). However, these theories have been challenged and more data is required to clarify seamount characteristics. Nevertheless, seamounts are known to support benthic and pelagic ecosystems, and to act as a site of connection between the two.

2.4 Seabed technology

The study of the seabed has historically been limited by technological ability to facilitate access and sampling. Even in 2010, less than 0.01% of the seabed had been sampled and subject to detailed study (Ramirez-Llodra et al., 2010). Human uses of the seabed have catalysed the development of such technologies, including the laying of pipelines for communications, developing infrastructure for offshore oil and gas operations, and scientific exploration.

The first samples were taken from the deep seabed during ship-based expeditions, with the first conducted specifically for research purposes by the HMS Challenger (1872–1876). Despite a period of systematic sampling, high biodiversity at the seabed remained unrealised until the 1960s, when the use of dredges and sledges enabled physical sampling. The use of submersibles then facilitated major discoveries such as hydrothermal vents and seeps in the 1970s and 1980s, and the use of images and videos to survey and document life. The ability to study the seabed remotely came with advances in communications and acoustic technology, which now permits the identification of complex habitat structures at the sub-metre scale, and in three dimensions. Developing molecular methods are allowing improved characterisation of phylogeny, connectivity and biodiversity.

This section provides an overview of state-of-the-art and developing technologies used to study the seabed.

Direct sampling methods

The development of box corers and epibenthic sledges enabled direct sampling of seabed sediments, before the advent of autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs) and submersibles enabled in-situ collection (Danovaro et al., 2014).

Traditional tools used to measure properties such as temperature, dissolved oxygen and salinity at the deep seabed include bottle samplers and sediment traps deployed from research vessels. These are now being replaced by sensors deployed across the oceans as part of the Deep Ocean Observing Strategy (Ramirez-Llodra et al., 2010).

Microsensors can be deployed by ROVs or divers to determine the variation of sediment properties with depth at the µm to mm scale, such as pH or nutrient concentrations, which are characterised by steep gradients and thus require sensitive measurements. At the cm scale, benthic chambers positioned on the seabed by ROVs incubate the underlying sediment while replicating currents. Continuous measurements are made to determine sediment–water flux of components such as oxygen, sulphide and pH levels.[2] Finally, eddy correlation methods provide a more robust measurement over larger areas, up to several m^2, by replicating turbulence to measure oxygen flux through the sediment–water interface.

However, new micro-scale methods and time series studies are needed to study the seabed as a continuous benthic–pelagic interface, to accurately account for its contribution as a global nutrient source and carbon sink (Lessin et al., 2018).

Remote mapping and observation

Bathymetry refers to the topography of the seafloor, which 'directly and indirectly influence[s] most ocean environmental conditions', including 'light penetration, sedimentation, and current direction and velocity and thereby temperature, stratification, and oxygen concentration' (Costello et al., 2010). This makes it equivalent to onshore topography as a driver of environmental conditions and species distributions.

Topography on land can be directly mapped using radar from satellites; however, electromagnetic waves cannot penetrate water, so this technique cannot be used to map bathymetry (Calmant et al., 2002). The most accurate way to map seabed bathymetry is acoustically, whereby ship-based multibeam sounding is directly used to produce high-resolution maps of local seabed features <100 m in size. However, this is a time-consuming process that is complicated by acoustic scattering from the seabed due to dynamic processes within and below the sediment–water interface (Anderson, 2007). Accordingly, global-scale bathymetric maps are instead produced with the use of satellite-hosted radar altimeters, which map gravity anomalies above or below the equipotential ellipsoid of the sea surface (which approximates the geoid). These anomalies reflect kilometre-scale topographic variation of the seabed beneath, which in turn exerts gravitational effects on the overlying mass of the water column. Accordingly, a map of sea surface gravity anomalies can be used to produce a coarse bathymetric map. These measurements are calibrated using acoustic sounding measurements where available (Wölfl et al., 2019).

[2] 'Benthic chamber module', Max Planck Institute for Marine Microbiology, https://www.mpi-bremen.de/en/Benthic-Chamber-Module.html (accessed 2 February 2020)

The use of acoustic and satellite altimetry methods in tandem is vital to overcome their individual limitations. One limitation of the altimetry method is that large-scale features interpreted from altimetry data can in fact reflect extinct structures buried below several kilometres of sediment. If composed of dense basaltic oceanic crust, these features can exert sufficient gravitational effects on the sea surface – even through the overlying sediments – and thus appear as the present-day seafloor. A map of the same area produced using acoustic sounding would not reveal such a feature. Hence, a comparison of images produced by the two methods can be used to identify such buried structures that provide information on wide-scale tectonics, although this relies on accurate discernment of seafloor and buried structures (Wille, 2005).

Although the ability to view bathymetry at higher resolution has transformed perceptions of the deep seabed, accurately calculating it remains a challenge. Costello et al. (2010) developed a numerical method to obtain seabed surface, sea surface and volume estimates from an earlier altimetric map by Smith and Sandwell (1997). Costello et al. calculated that 71.2% of the seabed has a slope of <1°; and that only 4.5% of the seabed has a slope of >6°. They note that more extreme slopes of up to 90° were underestimated by altimetry techniques, but Costello explicitly remarks that 'the seabed is flatter than often portrayed' (Costello, personal communication, 20th November 2019). Meanwhile, Danovaro et al. (2014) analysed bathymetric data from 200–6,000 m depth in 200 m increments, to produce an estimate of total deep seabed area some 20% higher than previous orthogonal projections.

Overall, the inconsistent application of mapping techniques provides a fragmented, incomplete view of seafloor bathymetry. Many new initiatives, particularly the Nippon Foundation-GEBCO Seabed 2030 Project, are now encouraging an acceleration in seabed mapping efforts to enable the identification and monitoring of resources, habitat mapping, protection of marine species and understanding of basin-scale tectonics, among other applications (Wölfl et al., 2019). The Seabed 2030 project aims to produce a complete open-source map of the seabed by 2030. In a paper introducing the project, Mayer et al. (2018) consider at what resolution the seafloor should be mapped: 'ideally, one would want a resolution commensurate with that at which our land surfaces are mapped (sub-meter resolution)'.

Soundscape ecology is an alternative method proposed to map benthic environments at the habitat scale. Hydrophones may be used at, for example, hydrothermal vents to record unique, habitat-specific 'soundscapes' composed of geophony (e.g. vent emissions) and biophony (e.g. marine fauna). In turn, long-term recordings can be used to assess ecosystem health and disturbance by sound from human activities, or 'anthrophony' (Lin et al., 2019).

Seabed classification and visualisation

The use of direct imaging techniques, which enable the precise study and classification of discrete seafloor areas, accompanied the rise of ocean observation and environmental impact assessment (EIA) in the 1990s (Anderson, 2007). Acoustic and spectral tools are now routinely applied to potential sites of resource extraction for prospecting and environmental protection purposes alike, particularly in shallow waters. As with bathymetric mapping, the lack of light below the photic zone and the ability of seawater to absorb most wavelengths of the electromagnetic spectrum complicate the possibility to image deep seabed environments from a distance. Therefore, ROVs and AUVs have been developed to do so without causing any disturbance to the seafloor. In this way, standard cameras and video equipment aided by lighting systems have been used to image transects and photographic surveys of the deep seabed (Vanreusel et al., 2016; Simon-Lledó et al., 2019b).

While spectral imaging typically relies on the visible frequencies of light, in environments where these are unavailable hyperspectral imaging makes use of non-visible bandwidths. Dumke et al. (2018a, 2018b) published the first hyperspectral images obtained from the deep seafloor, which show an area of seabed close to an experimental SBM area (DISCOL, see section 3.2) at a depth of 4,195 m and a very high spatial resolution of 1 mm per pixel. Sediments, minerals and megafauna defined as objects of interest were identified through visual inspection of video footage, and their spectral profiles were subsequently used to train a Support Vector Machine method. This allowed the identification of objects from hyperspectral imagery. The authors noted that more fauna could be identified and classified using this technique, reporting an accuracy of >90%, than by visual identification from video footage.

Optical techniques are also used to produce images of seabed environments that can be used for further study. Images acquired by AUVs can be stitched together to produce a 2D mosaic of the seabed, which can be draped over a bathymetric map to give the illusion of a 3D image. Images can also be combined using photogrammetry techniques to directly replicate seabed geometry (Kwasnitschka et al., 2016).

Furthermore, bathymetry can be visualised on a global scale using new 3D technology. For example, Sandwell et al. (2014) most recently produced a global bathymetric model using altimetry data, which can be viewed on a 3D globe where vertical scaling can be manipulated (Figure 2.6(a)). The authors also present example views produced using the tool (Figure 2.6(b)).

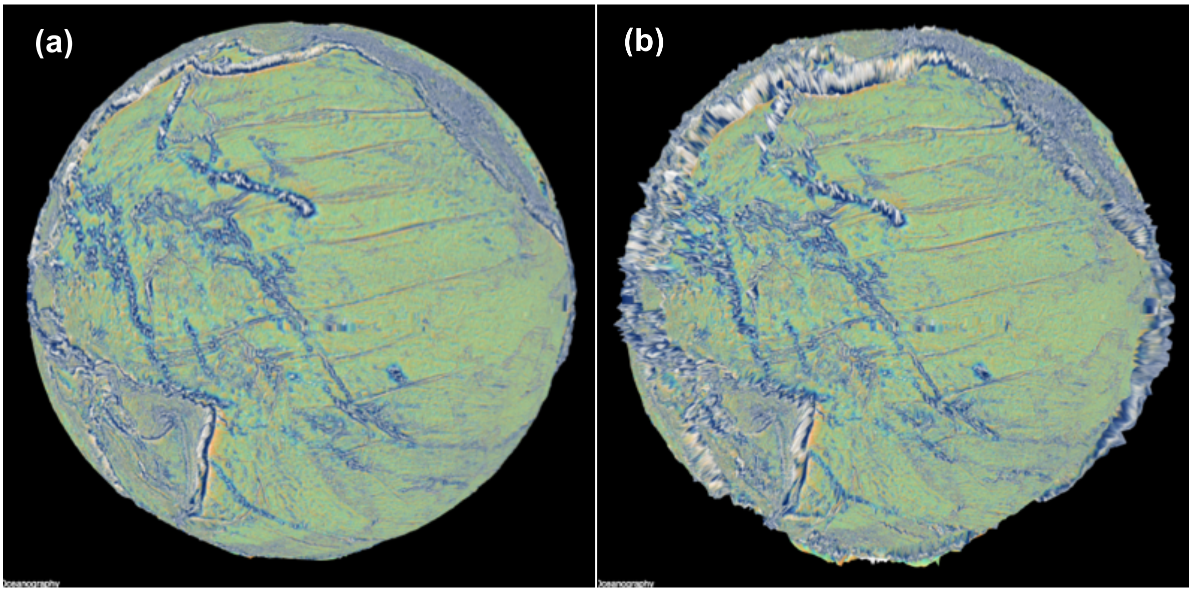

Figure 2.6 *– Global bathymetric model produced using satellite altimetry, (a) displayed on a 3D globe. (b) Example of vertical scale manipulation. From Sandwell et al. (2014), http://portal.gplates.org/portal/vertical_gravity_gradient/*

The oil and gas industry have used seismic technology since the 1970s to image strata below the seabed at selected sites of exploration and production, and are now able to use virtual reality (VR) techniques to view high-resolution 3D models. A single isosurface, often a stratum, can be isolated and explored within an immersive data viewing suite, where scientists can rove around its surface and choose to overlay various properties.[3] In contrast, the creation of 3D subsurface models by the onshore mining industry largely relies on interpolation between borehole datapoints (Turner, 2006). In addition, VR techniques are being employed by marine research institutes to view 3D renderings of deep-sea environments constructed by photogrammetry. This enables the scientific study of such environments on land,[4] and facilitates immersive experiences for the public.[5]

[3] See: https://www.shell.com/energy-and-innovation/overcoming-technology-challenges/finding-oil-and-gas.html

[4] 'From science fiction to (virtual) reality in deep-sea research', Monterey Bay Aquarium Research Institute, 7 February 2018, https://www.mbari.org/underwater-virtual-reality/ (accessed 12 January 2020)

[5] 'Virtual Deep Sea: 3D-dive to the sea floor', MARUM, https://www.marum.de/en/Discover/Virtual-Deep-Sea.html (accessed 12 January 2020)

2.5 Human activities

The finding of 'a plastic bag and sweet wrappers' on the seabed of the Mariana Trench at 10,927 m depth, by the deepest recorded submersible dive,[6] made headlines as a symbol of the reaches of human pollution into the oceans. However, the deep seabed has long been the ultimate destination for many forms of waste. These include land-sourced chemical pollution and physical debris; lost cargo and discarded fishing equipment; toxic, radioactive and terrestrial mining waste; and operational and accidental pollution from oil and gas development. The location of observation equipment, pipelines and other human infrastructure at the deep seabed also impact the surrounding environment. In addition to these visible forms of pollution and damage, awareness is growing of hazards posed to the deep seabed by increased atmospheric CO_2 levels, which will affect temperature, pH level, oxygen and OM in the deep sea (Levin and Le Bris, 2015)

The individual and cumulative impacts of human activities have the potential to do irreversible damage to deep seabed ecosystems (Mengerink et al., 2014). However, due to a lack of available data, the deep sea was the ecosystem with the fewest reported impacts due to climate change in the recent IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Pörtner et al., 2019).

With growing access to and knowledge of the deep seabed comes greater awareness of human-led impacts affecting its environment and ecosystems. This has led to scientists calling for conservation and more sustainable use of the deep sea and seabed, in addition to the need for more data at greater spatial and temporal ranges, and further collaboration between researchers. Observation efforts are currently being led by the Deep Ocean Observing Strategy (DOOS) under the auspices of the Global Ocean Observing System (GOOS). The DOOS promotes coordination between research bodies and aims to enhance the coverage of deep-sea observations through regional, interdisciplinary projects. Levin et al. (2019) likewise call for more integrated research efforts in the deep-sea environment, particularly regarding continuous and long-term observations. Clearly, documentation and understanding of the deep seabed is vital in view of the threats produced by human influence.

The emerging deep-sea mining industry is one such influence which poses a direct and significant risk to the deep seabed. Although it has been discussed for decades, the possibility of mining operations commencing appears to be approaching, and a variety of seabed environments and geological settings are poised to host extraction. Therefore, it forms the central subject for the remainder of this thesis.

[6] 'Mariana Trench: Deepest-ever sub dive finds plastic bag', BBC News, 13 May 2019, https://www.bbc.co.uk/news/science-environment-48230157 (accessed 22 January 2020)

3. Seabed mining

Seabed mining (SBM), or deep-sea mining, refers to the extraction of economically valuable minerals at the seabed. The term covers a variety of minerals found in numerous geological settings, but primarily refers to manganese nodules, seafloor massive sulphides and cobalt-rich crusts. Seabed mineral deposits were first found by the Challenger Expedition (1872–1876), when manganese nodules were recovered from the Pacific, Indian and Atlantic Oceans.[7] Technological limitations delayed access to the seabed and ideas of commercial development until the 1960s, when views of the deposits changed from interesting geological oddities to resources with economic potential. Technical investigations began in the 1970s as exploratory cruises were commissioned, areas were claimed and mining technology was developed by national agencies. With the discovery of hydrothermal vents in the late 1970s came the prospect of seafloor massive sulphides as potentially mineable deposits, followed by cobalt-rich crusts in the 1980s, when large-scale environmental studies on the impacts of SBM began to be funded and pursued. Although research and development efforts continued, interest in SBM had waned by the end of the 1990s due to low global metal prices (Hein et al., 2013).

As discussed in the previous chapter, technology used to explore and image the deep seabed has continued to develop since these discoveries. Renewed economic interest in SBM from governments and private mining operators comes as scientific studies on deep seabed environments have expanded their reach and findings, thereby propelling resistance to SBM on an environmental basis. The legal regimes for the deep seabed and specifically for SBM have developed alongside these scientific and economic interests, and are currently grounded in UNCLOS III. Underlying historical and current interest in SBM is a complex interplay of legal, scientific and economic factors, as reflected in the number of publications on the topic over time (Figure 3.1).

