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Research article

Governing deep sea mining in the face of uncertainty

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ABSTRACT

Progress towards deep sea mining (DSM) is driven by projected demands for metals and the desire for economic development. DSM remains controversial, with some political leaders calling for a moratorium on DSM pending further research into its impacts. This paper highlights the need for governance architectures that are tailored to DSM. We conceptualise DSM as a type of complex orebody, which encompasses the breadth of environmental, social and governance (ESG) risks that make a mineral source complex. Applying a spatial overlay approach, we show that there are significant data gaps in understanding the ESG risks of DSM. Such uncertainties are compounded by fact that there are no extant commercial DSM projects to function as a precedent – either in terms of project design, or the impacts of design on environment and people. Examining the legislation of the Cook Islands and International Seabed Authority, we demonstrate how regulators are defaulting to terrestrial mining governance architectures, which cannot be meaningfully implemented until a fuller understanding of the ESG risk landscape is developed. We argue that DSM be approached as a distinct extractive industry type, and governed with its unique features in frame.

1. Introduction

Global demand for minerals and metals is driving the exploration and creation of new resource frontiers. Whether viewed through the lens of climate change, heightened dependency on advanced technologies, or the demands of a growing global consumer base, the need for bulk commodities and speciality metals is expected to rise (Svobodova et al., 2020; Lèbre et al., 2019). Future market demand is likely to double or even triple by mid-century, as shown by the Organisation for Economic Co-operation and Development Global Material Resources Outlook to 2060 (OECD, 2019).

Deep sea mining (DSM) holds potential for meeting a considerable proportion of future demand. Deep sea deposits exceed the global terrestrial reserve base of several key metals (Hein et al., 2013; see also Petersen et al., 2016; Okamoto, 2015; Boschen et al., 2013). Many of the minerals identified as being critical to electronics, batteries, and other low-carbon technologies are also those existing in seabed mineral resources (Arrobas et al., 2017; Graedel et al., 2015). Many prospective DSM areas are located in the exclusive economic zones (EEZ) of island nation states such as the Cook Islands, Samoa, and Kiribati, where economic and social transformation could be driven by receipt of resource rents. Developers emphasise the potential for DSM to replace some terrestrial sources of metals associated with environmental and social impacts (Hein et al., 2020; Paulikas et al., 2020a, 2020b; Sanderson, 2018; Petersen et al., 2016).

We characterise DSM as an emerging resource frontier. It is a frontier because drawing metals from the sea floor forces the extension of existing geographic boundaries for resource extraction, and because technological innovations will be required to extract deposits that can be located 5 km below sea level. DSM is emerging because no commercial production of deep sea minerals is currently taking place. Nautilus Minerals' Solwara 1 Project in Papua New Guinea is the only commercial-scale operation to have received mining approval. Approved in 2011, the project was withdrawn in 2019 following difficulties procuring vessels (Hosie, 2018), financial and corporate issues (Decena, 2019), and community and civil society opposition (Filer and Gabriel, 2018; see also Childs, 2019). Nautilus Minerals was assigned into bankruptcy in November 2019 (PWC, 2019).

The collapse of the Solwara 1 Project added to pre-existing doubts and concerns about the viability of DSM. Many of the concerns relate to

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uncertainty around environmental impacts of DSM. In August 2019, the national leaders of several island states, including Fiji, Vanuatu, Kiribati and Papua New Guinea, supported a 10-year moratorium on DSM to allow time for scientific research (PIF, 2019). A European Parliament declaration in January 2018 similarly called for a moratorium on DSM 'until such time as the effects of deep-sea mining on the marine environment, biodiversity and human activities at sea have been studied and researched sufficiently' (European Parliament, 2018). More recently, Fauna and Flora International, an international non-government organisation, released a risk assessment of DSM (Howard et al., 2020). It also recommended a moratorium on commercial extraction pending further research and governance improvements.