This chapter first introduces the three main seabed mineral types, including their geological settings, distribution, formation and associated ecology. This is followed by reported impacts of SBM operations and implications on the deep seabed environment, and a brief analysis of the developing regulatory framework.

[7] 'Treasures of the abyss', Geoscientist Online, https://www.geolsoc.org.uk/Geoscientist/Archive/May-2013/Treasures-from-the-abyss (accessed 17 February 2020)

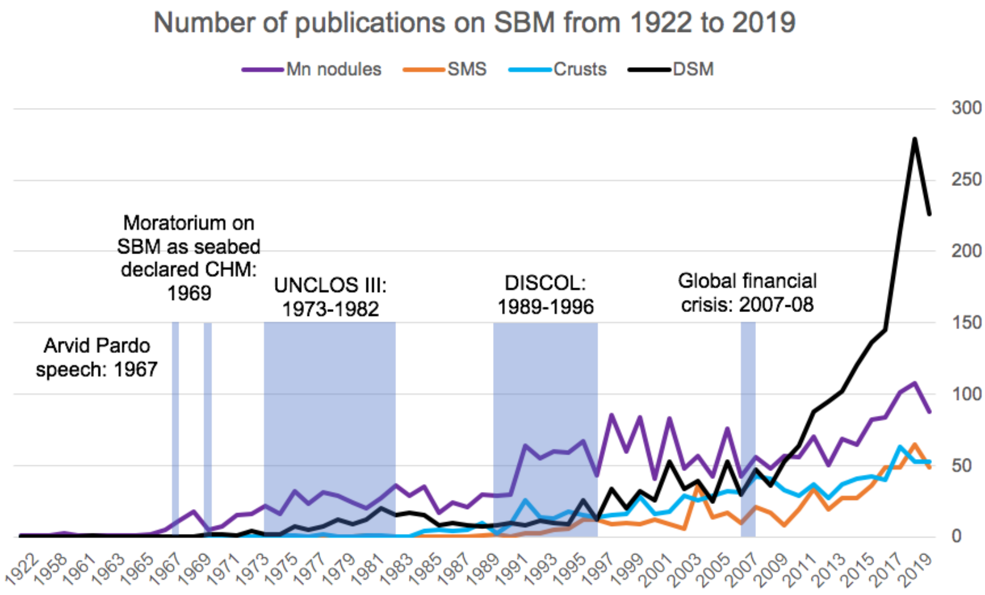

Figure 3.1 *– Number of publications per year found in all Web of Science database records, as of 11 December 2019. Search terms used for* ***Mn nodules****: 'manganese nodules' or 'polymetallic nodules', for* ***SMS****: 'seafloor massive sulphides' or 'seafloor massive sulfides', for* ***CRCs****: 'cobalt-rich crusts' or 'ferromanganese crusts', for* ***SBM:*** *'deep-sea mining' or 'seabed mining'*

3.1 SBM deposit types

As mentioned, SBM deposits of commercial interest are typically classified into three main types, which are distributed throughout the global oceans (Figure 3.2). In answer to research question 1 ('what is the nature of SBM deposits at the deep seabed?') this section explores the tectonic setting, formation and mineralogical composition, physical situation on or within the seabed, and typical ecosystems associated with each type, in addition to current knowledge gaps. The main findings are then summarised in Table 2.

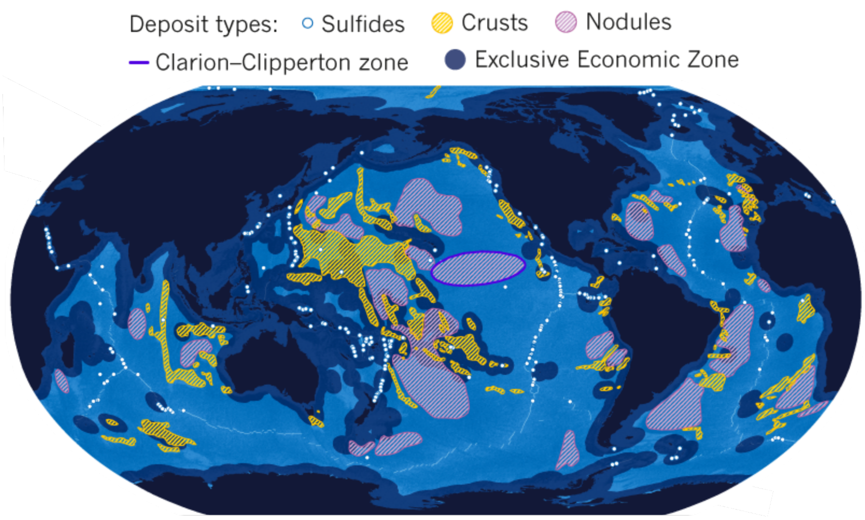

Figure 3.2 *– Global distribution of SBM deposit types (Heffernan, 2019)*

Manganese nodules

Manganese (Mn) nodules have received the most attention, have the longest research history (Figure 3.1) and are thought to hold the greatest economic promise of the three main deposit types (Hein et al., 2013). They primarily consist of Mn, Fe, Cu, Co and Ni, and may be enriched in trace metals and REEs. Nodules are found on the abyssal plains at depths below 4,000 m, where nodule-rich areas, often referred to as 'fields', can extend over thousands of square kilometres. Nodule concentrations of economic interest are located at the Clarion–Clipperton Zone (CCZ) in the north-central Pacific Ocean; in the exclusive economic zones (EEZs) of southern Pacific islands; in the Peru Basin of the south-east Pacific Ocean; and the central Indian Ocean (see Figure 3.2). Most research on nodules has been conducted at the CCZ, which is considered representative of most abyssal plain environments, and where the strongest knowledge base of any SBM deposit type is said to be situated (Petersen et al., 2016).

Individual nodules are potato-shaped, 4–12 cm in diameter and partially embedded in the sediment (Figure 3.3), which is typically oxic to a depth of at least 2–2.5 m (Blöthe et al., 2015). Nodules grow slowly at rates of 1–10 mm 10^{-6} years, mostly hydrogenetically, whereby minerals precipitate from ambient seawater, and/or diagenetically, with minerals sourced from underlying sediments and pore water. Mn present in seawater, sourced hydrothermally, attracts positively charged ions such as Ni, Cu and Co to its oxide surface; while seawater Fe sourced from terrigenous sediments attracts negatively charged ions such as REEs to its oxide surface. With their scavenged ions, the electrostatically charged Mn and Fe oxides attract and join abiotically to form colloids, which in turn accumulate around a nucleus such as a fragment of rock or old nodule in concentric layers. Incorporation of the oxides into the nodule matrix is thought to be microbially mediated (SPC, 2013a; Mewes et al., 2014).

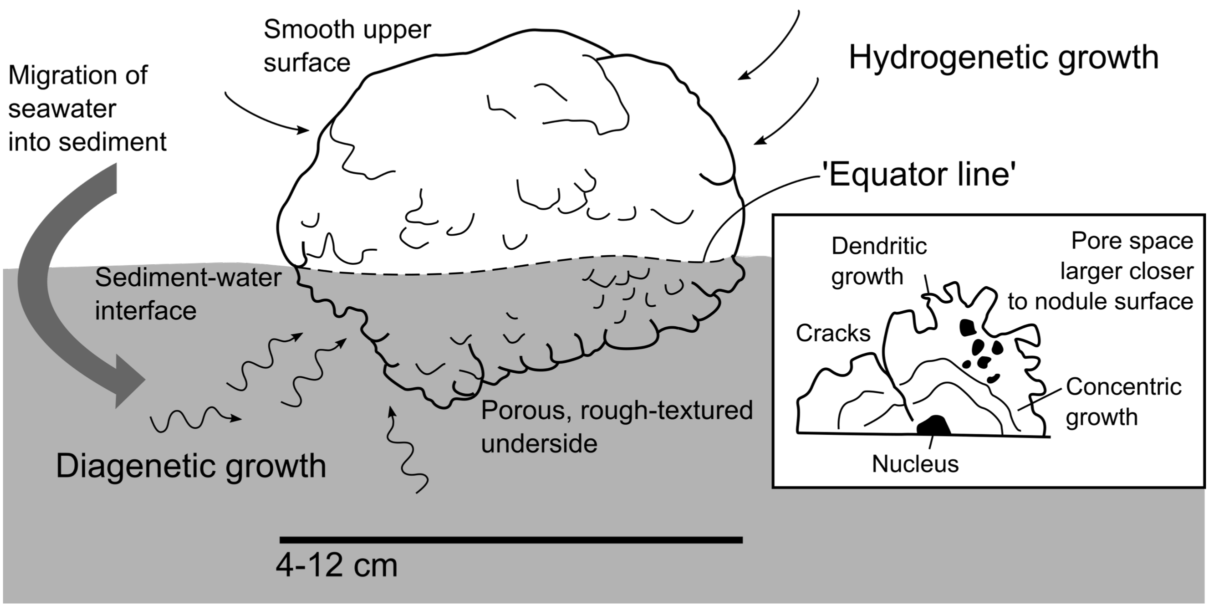

***Figure 3.3** – Schematic illustration of Mn nodule formation and situation at the seabed*

Low local sedimentation rates of < 5 mm kyr^{-1} are essential for nodule formation, to prevent growing nodules from becoming submerged and to leave pieces of debris exposed as nuclei for precipitation. As noted in section 2.1, abyssal plains are typically covered by sediment transported from higher bathymetry. However, this is less the case for plains at the CCZ, due to the low input of terrigenous sediment in the area (Mewes et al., 2014), thus making it conducive for nodule formation. Also beneficial is the presence of currents at the seabed – strongly impacted by local bathymetry – that sweep away fine particles, and the active presence of burrowing organisms, which are thought to maintain nodule positions in the upper part of the sediment (Vanreusel et al., 2016).

Nodule-rich areas are known to support higher biodiversity than nodule-free abyssal plains. Nodules provide some of the only hard substrate in the abyssal environment, and thus encourage unique species assemblages within the surrounding sediments, in addition to on and within the nodules themselves. For instance, fauna attached directly to nodule surfaces can comprise 60–70% of total faunal abundance in nodule-rich areas (Simon-Lledó et al., 2019b). Furthermore, a connection has been proposed between the topography-driven current variations favourable to nodule formation, and the increased delivery of OM and nutrients needed to support such a diverse ecosystem (Simon-Lledó et al., 2019b). Indeed, parts of the CCZ seabed featuring higher particulate organic carbon flux have been found to sustain higher levels of faunal abundance and biomass (SPC, 2013a).

Nodules at the CCZ have been observed to support a significantly enriched community of mobile and sessile epifauna, especially suspension feeders, compared to nodule-free areas (Vanreusel et al., 2016). Small sponges, molluscs and encrusting bryozoans have been found attached to nodules, with nematode worms and crustacean larvae found within nodule crevices (SPC, 2013a). At the micro-scale, nutrients, molecular oxygen and dissolved metals penetrate and circulate through nodules themselves, by way of cracks and connected pore space within (see Figure 3.3 inset), with the latter observed to reach 26–61 vol%. A complex closed system of Mn-cycling microbial communities has been found within this pore space. This diverse microbial community within nodules is distinct from that of the surrounding sediment, and both are enriched compared to the average level of deep-sea microbial abundance (Blöthe et al., 2015).

In summary, Mn nodules represent high seabed heterogeneity at the CCZ and constitute a unique habitat for diverse micro to megafauna, including within, on and around nodules. However, their inaccessibility has made them difficult to study, and the majority of studies have been conducted at the CCZ, leaving other nodule provinces poorly understood. Mapping and visualisation techniques are crucial for exploration, to identify nodule distribution and abundance in target areas prior to sampling.

Seafloor massive sulphides (SMS)

SMS are deposits of hard mineral-bearing substrate chiefly composed of sulphides and metals. They were discovered in 1979 and exploration began in the 1980s; they were even included in global SBM resource estimates prior to the discovery of hydrothermal vent systems that hosted them (Boschen et al., 2013). Exploration for SMS deposits has increased in the past two decades as mining companies seek to secure early mover advantages; in this way, the progression of SMS exploration follows the early peak of activity that surrounded Mn nodules in the 1980s (Hoagland et al., 2010).

The deposits are located throughout the world's oceans at various tectonic settings, particularly at plate boundaries, but mostly at active or inactive hydrothermal vents associated with MOR systems. Deposits have been found at a wide variety of MOR settings, at variable spreading rates, and with high variation in mineral composition; there are an estimated 6 $x10^8$ tonnes of SMS worldwide (Hannington et al., 2011). Large SMS deposits may extend over hundreds of metres, and form where the bathymetric and sedimentary configuration permits them to accumulate over 10^3–10^4 years. Over 200 sites of hydrothermal mineralization are known on the seafloor, with around 10 having a sufficient grade and tonnage to be considered for SBM (Miller et al., 2018), and many located in shallower waters in the Pacific region. The best studied SMS prospect is the Solwara 1 deposit, in the EEZ of Papua New Guinea, where the first commercial mining license was granted in 2011.

The deposits have the lowest exploitation potential of the three SBM forms (Petersen et al., 2016). They are formed at or below the seabed by minerals precipitated from hydrothermal fluids (see Figure 3.4). Seawater penetrates up to several kilometres into the seabed through cracks and percolation through sediments. At depth, it is warmed by heat generated from magma, or even by direct mixing with enriched magma. As the seawater reaches high temperatures it leaches metals from the surrounding sediments and begins to rise buoyantly towards the seabed as hot, acidic, reduced hydrothermal fluid bearing dissolved sulphur and metals. As this fluid reaches the seabed it emerges back into contact with cold seawater, causing minerals to precipitate on the seabed at the site of emission, or to be transported laterally in a hydrothermal plume. Sulphide minerals, including copper and zinc sulphide, accumulate to form chimneys and mounds. They may also precipitate within the seabed, although far less is known about sub-seabed SMS deposits as they are difficult to sample (SPC, 2013b).

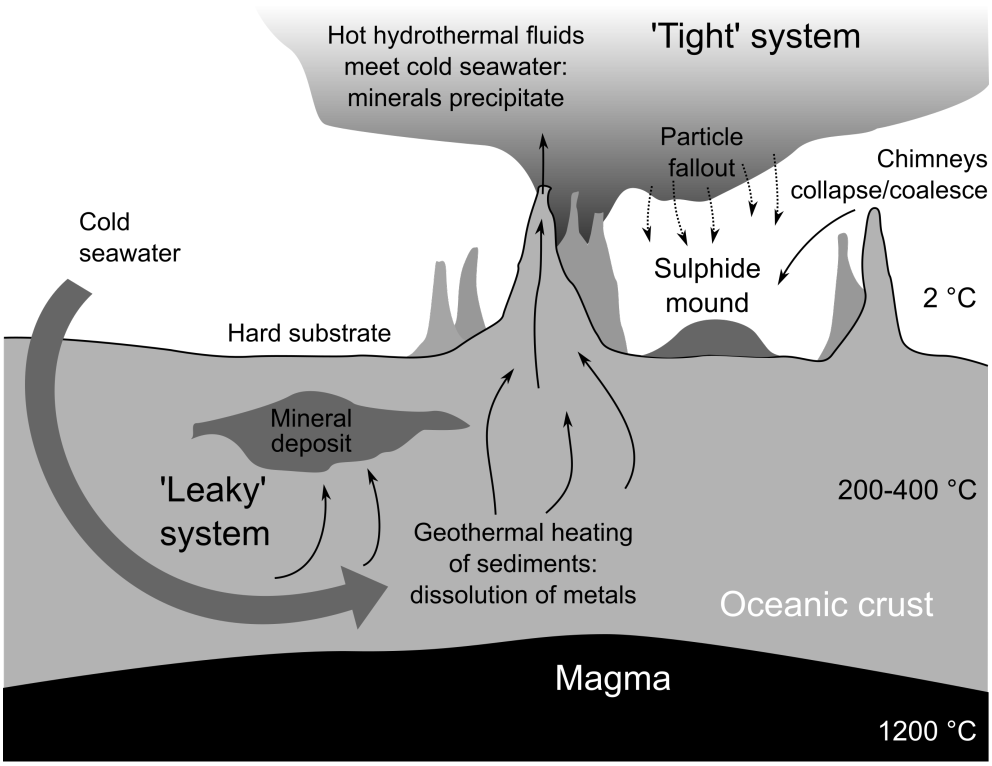

Figure 3.4 *– Schematic illustration of SMS formation and situation at the seabed*

SMS deposits have high sulphide, Cu, Au, Zn, Pd, Ba and Ag contents, although compositions vary widely depending on host rock, fluid temperature, and secondary weathering, among other factors. Some SMS deposits contain very low quantities of minerals of economic interest. However, the accurate quantification of SMS deposits is challenging; distinguishing between active and inactive vents can be challenging, since they are often found together, and although active systems can be identified by plume signal detection, many inactive systems are thought to be undiscovered (Boschen et al., 2013).

Hydrothermal vent environments are found at 1,000–4,000 m depth, with high temperatures reaching 400 °C and highly acidic (pH 2–3) conditions. They host unique ecosystems based on chemosynthetic bacteria, which utilize the metal- and sulphide-rich vent fluids as an energy source. These specialised microbes have made vent environments important for studies on the origin of life (e.g. Martin et al., 2008). Active vent systems have a relatively low diversity but high biomass, with many organisms existing in symbiosis with chemosynthetic bacteria. Species must adapt to variable temperature and chemical conditions within individual vent environments, which are often isolated, in addition to spatial changes in fluid emission and even volcanism at active sites. As a result, site-specific species assemblages are common. Furthermore, parts of a single vent system may be active while other parts are inactive; this arrangement may be changeable with volcanic or tectonic activity. Such ephemeral, variable local conditions require that vent fauna are tolerant or adaptive. They are also highly specialised; at least 600 species are endemic to vent environments (SPC, 2013b). On a wider scale, the tectonic isolation of some vent environments has led to the development of highly specialised communities over millions of years. Locally, species composition exhibits zoning within the <100 m central vent area, for instance within and between chimneys, and through the surrounding <1,000 m distal zone in a 'halo effect' (Boschen et al., 2013).

Inactive vents also support communities of largely sessile, slow-growing filter feeders that benefit from the shelter and hard substrate that SMS provide, in addition to infauna within sediments at a distance from active vents, which are supported by the active vent communities nearby; however, these communities are poorly understood (SPC, 2013b). A third faunal community adapted to the weathered deposits of vent systems has also been hypothesised (Van Dover, 2000).

Links between faunal populations at vents have not been fully determined, and many species remain unknown; new species findings continue with the exploration of vent systems (Van Dover, 2011). Due to the high geological, geochemical and ecological variability within, and between, vent systems at local and regional scales, knowledge of SMS deposits remains limited.

Cobalt-rich crusts (CRCs)

Defined as mineral-rich crusts that grow on hard, rocky seabed substrate free of sediment, CRCs are found throughout the ocean at disturbed topography, including ridge and seamount flanks and summits. Most potentially valuable concentrations are situated at 800–2,500 m depth, as Co and Ni are enriched here compared to deeper waters (Hein et al., 2009). The seamount chains and extinct volcanoes of the western and central Pacific host particularly large deposits, so that rich CRC deposits are found in the EEZs of numerous Pacific islands; however, they are less common in the Atlantic and Indian Oceans (SPC, 2013c).

Crusts are primarily composed of Mn and Fe, with valuable Co, Cu, Ni, Pt and REE content due to the enrichment of minerals in seawater that results from upwelling forced over seamounts. Similar to Mn nodules, CRCs form via hydrogenetic precipitation of minerals in seawater (see Figure 3.5) which takes place as hydrated ions react to form larger colloids, and is thought to be microbially mediated (Halbach et al., 2017). Furthermore, microbes are thought to encourage crust growth by providing nuclei through biomineralization processes (Orcutt et al., 2020). Crust components are sourced from particulate and dissolved minerals, in addition to carbonate skeletons of plankton transported in faecal pellets. The formation of crusts is thus intimately related to local redox conditions and the availability of organic material, and depends on a complex combination of factors: at the local scale by the small-scale relief of underlying substrate; and at the regional scale by seabed morphology, currents, subsidence and climatic factors (Halbach et al., 2017).

Crusts accumulate very slowly in layers of hydrated minerals below the OMZ under oxic conditions, which may be interrupted by hiatuses lasting up to 10–20 Ma (Halbach et al., 2017).

Therefore, episodes of suboxic conditions and diagenesis are recorded between crust layers. Their relief also follows the local topography of the underlying substrate, so that a crust surface may follow the form of a lava flow or boulder field, for example. The smoothness or roughness of crusts is a major driver of their potential for mining, due to the difficulty for vehicles to navigate crust terrain. The firm attachment of CRCs to underlying substrate also makes them technically challenging to mine, and the need to develop methods to detach crust without mining large amounts of waste rock beneath is likely to slow the development of crust mining beyond Mn nodule or SMS mining. However, well developed crusts on seamount slopes have been observed to detach in large 'plates' which slowly fragment and slide downslope (Halbach et al., 2017).

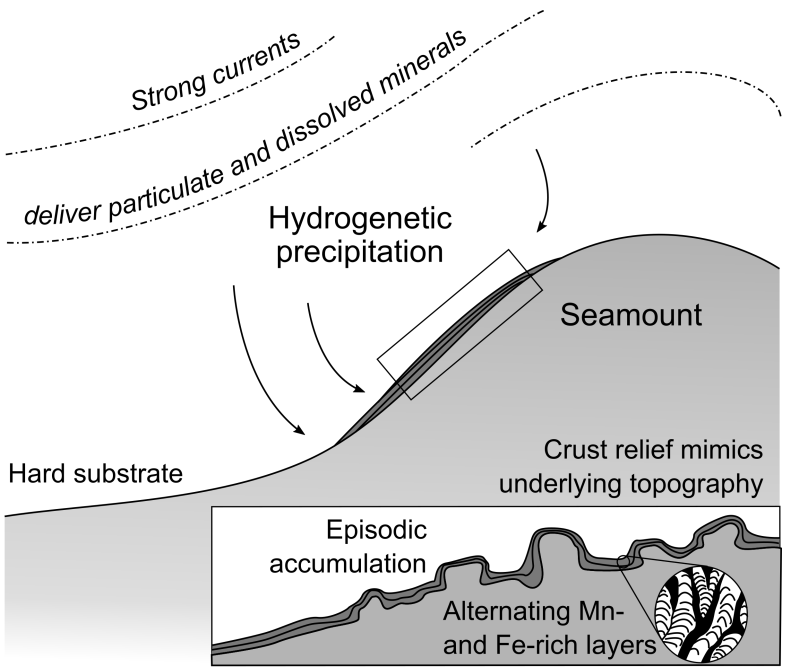

Figure 3.5 *– Schematic illustration of CRC formation and situation at the seabed. Inset shows crust microtexture*

Most CRCs are found at seamounts, which often host high primary productivity and biodiversity, even in open ocean (according to the seamount oasis theory, as discussed in section 2.3). As such, they represent an important site of connection between benthic and pelagic ecosystems for feeding, breeding and migratory purposes (Miller et al., 2018). Crust-bearing environments are also characterised by large depth variations, rocky substrates and strong currents, which sweep hard substrates free of sediment. Sessile benthos and suspension feeders are common at CRCs, as the lack of sediment is advantageous for capturing food particles; in contrast, burrowing animals are less common due to the unavailability of soft sediment (SPC, 2013c). Slow-growing, fragile cold-water corals and sponges dominate seamount environments, and support a diverse range of megafauna by providing habitats.

Although numerous studies have been published on seamount ecology, less research has focussed purely on CRCs. It is unknown whether faunal communities differ between seamounts with and without CRCs, although differences in benthic faunal abundance have been observed according to CRC richness and depth in one area dominated by seamounts (Schlacher et al., 2014). There is also a possibility that the chemical composition of crusts, particularly metals, influences the abundance and distribution of faunal communities. However, the influence of crust composition is difficult to observe separately from the influence of depth. Seamount benthic communities remain an active area of research, as the role of seamounts in the wider benthic ecosystem is the subject of ongoing debate. As a result, ecosystems associated with CRCs are poorly understood.

***Table 2** – Main characteristics of the three SBM deposits*

	Manganese nodules	**Seafloor massive sulphides (SMS)**	**Cobalt-rich crusts (CRCs)**
Other terms	Polymetallic nodules	Polymetallic sulphide deposits	Ferromanganese crusts
Environment	Abyssal plains at ~4,000–6,500 m depth	Active/inactive hydrothermal vent systems along MORs. Varying depths, mostly 1,000–4,000 m	Slopes and summits of seamounts from 600–7,000 m
Setting	Fields of 4–12 cm diameter nodules partially buried at sediment–water interface	Chimneys, debris and mounds on the seabed 10–100s m wide; and within oceanic crust	Crusts attached to rocky substrate, may reach 25 cm thickness
Formation	Layered accretion of Mn and Fe around a central substrate. Slow formation rates of 1–10 mm per Myr	Precipitation from hydrothermal fluids as chimneys and mounds on/below the seabed. 10^4 years needed to form largest deposits	Direct precipitation from water column onto rocky substrate. Slow formation rates of 1–5 mm per Myr
Valuable components	Ni, Cu, Mn, Co Also Ti, Mo, Li, Tl, Te, REEs, traces of Pt and Te	Cu, Zn, Ag, Au Also Cd, Pb, Ba	Co, Ni, Mn, Cu Also Ti, Mo, W, Tl, Te, Ni, Pt, REEs
Est. reserves compared to continental deposits	CCZ nodule reserves of Tl, Mn, Te, Ni, Co and Y exceed global terrestrial reserves	N/A	Central Pacific crust reserves of Tl, Te, Co and Y exceed global terrestrial reserves
Approx. size of exploration contract areas	75,000 km^2	10,000 km^2 (100–1,000s m^2 per site)	3,000 km^2 (20–1,200 km^2 per site)
Main references	(Mewes et al., 2014; Blöthe et al., 2015; Vanreusel et al., 2016)	(Hannington et al., 2011; Boschen et al., 2013; Van Dover, 2014)	(Hein et al., 2009; Halbach et al., 2017)

Other deposits

An area of submerged continental crust approximating one-third of total onshore land mass extends into the oceans. Since this is essentially an extension of onshore bedrock, huge quantities of mineral resources are theoretically hosted therein, in areas within national jurisdiction. Knowledge of the distribution and magnitude of these deposits is limited, largely due to the inability to drill beneath continental sediments, although subsea deposits have previously been accessed from mine shafts originating on land (Hannington et al., 2017).

Meanwhile, commercial offshore mining operations have been taking place in shallower waters (<50 m water depth) for decades. These include mining for aggregates, namely sand and gravel from northwest Europe; placer deposits, especially diamonds mined in offshore Namibia; and tin, from southeast Asia (Ingels et al., 2016).

Gas hydrates, particularly methane hydrates, are not technically mineral deposits, but the status of exploration and potential impacts are similar to the three deposit types considered thus far. They consist of gas trapped within lattices of frozen water molecules, and are found at very high pressure and low temperature, mostly buried within continental margin sediments at depths of 1,000–3,000 m (Miller et al., 2018). The presence of large volumes of gas makes them of great economic interest, but more knowledge of their formation and decomposition mechanisms is necessary for responsible production.

3.2 Impacts of SBM on the seabed

Commercial-scale SBM operations are predicted to produce a range of impacts at the seabed. Impact studies have employed modelling and observations from simulated testing, but most assessments thus far have been speculative. Environmental impacts are likely to vary depending on numerous factors, including deposit type, operational aspects, and ecosystem resilience. Following a description of the operational stages of SBM, these factors are explored for each SBM deposit type, in order to link research questions 1 and 2.

SBM operations

Following prospecting and exploration, the exploitation phase would occur in four stages, as shown in Figure 3.6:

1. Disaggregating mineralised material from the seafloor;
2. Transporting the material from the seafloor to the surface;
3. Dewatering the material; and
4. Transporting the material to market. (SPC, 2013a)

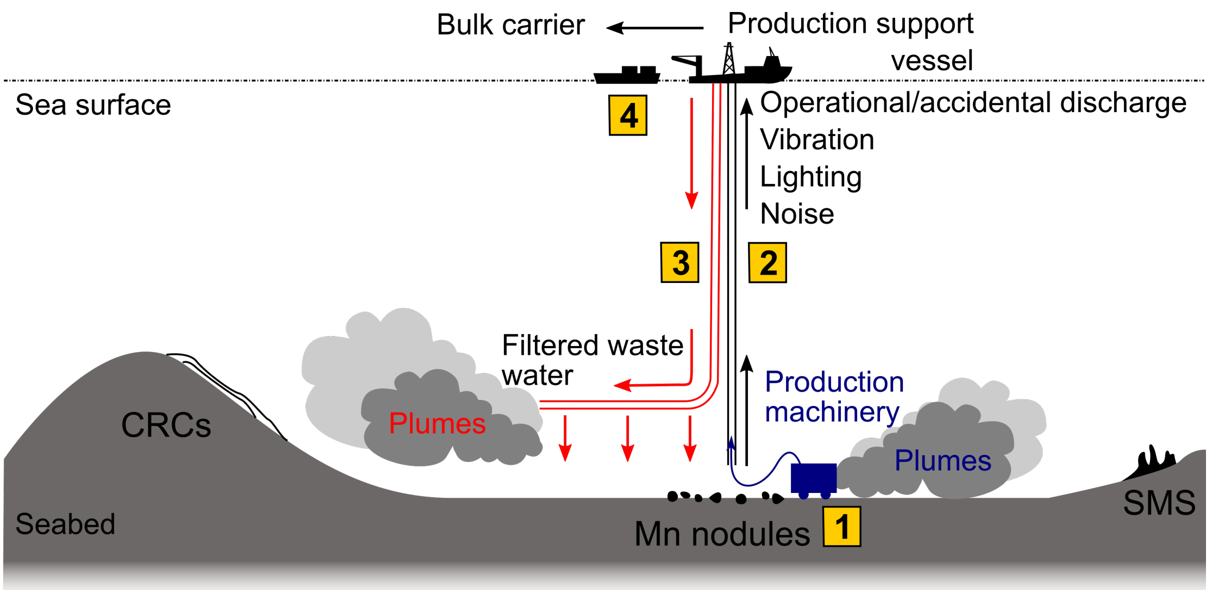

Figure 3.6 *– Stages of SBM operations, corresponding to numbered list above. Modified from SPC (2013a)*

At the deep seabed, each stage is associated with direct impacts occurring in situ, in addition to implications on wider spatial and temporal scales, as listed in Table 3.

Table 3 – Processes, impacts and implications at the seabed associated with operating stages of SBM

<table>
<tr><th>Processes</th><th>Direct impacts</th><th>Implications</th></tr>
<tr><td colspan="3">Stage 1: Digging/scraping/sucking of substrate to disaggregate material from seabed</td></tr>
<tr><td>Removal of seabed substrate and hard mineral deposits</td><td>Physical removal of slow-moving mobile, and sessile epifauna and shallow infauna in path of operations.
Removal of hard substrate habitats.
Removal of labile organic matter.
More compacted, previously buried sediment exposed.</td><td rowspan="3">Reduced habitat heterogeneity and complexity.
Decline in established species.
Reduced biodiversity, locally and in surrounding areas.
Later domination by scavenger species.
Possible recolonization by species from nearby environments.
Disruption of ecosystem connectivity.</td></tr>
<tr><td>Disturbance of surrounding seabed sediment</td><td>Exposure and dislodging of buried infauna.
Mixing of oxic uppermost and suboxic buried sediment: changes to porewater chemical flux; altered pore fluid and water column chemistry.
Changes to physical characteristics of sediment surface.</td></tr>
<tr><td>Sediment suspension and re-deposition</td><td>Reduced capacity of filter feeders to capture food particles.
Blanketing of mined and surrounding area reduces capacity of surface feeders to locate and access food.</td></tr>
<tr><td>Sedimentary compaction by machinery/ equipment</td><td>Infauna crushed.
Pore space reduced.</td><td>Sediments less hospitable for recolonising burrowing fauna.</td></tr>
<tr><td colspan="3">Stage 2: Transport of slurry (nodules + seawater) from seabed to sea surface through a fully or partially enclosed lifting system: impacts largely confined to the water column</td></tr>
<tr><td colspan="3">Stage 3: Dewatering of slurry aboard production support vessel: seawater separated from mineral ore at production vessel and discharged near the extraction site, either into the water column or at the seafloor</td></tr>
<tr><td>Introduction of discharge water containing unfiltered fine sediments to water column (<200 m depth)</td><td>Reduced surface water clarity blocks the penetration of sunlight, leading to lowered primary productivity by phytoplankton and reduced organic flux to seabed.</td><td>Reduced faunal abundance at food-limited deep seabed.</td></tr>
<tr><td>Introduction of discharge water containing unfiltered fine sediments to seabed</td><td>Reduced capacity of filter feeders to capture food particles.
Blanketing of mined and surrounding area reduces capacity of surface feeders to locate and access food.</td><td>Implications for filter-feeding and surface-feeding fauna as for stage 1.</td></tr>
<tr><td>Introduction of water mass with different properties</td><td>Possible disruption to local hydrodynamic conditions, e.g. currents.</td><td>Impacts on conditions in wider area.</td></tr>
<tr><td colspan="3">Stage 4: Material on-board production vessels offloaded onto barges and transported to markets. Environmental impacts standard for large vessels, including operational and accidental discharge, debris and garbage which may reach the seabed</td></tr>
</table>

The system of dewatering aboard a production support vessel (PSV) and returning waste water to the seabed is intended to reduce impacts to the water column. However, local disturbance to seabed sediment will arise both at the site of extraction at the seabed, from contact with machinery, and directly above the seabed, where waste water separated from mined material is released back into the ocean. As a result of this disturbance, material from the upper 15 cm of the seabed becomes suspended within the water column in the form of sediment plumes. According to local hydrodynamic conditions, plumes will be subject to lateral transport away from the mining site, thus expanding the spatial extent of their influence, even though sediment disperses with distance from the plume origin. Plumes may also interact with turbulence already present at the abyssal seabed as a result of surface-generated eddies originating thousands of kilometres above (Aleynik et al., 2017).

Plumes are suggested to disrupt the feeding mechanisms of filter feeders on the seabed, and eventual resettling of suspended sediment back onto the seabed is suggested to 'smother' benthic ecosystems, even with when the resettled layer is less than 1 cm in depth. This could prevent recolonization of mined areas, and impact on nearby unmined nodule areas. The extent of resettling depends on multiple properties, such as sediment concentration and turbidity of the plume, as well as the likelihood of particle flocculation to form heavier, earlier-settling sediment (Gillard et al., 2019).

Sediment plumes are the most extensively studied form of impact. However, all four stages described in Table 3 are likely to induce impacts at the seabed from noise, light and vibration produced by machinery, which have not been individually studied in detail for SBM.

The specific nature of each deposit type and setting also makes them susceptible to particular impacts. Firstly, the spatial scale of each deposit type is an important control on the extent of SBM impacts. According to Petersen et al. (2016) the footprint of mining activity at a single site would be several hundreds of km^2 per year for Mn nodules; several tens of km^2 per year for CRCs; and an area <0.2 km^2 for the Solwara 1 SMS site. However, these estimates are purely areal and do not take volume into account.

Secondly, the physical setting of minerals dictates the required mining technology and resulting effects on the seabed. Mn nodules are considered the most straightforward deposit to mine, since they are loosely embedded in sediment. Hydraulic systems have been proposed to grab nodules using a hydraulic, mechanical or hybrid collector and lift them to the PSV via a pipe (SPC, 2013a). However, it may be necessary to dig 5–50 cm into the sediment to unearth nodules, thus removing the upper reactive sediment layer. Since hard substrate is the major target for SMS mining, soft sediments are less likely to be disturbed. However, Orcutt et al. (2020) describe the process of SMS mining as analogous to terrestrial open-pit mining, as the 'top layer of sediment and crust is removed as overburden, and the exposed ore is removed in successive layers until the deposit is completely removed or "mined out"'.

They discuss how the sudden exposure of sulphide minerals to oxic waters is likely to trigger 'a cascade of abiotic and microbially catalysed reactions', with the possibility to alter local dissolution processes and reduce pH. This process is known as acid mine drainage onshore, manifested as an acidic outflow of water from the mining site containing toxic leached metals. Orcutt points out that an underwater open-pit mine would remain open to the water column, where components of pH buffering ability and microbial activity underwater are barely understood. Mining CRCs poses different challenges, as crust surfaces exhibit high heterogeneity and varying thicknesses, and the irregular relief of the crust surface and potentially steep seamount slopes present difficult terrain for mining vehicles to drive over. Crusts are also firmly attached to the underlying substrate, making it challenging to remove only mineralised material without large quantities of waste rock (SPC, 2013c).

In addition to operational impacts, accidental events of varying scales also have the potential to incur damage. These may include spills of oil or other hazardous materials from vessels, massive discharge of material from lifting systems if damaged, or even collisions between vessels, equipment or marine mammals.

Implications for ecosystems

Certain impacts are likely to effect the environments and ecosystems of all three SBM mineral types. The removal and disturbance of the upper sediment layer in the contexts of all three mineral deposit types will disrupt the balance between OM distribution, microbial activity and bioturbation, which provide the foundation to the deep seabed ecosystem, as explained in section 2.2. Thus, disturbance to fauna of all sizes can also be expected. Furthermore, seabed disturbance will also impact on pelagic fauna, as the seabed acts as a site of connection between the two. For example, certain pelagic organisms migrate vertically to the seabed every night to feed; and pelagic species such as octopus which lay eggs in sheltered areas of hard substrate.

The general characteristics of organisms living at the deep seabed also make them vulnerable to short-term disturbance, namely that they tend to be slow-growing, long-lived, fragile and require stable environments. As a result they are generally highly sensitive to sudden change, and slow to adapt or recover. However, ecosystems at the three discussed environments already face disturbances, mainly from deep sea fishing – especially at seamounts – and volcanic events at hydrothermal vents. Fauna thus have varying levels of resilience and ability to recolonise in response to rapid disturbance. In a meta-analysis of impact studies, Gollner et al. (2017) report considerable variation in the recovery of different species to short-term disturbances that simulate mining. Notably, the removal and/or disturbance of seabed substrate alters community composition in all environments, which may persist on geological timescales.

The ecosystems particular to different deposit settings are also likely to be impacted in different ways. Regarding SMS mining, the majority of vent ecosystems are situated on hard basalt substrate (Van Dover, 2014), so disrupting and removing substrate is likely to have significant impacts. As mentioned, vent environments, and thus SMS deposits and their associated ecosystems, are often isolated for millions of years, leading to the development of highly adapted, unique faunal communities (Boschen et al., 2013), which makes them highly vulnerable to localised disturbance. Although discrete vent sites have been the subject of numerous studies, wider-scale research on the distribution and connectivity of vent ecosystems, including the abilities of species to disperse and recolonise, is lacking.

As the only primary producers in vent environments, chemosynthetic bacteria and archaea support life at vents through symbiotic functions, production of biomass and habitat creation by microbial mats. Disruption to fluid pathways and metal availability has the potential to influence microbial populations and activity at vents, with potential 'cascade' effects on the ecosystems they support (Orcutt et al., 2020). Where active hydrothermal vent systems are mined, leading to the removal of SMS communities, the continued precipitation of minerals will reconstruct chimney structures and enable recolonization. A number of studies imply that this could take place rapidly, chiefly through the transport of mobile larvae from neighbouring vent communities, but could result in altered communities (e.g. Van Dover, 2014). Given the highly variable nature of environments hosting SMS deposits, in terms of ridge spreading rates, temperature, seawater chemistry and other factors, the speed and nature of recolonization may likewise vary widely. Meanwhile, the recolonization of background species is expected to be significantly slower, predicted on the time scale of years to decades, while vent-proximate habitats may also experience impacts and undergo specific recolonization (Gollner et al., 2015). While fluid emission at active vents is unlikely to be altered by mining activities, impacts at inactive sites may persist at longer time scales, as sessile organisms attached to hard substrate at inactive vents are slow-growing and may take decades to centuries to recover.

Secondly, although studies on the specific ecology and susceptibility of CRCs to mining are rather limited, the very slow growth rates of dominant seamount fauna, namely corals and sponges, and their isolated situation on seamounts in open ocean, likely makes them highly vulnerable to human activity. Likewise, recovery of vulnerable species and their assemblages from human impacts is predicted to be very slow (SPC, 2013c). Microbial ecosystems at CRCs are said to be too poorly understood to determine effects on mining (Orcutt et al., 2020). Furthermore, as mining technologies for CRCs are poorly developed, it is difficult to speculate on their impacts; but the total removal of crusts and attached hard substrate in some areas is likely to be highly destructive to attached sessile fauna.

Thirdly, impacts of Mn nodule mining are arguably the most widely studied of the three deposit types, albeit for a limited number of areas, so impacts for nodule mining will be described in greater detail than for SMS or CRC mining. The DISCOL (DISturbance and re-COLonization) experiment was conducted from 1989–1996 in a 10.8 km^2 area of the CCZ at 4,140–4,200 m water depth. Mining of Mn nodules was simulated by driving an 8 m wide plough-like instrument over the DISCOL experimental area (DEA), based on prospective mining equipment at the time. In the 20% of the DEA that was ploughed, the instrument removed Mn nodules and disturbed the sediment surface in its path, churning up clasts of consolidated sediment that were previously buried. The surrounding unploughed areas and nodules were blanketed in a layer of redistributed sediment up to 30 mm thick (Thiel et al., 2001). Immediate changes in the composition of benthic megafauna >1 cm were observed, particularly among nodule-attached organisms. After 1997 'the political agenda changed' and DISCOL was no longer funded.[8] However, the DEA was revisited numerous times by researchers to examine the longer-term impacts, 0.1, 0.5, 3, 7, and 26 years after the experiment. The original disturbance of sediment by plough tracks was observed even on the most recent visit.

Two studies observing megafauna conducted 7 (Bluhm, 2001) and 26 (Simon-Lledó et al., 2019a) years after DISCOL returned similar findings, whereby differences in standing stock and biodiversity were consistently observed in the tested area compared to reference areas, with varying effects for different faunal groups. Sessile suspension feeders were more vulnerable, and had not recovered to pre-experiment levels after 7 or 26 years (Bluhm, 2001; Simon-Lledó et al., 2019a). In contrast, mobile deposit feeders, scavenger and predator populations had recovered and even increased, possibly due to the enhanced availability of OM in previously buried sediment exposed by ploughing, and death and burial of biomass during disturbance. Both studies concluded that long-term changes had been effected by SBM simulation, with organisms of different sizes and functional groups having different sensitivities, although baseline understanding and selection of reference areas needed to be improved.

Studies on the DEA also offer insights into impacts on microbial activity. Haffert et al. (2019) studied sediment biogeochemistry at the DEA, and determine that labile OM availability controls microbial recovery from disturbance by DISCOL, as removal of the upper sediment layer disrupts biogeochemical cycling in a number of ways. These include the prevention of bioturbation, the decrease of OM degradation rates, and thus reduced microbial activity, which in turn is unable to support pre-disturbance faunal abundance. The authors conclude that due to the very low sedimentation rates in the CCZ, recovery of the seabed ecosystem could take millennia. However, the style and magnitude of impacts on this cycle also depend on the type of disturbance, meaning the amount of labile OM removed and the prior thickness of the reactive surface sediment layer. The style of disturbance, i.e. complete sediment removal, mixing or resuspension, will also determine the impact.

Depending on the supply and re-establishing of the labile OM fraction, the sedimentary ecosystem may take up to 1,000 years to recover following the removal of Mn nodules

[8] https://www.discol.de/home (accessed 10 January 2020)

(Stratmann et al., 2018). Furthermore, the removal of hard substrate offered by nodules means the new ecosystem will depend entirely on biogeochemical processes based in and on the sediment. The removal of the upper sediment layer would invite oxygen penetration into sediment that was previously buried, thus disrupting other microbial and microbially facilitated reactions such as denitrification and Mn(IV) reduction (Volz et al., 2019). Overall, total faunal carbon stock within plough tracks was found to be 54% of the stock outside plough tracks, 26 years post-DISCOL, and total carbon cycling within the faunal ecosystem remained reduced (Stratmann et al., 2018).

Limitations of impact studies

Many national and international efforts are ongoing to coordinate research on deep-sea environments and the possible impacts of SBM, including the EU-funded MIDAS project (Managing Impacts of Deep Sea Resource Exploitation). The impact studies published thus far offer a scattered picture of the possible environmental implications of SBM, for a number of reasons.

Since mining technology is still being developed, there is no possibility of conducting tests at the seabed that accurately reflect modes of extraction. In addition to operational simplicity, for example the plough system used in DISCOL, tests that have been carried out in-situ subject a very small area to a single episode of disturbance. This is unlikely to replicate the spatial and temporal scale of SBM operations.

The data collected from already licensed exploration areas are similarly limited in scope. Small areas of understanding cannot account for the total footprint of licensed areas, considering the high variation in topography, oceanographic conditions and faunal communities at mineral-rich areas of the deep seabed. Furthermore, many studies observing the effects of disturbance to potential SBM areas use ROVs, AUVs and photogrammetry, and focus on megafauna, since these methods are efficient, and megafauna can be quickly identified in the captured images. As a result, understanding of impacts on microbial and infaunal communities is limited.

Baseline knowledge of all deep seabed areas is lacking, as is understanding of the likely impacts of SBM operations at all spatial and temporal scales. Moreover, impact studies should also be considered in combination with other anthropogenic stressors on the deep seabed (Levin et al., 2016). Due to the high rate of species extinction and the vast extent of the environment, it would be impossible to determine an ecological baseline for the deep seabed, or even to fully document its biodiversity, within the next few generations (Ingels et al., 2016). This inhibits the possibility of developing an accurate EIA for any human activity at the seabed, even though EIAs are mandatory for contractors applying for an exploration license.

In their call for deep ocean stewardship in the face of SBM, Mengerink et al. (2014) mention the lack of knowledge about mining impacts and ecosystem resilience; the likelihood of slow to no recovery for many habitat types; the lack of ability to monitor and restore damaged systems; and the potential disturbance to seafloor and water column life far beyond mining sites. The extent of these uncertainties, in addition to the high variation in setting, formation and associated ecology of the three mineral deposit types considered for SBM, presents a great challenge for the regulation of mining at the seabed. The legal framework is discussed in the next section.

3.3 Regulatory framework for SBM

This section discusses the regulatory framework that applies to the deep seabed in relation to SBM, especially to marine environmental protection. The suitability of the framework is also assessed in answer to research question 2, 'how does the regulatory framework account for impacts of SBM on the seabed?'. This begins with the definition and delimitation of the deep seabed as 'the Area' by the 1982 Law of the Sea Convention (hereafter the LOSC) (United Nations, 1982).

As mining operations have not yet taken place in the Area, the framework provided thus far only governs mineral exploration, based on the legal status of and principles applying to the deep seabed, the collection of environmental baseline data and likely impacts of SBM activities. Regulations establishing actual measures to avoid harming the marine environment during mining operations are currently being drafted (see 'The ISA and the Mining Code').

UNCLOS

Ocean and seabed space is governed by the overarching legal framework of the LOSC. Although the seabed is, of course, present in all maritime zones, it is explicitly treated in articles on the territorial sea, EEZ, continental shelf and the Area, the latter being effectively the deep seabed (Figure 3.7). Note that all article citations in this section refer to the LOSC.

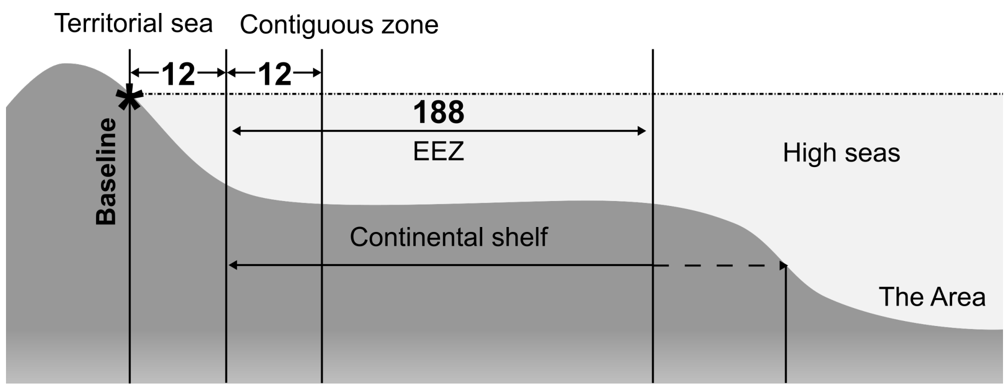

Figure 3.7 *– Maritime zones as defined by the LOSC (values in nautical miles). Modified from Rothwell and Stephens (2016)*

The territorial sea and EEZ regimes simply refer to the 'seabed and its subsoil', over which coastal States are conferred sovereign rights to explore, exploit, conserve and manage living and non-living natural resources (art. 56(1)). The continental shelf regime (Part VI) lays out more detailed provisions relating to coastal State rights over the seabed. Sovereign rights are assigned to explore and exploit the natural resources of the continental shelf, which do not 'depend on occupation, effective or notional, or on any express proclamation' (art. 77(3)). These natural resources are defined as 'mineral and other non-living resources of the seabed and subsoil', in addition to sedentary species (art. 77(4)). Coastal States also have the exclusive right to authorize and regulate drilling on the continental shelf 'for all purposes' (art. 81).

Part VI offers arguably the most in-depth consideration of seabed composition and bathymetry. Again, the continental shelf 'comprises the seabed and subsoil of the submarine area', either extending 'throughout the natural prolongation of its land territory to the outer edge of the continental margin', or to 200 nm from the territorial baseline (art. 76(1)). The continental margin is then defined:

The continental margin comprises the submerged prolongation of the land mass of the coastal State, and consists of the seabed and subsoil of the shelf, the slope and the rise. It does not include the deep ocean floor with its oceanic ridges or the subsoil thereof. (art. 76(3))

The possibility to extend the continental shelf beyond 200 nm, to the limit of its natural 'prolongation', depends on the relevant State establishing an outer edge by fixed points,

(i) …at each of which the thickness of sedimentary rocks is at least 1 per cent of the shortest distance from such point to the foot of the continental slope; or (ii) …not more than 60 nautical miles from the foot of the continental slope (art. 76(4))

with the foot of the continental slope 'determined as the point of maximum change in the gradient at its base'. The outermost limit of these fixed points is 350 nm from the territorial sea baseline, or 100 nm from the 2,500 m isobath (art. 76(5)). The latter option does not apply to submarine ridges, but may apply to 'submarine elevations that are natural components of the continental margin, such as its plateaux, rises, caps, banks and spurs' (art. 76(6)). A Commission on the Limits of the Continental Shelf is established under UNCLOS III to receive submissions on continental shelf extensions, which should include 'charts and relevant information, including geodetic data, permanently describing the outer limits of its continental shelf' (art. 76(9)).

Approximately 60% of the seabed is situated outside areas of national jurisdiction, and is governed by Part XI, 'the Area'. The regime of the deep seabed was a major driver behind the convening of UNCLOS III (Rothwell and Stephens, 2016). The text of the convention was finalised in 1982 and reflects the interests and tensions of states regarding SBM in the decades leading up to UNCLOS III. Accordingly, a brief account of this period now accompanies the provisions of Part XI.

Due to the limited technological capacity of states to explore and exploit the deep seabed, SBM had not been discussed at UNCLOS I or II. With awareness of the economic potential of deep seabed mineral resources in the 1960s, growing interest led to a spate of funded research. As no regulatory regime for the seabed was in place at the time, no guarantee of ownership could be provided. The discovery of 'substantial' onshore mineral deposits further discouraged commercial efforts, and SBM was dropped from the political agenda of interested countries. However, the impetus remained to develop a legal regime for areas of the seabed beyond national jurisdiction.

Prior to the development of any regime, approaches to the seabed were either based on the principles of *res nullius*, whereby the seabed was equated to unclaimed land that could be occupied, or *res communis*, where no claims to ownership could be made by any State (Allott, 1992). In 1967 Arvid Pardo, the Ambassador for Malta, proposed that the seabed be declared the common heritage of mankind (CHM). In response, the UNGA established the Ad Hoc Committee to Study the Peaceful Uses of the Sea-Bed and the Ocean Floor Beyond the Limits of National Jurisdiction (the Sea-Bed Committee), which in 1969 proposed a precautionary moratorium on SBM, and adopted Resolution 2749 declaring the seabed the CHM.[9]

These events led to the convening of UNCLOS III in 1973, with the input of the Sea-Bed Committee. The Convention was characterised by the strong consensus of member states on the wish for extended zones of sovereignty over natural resources, which eventually shaped the EEZ concept. There was also a general wish to consider the deep seabed regime in greater detail. Pardo's CHM proposal was largely accepted, with the exception of the United States, which in 1981 began to express concerns over the proposed regime on the grounds of free market principles. The text was concluded and opened for signature in 1982. Although U.S. resistance could not overturn the inclusion of the CHM principle, it did present a threat to the ratification of UNCLOS. Despite support from three other states, the convention text could not be altered at such a late stage. Instead, the supplementary 1994 Implementation Agreement Relating to the Implementation of Part XI was produced to modify the LOSC, as discussed in the next section.

The importance of the seabed regime to the LOSC is reflected in the mention of UNGA resolution 2749 (XXV) in the preamble, as well as the immediate definition of terms and scope relating to the Area in article 1:

> *'Area' means the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction. (art. 1(1))*

In this way, the Area is defined by way of exclusion. Meanwhile, 'activities in the Area' refer to 'all activities of exploration for, and exploitation of, the resources of the Area' (art. 1(3)).

Part XI of the LOSC later sets out the use of terms and principles governing the Area. The majority of this Part consists of lengthy provisions on the development of resources, and it first defines resources as 'all solid, liquid or gaseous mineral resource in situ in the Area or beneath the seabed, including polymetallic nodules'; and states that when recovered from the Area, resources 'are referred to as "minerals"' (art. 133). This underlines the explicit focus on SBM in the Area, and clearly confines resources of interest to non-living resources. Article 136 declares the Area and its resources to be the CHM – notably, this term is not defined in the

[9] 1970 General Assembly Resolution 2749 (XXV) on Declaration of Principles Governing the Sea-bed and the Ocean Floor, and the Subsoil thereof, beyond the Limits of National Jurisdiction, adopted 17/12/1970

LOSC – and states that activities in the Area shall be 'carried out for the benefit of mankind as a whole' (art. 140), echoing Arvid Pardo's 1967 proposal. Measures shall also be taken to 'ensure effective protection for the marine environment from harmful effects which may arise' from activities in the Area (art. 145). The remainder of Part XI lays out detailed provisions relating to mineral production and the responsibilities of the 'Authority' (explored further in the next section).

Part XII on the protection and preservation of the marine environment includes a dedicated article on the Area, mandating the development of international rules, regulations and procedures in accordance with Part XI to prevent, reduce and control pollution from activities in the Area (art. 209), while article 215 defers to Part XI regarding enforcement.

All in all, Part XI offers an extensive, largely self-contained set of provisions which mostly relate to SBM. Matters of environmental protection, scientific research, enforcement and dispute settlements are all covered in dedicated parts elsewhere in the LOSC, but where they relate to SBM they are either specifically mentioned in, or defer to, Part XI.

The ISA and the Mining Code

The LOSC establishes the International Seabed Authority (ISA), referred to as 'the Authority', and confers its jurisdiction over exploration and exploitation relating to mineral resources in the Area (art. 137). A significant proportion of seabed mineral resources are located outside national jurisdiction, and therefore fall under the power of the ISA: that is, 81% of the total favourable area of 38 million km^2 for Mn nodules, 58% of 3.2 million km^2 for SMS, and 46% of 1.7 million km^2 for CRCs are located in the Area (Petersen et al., 2016).

The duties of the ISA are mentioned throughout Part XI, and it is defined as 'the organization through which States Parties shall…organize and control activities in the Area' (art. 157). All states are members, and the ISA is composed of a Secretariat, an Assembly, a Council, a Legal and Technical Commission (LTC), and a Finance Committee. It does not have an organ dedicated to environmental matters, although the LTC are responsible for recommendations on environmental impacts. Through sponsoring States, the ISA awards 15-year contracts to mining operators to explore the potential for SBM in defined license zones. At the time of writing, the ISA has granted 30 exploration contracts: 18 for Mn nodules (of which 16 are for the CCZ), 7 for SMS and 5 for CRCs.[10] No commercial extraction has yet taken place.

According to the ISA, a principal function is 'to regulate deep seabed mining and to give special emphasis to ensuring that the marine environment is protected from any harmful effects which may arise during mining activities, including exploration'.[11] These duties are grounded in the

[10] https://www.isa.org.jm/deep-seabed-minerals-contractors (accessed 10 January 2020)
[11] https://www.isa.org.jm/scientific-activities (accessed 18 February 2020)

LOSC, as article 2(1) of Annex III states that 'the Authority shall encourage prospecting in the Area', while article 145 obliges the ISA:

> *…to ensure effective protection for the marine environment from harmful effects which may arise from such activities [in the Area]. To this end the Authority shall adopt appropriate rules, regulations and procedures for inter alia:*
>
> *(a) the prevention, reduction and control of pollution and other hazards to the marine environment…and of interference with the ecological balance of the marine environment…;*
> *(b) the protection and conservation of the natural resources of the Area and the prevention of damage to the flora and fauna of the marine environment. (LOSC art. 145)*

Many scholars have identified the tension existing between these duties (e.g. Zalik, 2018). Indeed, given that conducting SBM inescapably causes environmental damage (Niner et al., 2018), these duties may be considered as fundamentally opposed, even paradoxical. Other vague, open-ended obligations do nothing to clarify the ISA's balance of responsibilities. The ISA 'may carry out marine scientific research concerning the Area and its resources' and 'shall promote and encourage the conduct of MSR in the Area' (art. 143(2)); likewise, it is obliged to take measures 'to acquire technology and scientific knowledge relating to activities in the Area' (art. 144). The purpose of this research, and the nature of technology or knowledge, is not detailed. The ISA is also obliged to enable 'equitable sharing of financial and economic benefits' derived from SBM, 'through any appropriate mechanism' (art. 140). However, the expanded powers and functions of the ISA provided in article 160 offer no further specification of such a mechanism, and one has not yet been developed (Kim, 2017).

The principle of the CHM in relation to the Area is central to the ISA's mission, but has also attracted controversy. The ISA is mandated to act on the behalf of 'mankind as a whole', with regards to the vested interests of mankind in resources of the Area (art. 137). The ISA does not have ownership or control over the Area, but only over activities relating to mineral resources. Therefore, its jurisdiction does not extend to the general environmental protection of the seabed. Allen (2001) argues that the CHM principle leaves the seabed vulnerable since no single actor is given the responsibility to instigate regulations or measures to protect the deep-sea environment.

The vagueness of these obligations likely reflects the contrasting interests and intentions that different states had for the powers of the ISA during UNCLOS III negotiations (Rothwell and Stephens, 2016). As mentioned in the previous section, this conflict resulted in the late-stage addition of the 1994 Implementing Agreement. The ISA was originally intended to directly engage in SBM activities and distribute profits through the Enterprise; but the Implementing Agreement confined its duties to monitoring and assessment of mining operations by contractors (Bourrel et al., 2018), and protected research and development efforts prior to the LOSC through provisions relating to 'pioneer investors'. The Implementation Agreement's hollowing out of the power of the Enterprise to enact the CHM, replaced by free market principles, left the principle of CHM ‘an empty shell’ and constructed the seabed space as ‘empty and featureless’ (Jones, 2016).

The ISA has developed regulations for the exploration of the three deposit types, and is currently developing regulations for exploitation. Along with recommendations and other documents, these comprise the Mining Code, described by the ISA as ‘the comprehensive set of rules, regulations and procedures issued by the ISA to regulate prospecting, exploration and exploitation of marine minerals’ in the Area.[12] To date, regulations on prospecting and exploration have been adopted for Mn nodules (adopted 2013), SMS (adopted 2010) and CRCs (2012). The three sets of regulations specific to SBM types contain basic environmental requirements, which are largely identical for each mineral type.

Contractors must include an EIA and a programme for baseline studies in applying for exploration license, according to article 7 of the 1994 Implementation Agreement. In 2013 the ISA issued recommendations for contractors conducting an EIA (ISA document ISBA/19/LTC/8), which contain detailed technical provisions relating to the deep seabed environment. According to the explanatory commentary, ‘baseline data requirements include seven categories: physical oceanography, geology, chemistry/geochemistry, biological communities, sediment properties, bioturbation and sedimentation’ (para. 7). Most of the requirements detailed in these recommendations are valid for all three mineral types, although some do not apply to all mineral types due to their specific setting. The scope of the recommendations encompasses the necessary components of baseline data, and monitoring to conduct during and after activities ‘with potential to cause serious harm to the environment’ (art. 9). Multiple scholars have taken up the latter point and questioned what constitutes ‘serious harm’ here and where used in the LOSC, with Levin et al. (2016) concluding that numerous possibilities for serious harm to the environment are posed by all forms of SBM, even with significant uncertainties and lacking knowledge (see section 3.2).

Durden et al. (2018) describe the ISA’s current EIA requirements as ‘a portion of a robust EIA process’, since they do not account for uncertainties and are not sufficiently detailed, among other criticisms. They are also difficult to conduct due to challenging environmental conditions, lack of baseline data, and poor knowledge of what SBM technologies will actually entail, since they remain under development. Concerns have also been raised over the quality and consistency of data collected by different contractors, and the standardisation of EIAs has been called for (Thompson et al., 2018).

Bräger et al. (2018) compile and analyse the 100 mandatory environmental requirements issued by the ISA up to September 2018 through the discussed regulations and recommendations. While a near equal number of requirements apply to each of the three SBM

[12] https://www.isa.org.jm/mining-code (accessed 13 January 2020)

mineral types, those covering biological topics (55) significantly outnumber those covering physical (20), chemical (21), or sedimentological/geological (22) topics. The authors suggest that this reflects a focus on the living component of the CHM, even though most species in the Area are yet to be discovered. Furthermore, the authors divide the regulations into 12 'thematic themes'. In total, 63 regulations apply to seabed (i.e. benthic) sampling methodology, and 24 to water column (i.e. pelagic) sampling methodology. Meanwhile, 35 of the recommendations set minimum limits for the spatial and temporal extent of data collection, in order to reliably document species distributions, connectivity and variability through time and space. However, only 18 regulations specifically deal with potential impacts of mining operations, while 7 demand the use of area-based management tools to define Impact Reference Zones and Preservation Reference Zones. In summary, it can be said that the requirements for evaluating environmental impacts of SBM set by the ISA are insufficient.

A set of exploitation regulations is currently being drafted, which represent the 'ultimate regulatory phase in developing the common heritage of mankind', in the words of the ISA.[13] No mining operation in the Area can commence before completion of the Mining Code. The draft exploitation regulations, although by no means finalised, already indicate the final structure (ISA Secretariat, 2019). First, the general terms, scope and principles of the regulations, defined by the LOSC, are set out. Interestingly, a suggested addition to an early article setting out the fundamental principles of the regulations mentions the 'protection of human and non-human life and safety' (regulation 2(d)). Plans of work, rights and obligations of contractors are covered, in addition to financial terms, fees, enforcement, dispute resolution, and terms for mine closure. An entire part is dedicated to protection and preservation of the marine environment. The draft regulations defer again to UNCLOS here, namely to article 145 on the ISA's duty to protect the marine environment. Regulation 44 obliges the ISA to develop Regional Environmental Management Plans (REMPs) in every region under consideration, to include mining areas, areas of particular environmental interest (APEIs), preservation reference zones (PRZ) and impact reference zones (IRZ), which must be developed prior to the acceptance of any plan of work by contractors. The draft guidelines go into further detail on the development of environmental standards set out in regulation 45, and mandatory EIAs in regulation 47.

Annex IV goes further to specify details of an EIA, with a suggested addition that information should be provided based on data collected from 15 years of monitoring (Annex IV art. 1(b)). Furthermore, a suggested template requires a regional overview and site-specific description of oceanographic conditions, biology, geological setting, and nature and extent of the mineral resource, including seabed substrate characteristics (Annex IV art. 2).

[13] https://www.isa.org.jm/legal-instruments/ongoing-development-regulations-exploitation-mineral-resources-area (accessed 13 January 2020)

National legislation

Legislation has been developed by member states in relation to SBM in the Area, and in waters under their jurisdictions (i.e., not in the Area).

Regarding SBM in the Area, states are obliged to regulate the activities of contractors they sponsor within their domestic legal systems (Annex III, art. 4(4)). This effectively holds sponsored contractors to the obligations of the LOSC. Regarding protection of the marine environment, measures adopted in national legislation cannot be less stringent than those mandated in the LOSC. Accordingly, states were invited to submit such legislation to the ISA, which is compiled in a database.[14] As of 5 June 2018, 31 states had submitted information or legislation to the ISA, of which nine had adopted legislation relating directly to activities in the Area. Others related to onshore mining and SBM mining in areas within national jurisdiction. Of the states considered by the ISA in a comparative study, all emphasised the need to protect the marine environment. States either stated principles and obligations explicitly, or by reference to recognised international instruments, such as the LOSC or rules, regulations and procedures of the ISA. It was also pointed out that a number of States may have existing domestic legislation in place on protection of the marine environment, which could impact the activities of contractors (ISA, 2018).

The other category of national legislation pertains to mining activity in the areas within national jurisdiction. However, these should be informed by ISA instruments and should be 'no less effective' than international rules, standards and recommended practices and procedures (LOSC art. 208(3)). An environmental analysis of the Solwara 1 project, in the EEZ of Papua New Guinea, commissioned by Nautilus Minerals used terrestrial mining metrics to assess the impacts of SBM (Batker and Schmidt, 2015). The report concluded that the impacts to ecosystem services resulting from SBM would be less than those imposed by the terrestrial operations chosen for comparison. The report focused on the remoteness of the Solwara 1 site, and assessed a low impacts for metrics such as 'pollination' and 'soil formation', which evidently do not apply to the deep-sea environment, and cultural services such as 'recreation and tourism', based on the lack of access to the site. The report drew heavy criticism, as measures were not specialised for the unique components of the deep-sea ecosystem. Instead of measuring the value of the deep seabed analogously to land, a new paradigm is needed for measuring ecosystem services of the deep seabed.

[14] https://www.isa.org.jm/national-legislation-database (accessed 15 January 2020)

Other instruments

The 1992 Convention on Biological Diversity mandates the conservation of biodiversity and the sustainable use of its components (art. 1), and applies to terrestrial, marine and other aquatic ecosystems. It offers general principles and does not deal with specific environments or habitats. It continuously refers to genetic resources but does not directly deal with SBM.

The International Marine Minerals Society (IMMS) developed a series of voluntary guidelines for the mining industry in 2001, which it revised in 2011, including guiding principles for the responsible and sustainable development of SBM. It offers an environmental framework, general benchmarks and targets for mining operations, and is considered by the ISA as a basis for the development of its Mining Code.

Work on a legally binding instrument based on the LOSC to protect biodiversity in areas beyond national jurisdiction, that is, the high seas and the Area is currently underway, under UNGA resolution 72/249. The instrument applies to the conservation and sustainable use of marine genetic resources rather than mineral resources, so is not specifically applicable to SBM (United Nations, 2019); and Zalik (2018) notes that discussions on the instrument proceed 'in parallel to – rather than in coordination with – the ISA's development of an extractive regime'.

All in all, most analyses of the legal framework regulating SBM deem it to be fragmented, incomplete and unsuitable (Allen, 2001; Thompson et al., 2018). A range of alternatives have been proposed, which range from suspending contract granting until further marine protected areas (MPAs) are implemented (Wedding et al., 2015) to a stepwise 'ramping up' of mining operations with increasing knowledge (Niner et al., 2018), to stopping it altogether (Kim, 2017).

Recommendations for mineral exploration published by the ISA are largely standardised across each deposit type. Since mining technology has not been developed, specific operational impacts are not accounted for; and most environmental requirements focus on data collection and establishment of baselines, rather than imposing upper limits for environmental damage. Furthermore, the majority of articles provided in the LOSC to regulate SBM are administrative or financial. Those that do pertain to the marine environment demand, for example, 'effective protection' from harmful effects of mining activities to the 'ecological balance' and to 'flora and fauna of the marine environment'; and to 'prevent, control and reduce pollution and other hazards' (art. 145). None of these terms are defined, and the undisturbed status of ecological balance and flora and fauna are incompletely documented and understood. What is known is that mining activities will unavoidably impact the deep seabed environment in a number of ways, and remediation is not possible with current knowledge and technology (Niner et al., 2018). There seems to be little possibility to produce an accurate EIA that heeds to the precautionary principle when mining technology is not finalised and long-term baseline environmental data is mostly unavailable (Van Dover et al., 2014).

The purpose and duties of the ISA are formed from an unstable mandate to protect and exploit the deep seabed environment that arguably stems from the tension inherent within the LOSC, which vacillates between ideals of the ocean as a common space and a divided space: a distinction that is apparently as old as humankind's marine endeavours (Steinberg, 2001).

In answer to research question 2, the regulatory framework for SBM takes into account impacts on the deep seabed insufficiently and inappropriately, due to lacking knowledge on the actual mining process, state of the environment, and the spatiotemporal extent of impacts. Mining efforts are proceeding amidst a lack of clarity, and according to an unspoken presumption of economic value that outweighs the environmental or inherent value of the seabed. Advancing scientific understanding of the deep seabed continues as a challenging and lengthy process, in contrast to the relatively rapid efforts of the ISA over the past decade. However, such a binary characterisation (economic/environmental, science/industry) is not sufficient to capture perceptions and representations of the deep seabed; and deciding what constitutes an 'acceptable' level of damage to or irresponsible use of an effectively inaccessible environment, mostly known through data, are thus largely conceptual issues.

The next chapter draws on the content of Chapters 2 and 3 to explore these questions in a critical context.

4. Critical reflections on seabed space

Based on research question 3, this chapter brings together key findings from the previous chapters to consider seabed space from new perspectives, in the context of SBM. Three main themes are recognised from the previous sections that contribute to human understanding and perception of the deep seabed: knowledge, technology and value. These are considered in turn in the following section.

4.1 Epistemological themes

The previous chapters have explored the scientific techniques, classifications, images and legislation currently used to study, delimit and protect the seabed. From this data three main themes can be identified that construct the epistemological framework of the deep seabed.

Knowledge

Despite the scale of the deep seabed, the increasing capabilities of researchers to access and observe it, and the availability of tools to display and share data, a very small minority of the deep seabed environment has been directly studied. Accordingly, the deep seabed appears to be more characterised by a lack of knowledge than by what is known, at every scale. For instance, knowledge of microbial to megafaunal components of deep sea ecosystems, including their connectivity, is considered to be largely incomplete. Most deep seabed species are undiscovered or undocumented (Ingels et al., 2016), and exchange at the sediment–water interface is poorly understood temporally and spatially (Lessin et al., 2018). As such, existing studies represent discrete points of understanding, especially at habitats of particular scientific or economic interest. As the subject of targeted research on mineral formation, associated ecosystems and possible operational impacts of mining, seamounts, hydrothermal vents and the CCZ represent such 'islands of knowledge', which come to represent the unknown seabed that surrounds them. However, the significant heterogeneity within any habitat or environment of the deep seabed, as well as the seabed as a whole, makes the reliable extrapolation of this knowledge problematic.

Most studies critiquing the ISA's efforts to regulate SBM employ the precautionary principle and cite the lack of knowledge as a reason to stall or prevent SBM, due to the hampered regulatory ability to protect the environment from SBM operations. This opinion is likewise held by scientific experts within the Deep Ocean Stewardship Initiative (DOSI), and scientific studies of deep seabed ecology habitually mention the high degree of uncertainty as a limitation of their findings, or as a caveat to any broad conclusions. However, this paucity of knowledge seems a concern less central to the ISA as to the scientific community. Durden et al. (2018) point out that applicants for SBM exploration contracts are not currently required to recognise or account for uncertainties in their project design or assessments. Furthermore, the ISA's LTC is not obliged to mention uncertainties in presenting recommendations for approval of exploration contracts.

As numerous authors have noted, the deep seabed has also been a site of secrecy, conflict and covert operations by private and state entities in the race to develop technologies and gather data on SBM through the 20th century (Hannigan, 2016; Zalik, 2018). A lack of transparency in the ISA's activities has also been pointed out; LTC meetings are closed sessions and 'workshops to develop policy are primarily run by invitation only' (Thompson et al., 2018). In an evaluation based on information availability, participation in decision-making, and access to outcomes, Ardron (2018) assigns a score of just 44% to the transparency of the ISA's operations. Meanwhile, Zalik argues that the tension produced by diverging approaches to governance of the Area, particularly remnants of the *res nullius* concept and the protection of pre-LOSC claims to seabed space, is safeguarding private and proprietary knowledge, and undercutting technology transfer (Zalik, 2018). This is despite obligations by the LOSC to acquire and share scientific knowledge and technology (art. 143, 144), according to the principles of technology transfer and the Area as the CHM.

The importance of knowledge is also highlighted in the provisions for an extended continental shelf, which require 'charts and relevant information, including geodetic data, permanently describing the outer limits of its continental shelf' (art. 76(9)), as mentioned in section 3.3. The accuracy and resolution of such data has strong spatial, and thus geopolitical, implications for the delimitation of the boundary. This has led states seeking extensions to conduct detailed studies of bathymetry and sediment cover. Technical knowledge of sedimentary processes and basement structure was also required in developing Annex II of the LOSC, which modified the sediment thickness rule for the Bay of Bengal, due to the extent of the submarine fan therein.

Considering the contrasting approaches to acquiring and sharing knowledge, the overall lack of knowledge, and the selective sharing or use of existing knowledge paints a conflicted picture, particularly considering that the acquisition and presentation of knowledge is dependent on technology.

Technology

Previously, perceptions of the invisible portions of the ocean were provided by way of theology, myth and literature. Today, the ability to acquire images and data from the seabed relies wholly on technology used to access, observe and sample it. In this way, technology mediates our perceptions of the deep seabed both visually and experientially, as it is 'mapped, measured and "rendered intelligible" by geoscientific and environmental measurements, assessments and models' (Barry and Gambino, 2020).

This mediating effect is perhaps most prominent in the visualisation of bathymetric data. Three-dimensional maps of seabed topography are typically vividly coloured and make use of compressed scales to highlight what are in reality subtle depth variations. These disorientating views simultaneously compress the scale of the globe and exaggerate bathymetric slope, providing viewers with a warped and qualitative impression of the seabed. The ability to manipulate scale further distorts viewer impressions of the true scale of the seabed, as mentioned in section 2.4 ‘Seabed classification and visualisation’ (see Figures 2.6 a and b). In addition, uncertainties are glossed over by data extrapolation and digital smoothing effects to generate a continuous, visually pleasing product. Indeed, Sheppard and Cizek (2009) critique the use of 3D virtual globes to visualise landscapes, stating that they ‘engage more complex dimensions of human perception and aesthetic preference’, and ‘invoke not only cognition but also emotional and intuitive responses, with associated issues of uncertainty, credibility, and bias in interpreting the imagery’. These factors also apply to image manipulation techniques that are facilitating new viewpoints of scenes at the seabed, such as immersive VR experiences which place the viewer at the centre of the experience, thus making the viewer feel ever closer to the seabed or even *at* the seabed (Hessler, 2019).

This prevalence of data over physical samples that increasingly constructs the deep seabed has further implications for human perceptions, first in terms of how this data is collected. Following traditional direct sampling tools used since the 1960s, typically deployed from research vessels to collect or dredge sediments, AUVs and ROVs now permit more precise, targeted sampling and observation with minimal damage to the seabed. This shift from ship-based sampling to the remote and robotic may result in abstraction from the materiality of the seabed. However, the need to develop devices that can withstand extreme physical conditions and interactions with marine fauna in fact necessitate engagement with this materiality. In this way, new technologies create ‘new relationships that emphasise the linked materiality of the ocean and the technologies necessary to sense it’ (Lehman, 2018).

In the case of the deep seabed, technologies such as microsensors or benthic chambers closely interact with the seabed, as they engulf or penetrate it. Tools and machines developed for mineral extraction must also navigate and operate with given seabed relief, substrate and the attachment or situation of deposits, and acknowledge the physical differences between deposit types. Accordingly, they are designed in response to the materiality of the seabed. Submersibles also permit humans to physically visit the deep seabed, but a physical barrier remains between researcher and environment, preventing true immersion and creating a new sensory experience. Helmreich (2009) describes this melding of human and machine as an assemblage. Thus the experience of sampling the seabed has evolved as humans have become increasingly embedded within technologies.

Technology seeks to ‘de-mystify what it captures’ (Prescott-Steed, 2012) and to represent the material reality of the environment. However, the actor controlling the data capture process arguably controls the representation, by producing particular types of knowledge. As such, it is important to evaluate the ‘social, political and environmental situatedness’ (Lehman, 2018) of deep seabed technologies, in terms of their intended application and the use of the produced data. Hafsteinsson (2007) first argued for the critical consideration of scientific practices and technology used to capture images of the deep sea, which 'transforms its elements into visible, symbolic forms'. He frames such scientific images as secondary 'thing' agents, as an 'emanation' of the primary human agency of scientists. This may equally apply to data captured by prospective mining operators, as knowledge is used by states to transform parts of the Area from space to place, and ultimately as *territory*. Elden (2013) describes territory as 'a process, not an outcome' and as a 'bundle of political technologies…techniques for measuring land and controlling terrain'. This is exemplified by the ongoing 'quest' – in the words of Mayer et al. (2018) – of the GEBCO Seabed 2030 initiative to map global bathymetry, which includes the development of mapping and data processing tools.

This brief analysis has highlighted some of the contradictions inherent in deep seabed technology and its connection to knowledge. Human capacity to imagine and understand the deep seabed, including its physical features, ecosystems and biogeochemical processes, ultimately impacts the value assigned to it, as explored in the following section.

Value

Mediated by technology, human knowledge of the deep seabed fuels, and is fuelled by, the value assigned to it. Auster et al. (2009) highlight the divergent categories of utilitarian and ethical values usually applied to ocean conservation. Utilitarian values are guided by scientific and economic rationalism, and rest on the material wealth that can be obtained from the deep seabed, and the maintenance of its environmental health to ensure continuing functions that support human life. Meanwhile, ethical values centre around the inherent value of the deep seabed environment, and endorse protecting it simply because it exists (Auster et al., 2009). This includes aesthetic value, which may be limited by a lack of knowledge (Matthews, 2002). Certain values can be recognised in the approaches of different actors to SBM.

As part of an EIA or conservation or management plan, the values of an environment can be classified according to the benefits that its functions provide to human life, which are known as ecosystem services, to provide a quantitative basis for assessment. Such services of the deep seabed include provisioning services, such as valuable mineral deposits and pharmaceuticals from marine genetic resources; regulating services, such as climate regulation and waste disposal; and cultural services, such as aesthetic and educational properties (Le et al., 2017).

The economic value of mineral resources immediately emerges as the value directly associated with SBM, and thus with the Area – since the concept of the Area is inseparable from 'activities of exploration for, and exploitation of, the resources of the Area' (LOSC art. 1). To a degree, the LOSC recognises the intrinsic value of the Area via the CHM principle. As Allen (2001) points out, the Area *itself* is declared the CHM, in addition to its resources, and 'non-consumptive' uses of the deep seabed are not restricted, such as laying cables and pipelines. However, in articles relating to the Area and in defining the remit of the ISA, the

LOSC only refers to economic services supplied by the deep seabed in the form of mineral resources. In stating the obligation to conduct activities in the Area 'for the benefit of mankind as a whole' (art. 140), 'benefit' is arguably construed solely in economic terms by the ISA, while social and environmental factors are ignored (Kim, 2017; Thompson et al., 2018). Furthermore, article 144 obliges the ISA to 'acquire technology and scientific knowledge relating to activities in the Area'. Previously, activities in the Area were defined as 'all activities of exploration for, and exploitation of, the resources of the Area' (art. 1(1)). These articles further highlight the conflation of knowledge and economic value of the deep seabed.

This bias towards economic value is reinforced by language used in legal, industrial and scientific spheres relating to SBM, which appears to be based on terrestrial, agricultural ideas of extraction. For instance, Mn nodules are situated in 'fields' and will be 'harvested' by machines; extraction technology has even been directly compared to combine harvesters (SPC, 2013a). Repeated use of the word 'subsoil' in the LOSC, primarily in defining the Area as the 'seabed and ocean floor and subsoil thereof' (art. 1(1)), underscores this terrestrial connection; marine scientific texts instead refer to sediments or substrate.

Marine scientists have made recommendations on SBM with reference to the multifarious values of the deep seabed (Thurber et al., 2014), and engage with the ecosystem services approach to justify regulating SBM more stringently, adopting a 'ramping up' strategy, or even halting it altogether (Thompson et al., 2018). However, given that the ecosystem services concept is intrinsically linked to human benefits, this limits the possibility to link scientific knowledge to intrinsic values of the deep seabed environment in promoting conservation. Furthermore, the juxtaposition of economic and environmental value of the deep seabed is blurred when considering that mineral resources *are* nature; they grow through accumulation of minerals made available by organisms; their accumulation is microbially mediated; their matrix supports microbial life inside and on the surface; and their structures offer habitat for larger mesofauna, in turn supporting megafauna.

Attitudes towards value also inform approaches to recovery of SBM sites. According to Niner et al. (2018), the provision of financial means to recover disturbed ecosystems 'will not compensate' long-term damage that could last millennia. This finding exposes the imbalance of economic and ethical values of the deep seabed on different timescales. This discord in value provided across temporal – and spatial – scales is also discussed by Thurber et al. (2014).

Overall framework

The themes discussed in this section highlight intersections within the epistemological framework surrounding SBM. Technology plays a mediating role in the symbiotic relationship between knowledge and value at the deep seabed, which is manifested through extraction or conservation, as illustrated in Figure 4.1.

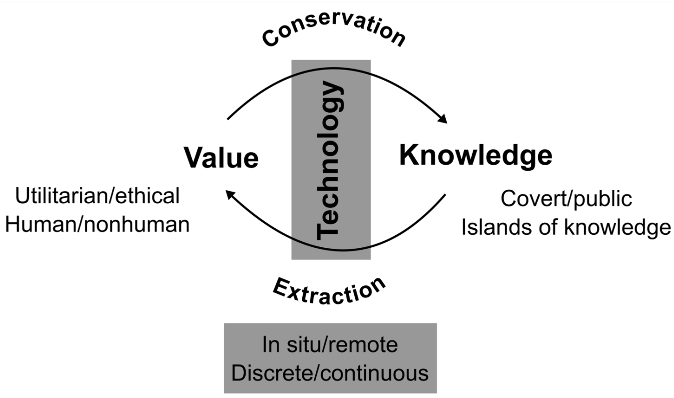

Figure 4.1 *– Relationships between technology, knowledge and value that constitute the epistemological framework of SBM*

Values of the deep seabed impact the purpose of gathering new knowledge, including data requirements, secrecy or transparency of research processes and findings, and the use and dissemination of knowledge. Likewise, existing knowledge and understanding at the seabed influences the values of SBM stakeholders. Technology controls the ability to acquire, present and interpret new knowledge, in addition to new forms of knowledge; and facilitates visual and sensory experiences of the deep seabed that drive perceptions of its value.

The ISA's mandate of sustainable exploitation embodies this complex tension between extraction and conservation. Marine scientists acknowledge and accommodate this tension in studies of the deep seabed, by mostly accepting that SBM will proceed but attempting to inform *how* it will proceed. As such, the deep seabed is mostly constructed by reference to human activities, and particularly as the 'background' to SBM. This accords with Sloterdijk's description of human endeavours in the ocean as a series of experiments, which ignore the external conditions that constitute 'the environment' (Sloterdijk, 2018). Environmental awareness has grown through the 20th century, including knowledge of environmental vulnerability to side-effects from these human 'experiments'. To achieve effective management of the deep seabed in the face of SBM, a broader and deeper understanding of its value to humankind should be cultivated; but also its value to more-than-humankind, that is, the organisms and matter of the deep seabed. These ideas are explored further in the next section.

4.2 Seabed space

Extending critical understanding of the deep seabed is necessary at this delicate point in the balance between extraction and conservation. In much research, and particularly from an SBM operational and regulatory perspective, the seabed has been considered as an inert accessory to ocean systems. It has also been described as 'fuzzy' (Anderson et al., 2008), and the site where SBM takes place 'at the surface of a surface beneath a surface' (Childs, 2018). Working from the premise that the seabed is in fact a distinct conceptual and material entity, this section explores ideas of volume, materiality and scale that characterise deep seabed space in the context of SBM, through the epistemological filters outlined in the previous section.

Surface, depth and volume

Historical perspectives of the ocean as a frictionless, traversable surface previously facilitated mercantilist and capitalist economies based on oceanic transport of goods, with the legacy of this view continuing to underline the postmodern capitalist flow of goods between fixed locations, as argued by Steinberg (2001). However, critical discussions of ocean space are increasingly accounting for its volume, as prompted by Elden (2013) and taken up by multiple scholars (e.g. Bridge, 2013; Grundy-Warr et al., 2015). Given that territory is made and controlled through volumes, Elden argues for the importance of considering Earth's three-dimensional materiality to be able to fully understand its intersections with the social and political.

The deep seabed has been depicted as a replica layer of the featureless ocean surface found below the water column; or a '"surface of earth" below a "surface of water"' (Childs, 2018). Instead of a surface for transportation, the deep seabed is framed as a natural placeholder of mineral riches, thus a flat space to be claimed, explored and exploited. The ability to present bathymetry or habitat classifications in 3D emphasises this view, by displaying an undulating surface with little indication of underlying strata. Furthermore, images and videos captured by ROVs, AUVs and submersibles frequently show the seabed as a featureless, monotone expanse of sediment that acts as a backdrop for alien-like organisms, often presented in documentaries or museums as isolated oddities (Figure 4.2). Meanwhile, the majority of SBM impact studies focus on disturbances to benthic megafauna rather than smaller organisms residing within and below the seabed, including microbes (Orcutt et al., 2020).

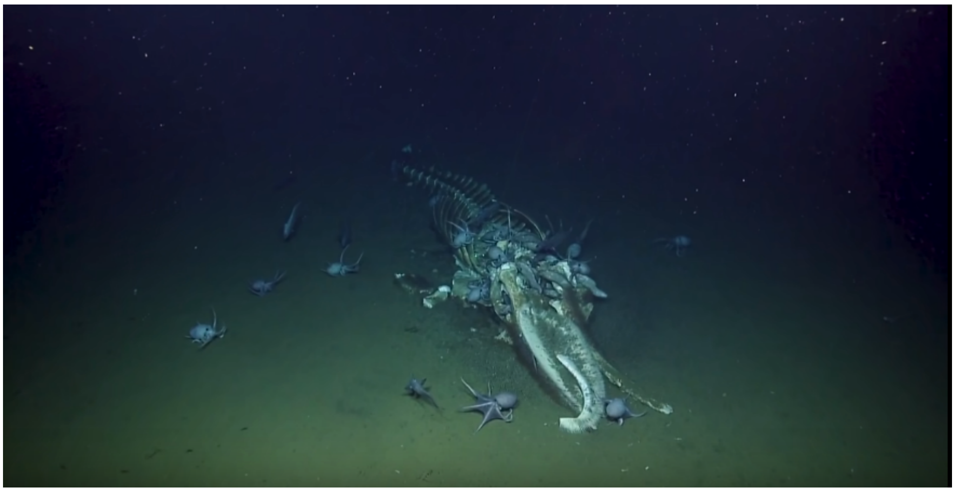

Figure 4.2 *– Screenshot taken from a livestream of the Nautilus expedition, acquired by the Hercules ROV on 16 October 2019. A whale fall attracts scavengers at the Davidson Seamount in the northeast Pacific Ocean. (https://youtu.be/CZzQhiNQXxU)*

In terms of the regulatory framework for SBM, the Area and continental shelf regimes represent the only delimitations prescribed by the LOSC that acknowledge any depth or volume to ocean space; all other maritime boundaries are drawn across the ocean surface from a top-down view. A volumetric aspect to the seabed is alluded to in the definition of the Area in the LOSC as the ‘seabed and ocean floor and subsoil thereof’ (art. 1(1)), and of the continental shelf as comprising ‘seabed and subsoil’ (art. 76(1)). No further explanation is provided of these terms; presumably they are intended to encompass all possible components of the seabed. The complex provisions of the LOSC on an extended continental shelf also acknowledge bathymetry in three dimensions, by obliging the ‘thickness of sedimentary rocks’ to be taken into account (art. 76(4)).

An interesting comparison can be made between the ‘discontinuous character of extractive spaces’ described by Bridge (2009) in relation to oil wells or mine shafts, and the SBM process. Typical extractive landscapes involve ‘discrete, molecular point[s] of access…to mineral-rich portions of the underground’. These points of access are fixed, mostly linear forms of infrastructure used to penetrate volumes of resources as efficiently as possible, due to the expense and physical difficulty of drilling through the subsurface. Likewise, SBM involves a discrete access point and linear, vertical extension, in the form of vessels descending riser pipes from the sea surface; but these are not fixed and can navigate across the sea surface, move through the water column, and connect with mobile rovers or submersibles at the seabed. Through the interconnection of these components, SBM operations move through the water column in three dimensions. However, technological constraints prevent exploration and production *below* the seabed surface; thus the ‘depth’ of the seabed itself remains untouched by SBM, at least below the lower limit of mineral deposits that are visible on the surface. In this way, SBM is more similar to the ‘expansive geographies of forestry or agriculture where production and the generation of value is diffused across a broad surface’ (Bridge, 2009).

This lacking attention to the seabed's volume can be attributed to a number of factors. First, knowledge of the dynamics and composition below the surface of the seabed is largely limited to the upper metre of reactive sediment, due to the difficulty of taking samples and measurements at greater depth. Second, life below the seabed is dominated by burrowing invertebrates and microbes, which are mostly unsampled, undocumented and unclassified taxonomically. Third, very little is known about mineral deposits below the surface of the deep seabed; the SBM industry focuses on deposits that are visible from the water column, which can be quantified by remote observation and sampled for mineralogical characterisation. However, all three deposit types are inherently connected to the seabed subsurface. Mn nodules may grow diagenetically through mineral precipitation from the sediment, and grow partially submerged within the sediment. Hydrothermal fluids form and migrate through the seabed to re-emerge and precipitate minerals that form SMS deposits, and also form deposits below the surface. Finally, CRCs form as an intrinsic component of seabed substrate. As such, the verticality and volume of the seabed are integral components of SBM mineral formation and situation.

The study of microbial life in the deep biosphere, based on a very small number of deep core samples, seems to be the only field that focuses explicitly on the extended depth of the seabed. In contrast, the study of uplifted marine sediments and fossils, and even ophiolites, is widespread at surface outcrops onshore. The juxtaposition of these disciplines neatly demonstrates the seabed not as a surface, but as a transition zone between biosphere and geosphere. From this perspective there is no simple answer to the question 'how *deep* is the seabed?', but exploring its materiality can provide some further insight.

Materiality

Geopolitics is detached from the materiality of the infrastructure, territory and resources it aims to control, argue Barry and Gambino (2020), and should attend more closely 'to the relations between physical and biological things'. This deeper focus on the 'geo' in the 'geopolitical' has been adopted by Steinberg and Peters in relation to ocean space, in proposing a 'wet' and then 'more-than-wet' ontology based on the fluidity, turbulent chaos and immanence of the ocean (Steinberg and Peters, 2015; Peters and Steinberg, 2019).

Seabed space is often depicted as empty, not least in its legal delimitation by UNCLOS as 'the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction' (art. 1(1)), which defines the Area by way of exclusion. This frames it as negative space, in contrast to accessible land and coastal areas, while other zones are delimited with reference to the distance from the territorial sea baseline. The word 'Area' reinforces this perception, as a two-dimensional term defined as 'a space allocated for a specific use' or 'the extent or measurement of a surface or piece of land'; and derived from the Latin for a 'vacant piece of level ground'.[15] Furthermore, the ISA draft exploitation guidelines repeatedly refer to 'mining areas', as opposed to mines, as would be discussed onland. These characterisations of the deep seabed as vacant, empty space, stripped of materiality, accord with capitalist frontier narratives perpetuated by scientists and mining proponents alike, especially in reference to mineral resources (Steinberg, 2001; Havice and Zalik, 2018).

For effective study and conservation of the deep seabed, its unique materiality must be acknowledged. Clearly, it is distinct from the water column in terms of the biogeochemical cycles taking place within sediment and across the sediment–water interface, the ways of life of burrowing infauna and sessile epifauna, and the physical change in state from liquid to sediment-dominated or hard substrate. However, it also acts as a porous, 'fluffy' zone of exchange for substances between biosphere and geosphere. In the words of Childs (2018) 'the subterranean is not solid but porous…where matter changes state between molten rock, liquid water, mineral-rich gas and precipitated ore'. The permeable membrane of the deep seabed can also be considered as a continuation of the liminal zone that can be experienced at the coast, thus as the interface between land and sea. The division of lighter, granitic continental crust and denser, basaltic oceanic crust underpins this division at the planetary scale, as arguably the most important material control on seabed processes and mineral formation.

Employing the Deleuze and Guattarian concepts of smooth and striated space reveal further possibilities. Ocean space has been described as 'smooth space *par excellence*' (Deleuze and Guattari, 1988), striated by lines of measurement, delimitation and order which render it 'forever encoded in the relationship between the smooth and the striated' (Jones, 2016). The seabed also appears to be captured in this paradox, depending on perspectives of volume and materiality. Ideas of striation naturally arise when considering the seabed in a vertical sense, as a surface or interface, or when thinking of it as the lower boundary of the ocean, with the sea surface as the upper boundary, both defined by broad state changes. Moving away from these conceptual, diagrammatic definitions, when the seabed is framed as a graded, porous, dynamic interface, it feels more like a continuous smooth space. Its heterogeneity in all dimensions, mineral precipitation at points of chemical concentration and saturation, and the disruptive movements of burrowing fauna call to mind the nomadic, vectorless features of smooth space, and its division into SBM license areas, or by contested continental shelf–Area boundaries, represent imposed striation that seabed processes and SBM impacts continuously overflow and defy.

The materiality of the seabed likewise overflows conceptual, and material, containment. For instance, as discussed in section 2.4 'Remote mapping and observation', satellite altimetry may erroneously image extinct oceanic crustal structures below the present-day seafloor due

[15] Oxford University Press (2019), https://www.lexico.com/definition/area (accessed 11 January 2020)

to their gravitational impact on the ocean surface. Distinguishing between these structures and true bathymetry is often impossible without the use of additional mapping methods. Furthermore, acid mine drainage is vividly envisioned at an ‘open-mined’ SMS deposit by Orcutt et al. (2020) (see section 3.2 Implications for ecosystems), where the sudden exposure of sulphides to oxic waters has the potential to destabilise the local chemical environment and microbial ecosystem. These two examples present interesting situations whereby various materialities of the seabed overlap and interact across spatio-temporal boundaries, in both cases exceeding and evading human attempts to control and contain.

A molecular-scale, elemental depiction of the seabed, with a focus on ephemeral state changes, situates it within the more-than-wet ontology of Peters and Steinberg (2019). Here, soft-bodied invertebrates, hydrothermal fluids, pore space and flocculent silts and clays at the seabed complement the spray, foam and bubbles that disrupt the ocean–air interface. Components of SBM, including hard nodules and concretions, fractures and crevices, and sediment plumes, enrich this vision of a wholly heterogeneous, mixed-state space. The wet and more-than-wet ontologies envision ocean space in contrast to land, whereby the continuously mobile and fluid ontology of the ocean is defined in opposition to the fixed, stable land, and the intersections of its various processes are even rhizomatic in character. But the seabed perhaps sits more comfortably with the fixed ontology of land, against, around and through which more mobile, fluid forces move. This further complicates characterisation of the seabed, as a solid yet dynamic framework. Some clarity may be sought by turning to scale.

Scale

The deep seabed exists on unique temporal and spatial scales. In contrast to previous ideas of a homogeneous ‘desert’, new data is revealing the deep seabed to be a site of high heterogeneity at all scales (Zeppilli et al., 2016), in terms of bathymetry, habitats and substrate cover, for example. High heterogeneity thus becomes a defining component of the deep seabed, as it increases diversity, enables numerous habitats and faunal assemblages, and influences regional ecosystem functions. By revealing the complexity and heterogeneity of the seabed at numerous spatial scales, new observation techniques have challenged traditional paradigms of deep-sea ecology, including total seabed area and food availability (Danovaro et al., 2014). Accordingly, spatial scale and dimensionality are vital for studying and understanding deep-sea ecology. High-resolution mapping tools increasingly allow identification of smaller-scale habitats and structures, and molecular techniques continue to advance. Although deep-sea microbes are critically understudied, they are thought to control global cycles of essential nutrients for primary production (Danovaro et al., 2014), broadly support deep-sea food webs, and are a vital source of OM as primary producers at aphotic environments (Orcutt et al., 2020). Subseafloor microbial chemosynthesis at active vents alone is estimated to produce 1.4 Tg carbon per year (McNichol et al., 2018). The influence of invisible microbes on ocean systems is ubiquitous, and illustrates the importance of scale in understanding the role of the seabed in ocean systems and cycles. At the same time, geologic and ecologic settings introduce heterogeneity at the basin scale, where knowledge gaps remain regarding the drivers and mechanisms of plate tectonics, including hotspots.

Time is also a complex concept at the seafloor. The accumulation, compaction and lithification of sediments occur on the scale of millions of years, as do the tectonic cycles that produce the overall structure of ocean basins. This prevalence of deep time is also seen in the generally slow, long life of deep-sea fauna, and slow rates of OM input and burial. However, a single timescale cannot be applied as a blanket concept, as continuous and short-term processes and cycles also make the deep seabed environment. For instance, the intricately interconnected biogeochemical cycles that govern the benthic realm occur at a range of timescales, with continuous chemical exchange and burrowing enabling 'ventilation' of the BBL, and seasonal variation observed in OM influx from the surface ocean. Short-term or instantaneous events also take place at the deep seabed, including deep eddies as 'echoes' of surface currents (Aleynik et al., 2017), turbidites, volcanic eruptions and earthquakes.

As Thurber et al. (2014) point out, though, there is a scalar discrepancy between the processes occurring at the deep seabed and the ecosystem services they provide to humans; for slow-paced seabed carbon burial to mitigate anthropogenic CO_2 emissions, for example. This discrepancy persists in the opposite case, as pollution and disturbance from human activities reach and disrupt seabed processes on obdurately human timescales (Ramirez-Llodra et al., 2011).

Mineral resources constitute unique spatiotemporal features at the deep seabed. An Mn nodule is the result of concentric growth at rates of millimetres per Myr, with ongoing microbial processes in pore spaces and secondary infill. Meanwhile, CRCs build up layerwise at similar rates, with precipitation interrupted by changes in water column oxicity, thus preserving a layered record of local conditions. The growth of SMS deposits is highly variable and controlled by vent activity, itself episodic, with a blurred boundary between active and inactive vents, inextricably linked to symbiotic processes at the base of the vent ecosystem. Thus each mineral deposit encapsulates its particular history of growth and erosive phases, local chemical and hydrodynamic conditions, and interactions with biota. Significant spatial heterogeneity is also introduced by each deposit type. On the abyssal plains, where variation in relief is scarce, Mn nodules provide hard substrate and microhabitats; the various features of CRCs, including cracks and planes, likewise offer shelter from strong currents; and vent structures hosting SMS grow in irregular vertical, lateral and subsurface structures.

These spatiotemporalities, loosely hierarchically organised from the microbial to the tectonic, are disrupted or overprinted by the mapping, measuring and extracting processes associated with SBM. For example, the limited number of in-situ benthic measurements, and minimal seabed area mapped in high resolution by acoustic sounding methods, mean that the majority of the deep seabed is represented by extrapolated or interpolated data. Meanwhile, areas of high resource concentration act as discrete 'islands of knowledge' (as discussed in section 4.1 Knowledge). Mining license areas and zones set aside for conservation (e.g. APEIs) likewise bound poorly resolved areas of the deep seabed and determine the boundaries of direct mining activity (see Figure 4.3). Hessler (2019) observes that the CCZ 'is represented as a kind of strange new island that seems to have appeared in the middle of the Pacific Ocean: like a colourful puzzle, a long stretch of the sea marked in different hues, each indicating which nation claims which part of the ocean floor'.

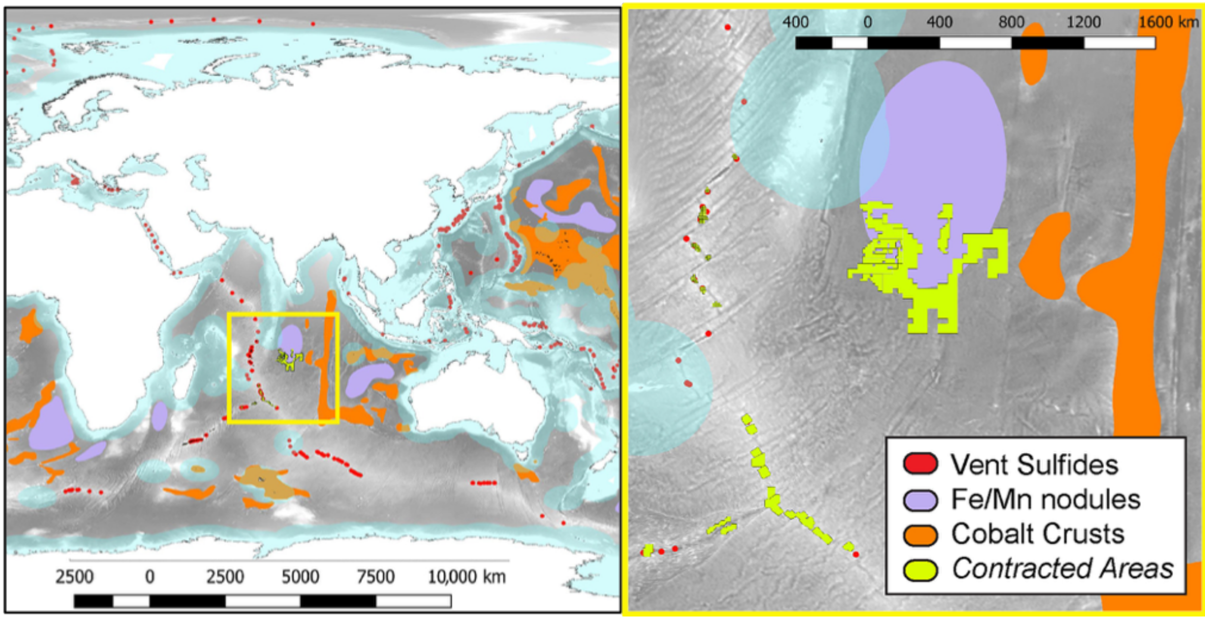

Figure 4.3 *– Superposition of mineral resources and exploration license zones in the central Indian Ocean. Left: global seabed resource distribution. Right: closeup view of yellow bounded box. From Orcutt et al. (2020)*

Extractive aspects of SBM will have a more direct impact. 'Landscapes of energy extraction are portals, worm-holes between two worlds in which time and space work differently' – so Bridge (2009) asserts in reference to subsurface hydrocarbon deposits. He notes that these worm-holes lead into the world of deep time, of processes beyond human control, and that the drilling process 'compresses time' by moving through hundreds of million years' worth of strata. In light of the variable speeds of SBM deposit formation, Childs (2018) points out how 'processes of extraction "make" resources in a relative instant'. In contrast to the focussed direction and discrete point of extraction represented by a borehole, SBM tools navigate over the seabed and lift or detach mineral deposits across a planned area. In this way they terminate mineral precipitation and the linked biogeochemical processes, and isolate the locus of these processes from its position in the landscape, thus altering the spatial makeup of the area. As discussed through section 3.2, impacts extend further than the direct zone of extraction; the areal footprint of mining activity at a single site would be several hundreds of km^2 per year for Mn nodules, several tens of km^2 per year for CRCs, and an area <0.2 km^2 for the Solwara 1 SMS site (Petersen et al., 2016). A comparable vertical footprint above and below the seabed has not been quantified. Variable estimates have been reported for species recovery in mined areas, as explored in section 3.2 Implications for ecosystems, but impacts due to habitat removal and other parameters are likely to persist over 'geological timescales' (Gollner et al., 2017).

As Childs (2018) asserts, 'the governance of [SBM] rarely speaks to the same temporal register as the geologic'. For example, the ISA's draft exploitation guidelines suggest that baseline data should be collected from just 15 years of monitoring (Annex IV art. 1(b)). Childs (2018) has advocated accounting for spatial and temporal dimensions in geopolitical considerations of SBM, in order for 'earth systems and the materiality of the deep seabed…[to be] taken seriously'. He also states that 'the geological processes of the ocean floor and its topology can move so slowly as to be inert, obdurate, even disconnected or bounded'. Like Childs, I assert that 'deep' geologic time must be acknowledged in order to understand and value the deep seabed and its resources; however, I reason that temporalities of the deep seabed do not 'vacillate between the dynamic and the fixed' but are continuous, cyclical, multiscalar, and inherent in the state of the seabed at any moment in time. This viewpoint is supported by the integration of faunal activity into the concept of seabed space, particularly the acknowledgement of benthic–pelagic exchange as facilitated by microbes and burrowing organisms.

4.3 Subseascapes: the seabed as an actor

The discussions of the previous sections can now be consolidated to reflect on the concept and material reality of the deep seabed, as it intersects with SBM.

Throughout the thesis, definitions and delimitations of the deep seabed have tended to vary with discipline or perspective, and are tied up with concepts of space, time, movement and scale. If the seabed is taken to mean the sediments coating the oceanic basement, then it is bounded vertically by the underlying geosphere, into which it gradually lithifies, and the overlying water column, where it arguably ends at the uppermost reaches of the reactive layer of sediment. The lateral limit of the seabed is the land, which positions the seabed as an interesting intermediate in the context of the land/sea binary; the continental shelf continues the land surface underwater, slowly grading into marine sediments atop oceanic crust. Yet exchange with the water column is continuous, and seawater penetrates deep into the seabed. Thus the seabed is neither land nor sea, but a sort of transition zone in all dimensions, in terms of its material composition; and scenes at the seabed would be better characterised as subseascapes.

However, the idea of a land/sea binary is cemented by the legal regimes that divide sovereign onshore territory and waters from areas of ocean space beyond national jurisdiction. In turn, this assists the construction of ocean and seabed space from a land-based – that is, human-based – perspective. For example, the CHM principle applies to *mankind* and mineral deposits are *resources*, while the rights *of* marine fauna go unacknowledged, in contrast to the rights of mankind *over* marine fauna (Jones, 2016). Although few areas on the planet are untouched by human activities, the deep seabed remains arguably the most distanced and autonomous. Thus, the principle of CHM – already seriously undermined by the legal arrangements of the ISA and its SBM regime – seems inappropriate to govern the Area, given the life-sustaining benefits afforded to non-mankind by the deep seabed, and its independent life. This liveliness is captured by the 'vibrant' materiality described notably by Bennett (2009).

In promoting the ocean as an actor, Lehman (2018) argues that it 'exercises agency, enrols others, and is enlisted itself to actively and dynamically shape reality' – actions that arguably apply to the deep seabed, according to its properties as described in this thesis. To involve it as an actor in the developing situation surrounding SBM would require new recognition of its expanse beyond boundaries, and value beyond the human.

5. Conclusions

The flurry of debate and ongoing research surrounding SBM offers the chance to consider the subject from a critical perspective, to find new ways to understand and value the deep seabed. This thesis has drawn from a broad literature review on deep seabed exploration and science, and a comprehensive review of the minerals, impacts and regulatory framework associated with SBM, to examine new, conceptual perspectives on the deep seabed.

The unique and extreme characteristics of the deep seabed have made it highly challenging to research, so that deep-sea imaginaries have been oversimplified. However, specific 'islands of knowledge' exist in relation to concentrations of economically promising mineral resources, which form through complex arrangements of tectonic, oceanographic and biogeochemical processes on deep geologic timescales. These deposits become an intrinsic part of the seabed, as they comprise distinctive features of the subseascape, while hosting and symbiotically facilitating life from the micro- to tectonic scale. Mining will indisputably have short-term and long-term impacts on the environments of all three deposit types, by removing essential ecosystem components, disturbing faunal communities and microbial processes above and within sediment, and disrupting the physical structure of the seabed. However, the scale and temporal nature of these impacts and ecosystem recovery is unknown, primarily due to the lack of operational tests and baseline understanding of the deep seabed. The regulatory framework represents a fragmented effort at protection that does not account for uncertainty or the specific materiality of the deep seabed, and that emerges from ideological conflict by prioritising expected economic value and human benefit over realistic or even precautionary treatment of the deep seabed.

Rather than an inorganic system that operates mechanically, with biologic life in a separate temporal register, the deep seabed is a living place that sees fauna integral to the processes of mineral growth, and reliant on the habitats that mineral deposits provide. Conceiving of the deep seabed as a porous, rhizomatic zone of continuous exchange allows a more sensitive view of its vulnerability to disruption by SBM, as a place that is not capable of infinite absorbance or regeneration beyond human timescales. By broadening perceptions of the seabed, valuing timescales beyond the human, and acknowledging the deep seabed as an actor, SBM actors can find new support for arguments to effectively protect the deep seabed.

5.1 Implications

The ideas presented in this thesis may contribute to new perceptions of the deep seabed in scientific research, legal characterisation and approaches to regulating SBM. Extensions of this research could include further integration of seabed space into discussions of ocean space; exploration of microbial life in the context of vibrant matter, the organic/inorganic and the biosphere/geosphere; and the critical study of marine pollution at the seabed, informed by biogeochemical studies.

5.2 Limitations

Subjectivity is a key limitation of the research design, which could threaten the validity of the study. Furthermore, the deep seabed is a broad topic which cannot be represented as a single environment. Accordingly, literature from a wide spectrum had to be consulted and only a general account of seabed features was provided. The limited number of studies on specific sites in the Area represents another limitation; since most of the findings relate to SBM, a 'baseline' understanding of the seabed was difficult to attain.

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