Mineral exploration of the deep sea is progressing. Thirty contractors worldwide are licenced to explore in international waters (ISA, n.d.-a). The Cook Islands passed a refreshed Seabed Minerals Act in June 2019, and has signalled its intent to pursue commercial DSM in the near future as a key part in its economic development strategy (Brown, 2019; SMA, 2019; SMA, 2014). Market demand for high-value metals such as cobalt, titanium and manganese will likely provide strong commercial incentives for developers in overcoming technological barriers to exploiting these resources.

This paper highlights the need for governance architectures that are tailored to DSM. To this end, we engage two critical questions: How are legislatures grappling with undefined environmental, social, and governance (ESG) complexities of DSM? And: To what extent do regulations to-date reflect the uniqueness of DSM as an emerging resource frontier? These questions need to be addressed before the future prospects of DSM can be fully assessed. A review of the literature on ESG risks of DSM is provided in section 2. In section 3, we characterise DSM as a kind of 'complex orebody' (Valenta et al., 2019), and apply a geospatial approach to assessing ESG risks of DSM. This analysis frames section 4, a critical review of the DSM governance systems established by the International Seabed Authority (ISA) and the Cook Islands Seabed Mining Authority.

2. Deep sea mining research: literature review

Research on the resource potential of seabed minerals dates back to at least the 1960s (e.g., Macdonald et al., 1980; Corliss et al., 1979; Scott et al., 1974; Backer and Schoell, 1972; Mero 1965, 1962). Commercial interest in DSM in the 1960s and 1970s drove the formation of multinational consortia aiming to extract deep sea minerals from the Clarion Clipperton Zone in the Pacific Ocean (Hein et al., 2020; Sparenberg, 2019; Glasby, 2002). By the 1980s, many such ventures had been discontinued, due to falling commodity prices and legal-political controversies around mining governance under the United Nations Convention of the Law of the Sea (UNCLOS) (Glasby, 2002). The early 2000s saw renewed interest in deep sea minerals, driven in part by projected minerals demand and supply risks (Sparenberg, 2019).

Three types of seabed mineral resources have been identified in literature (Miller et al., 2018):

(i) **polymetallic nodules**: primarily manganese and iron, though significant amounts of other metals also occur, including nickel, copper, cobalt, molybdenum, rare earth elements and lithium;
(ii) **cobalt-rich ferromanganese crusts**: manganese, iron and a wide array of trace metals such as cobalt, nickel, copper and titanium, as well as molybdenum, tellurium, platinum, zirconium, niobium, bismuth and rare earth elements; and
(iii) **seafloor massive sulphides**: high in sulfide content, but also rich in copper, zinc, gold, silver, and numerous other metals.

The Pacific region is particularly rich in deposits of all three types and has been previously studied by Miller et al. (2018), Smith (2018), SPC (2016) and Okamoto (2015). Global spatial distribution of these deposits as released by the ISA (Mahapatra and Chakravartty, 2014) and their location in EEZs is shown in Fig. 1. As Petersen et al. (2016) suggest, researchers should be mindful in differentiating between types of deep sea minerals, their biophysical environments, and the political and legal contexts in which they are located (e.g., whether located in international waters or national EEZs).

Across the scholarly literature on DSM, the predominant focus is on environmental risks. Danovaro et al. (2014) characterise deep sea ecosystems as a 'major ecological research frontier' with complex structures and interactions, notwithstanding limited current knowledge on marine biodiversity (Canonico et al., 2019). Ecological richness has been observed in areas with significant mineral resource potential (Maxmen, 2018; De Smet et al., 2017; Amon et al., 2017). As to the potential ecological impacts of DSM, modelling suggests that deep sea ecosystems would be slow to recover from physical disturbances and/or toxic releases associated with mineral exploitation (Hauton et al., 2017; Jones et al., 2018; Miljutin et al., 2011). Van Dover (2014) raises the potential for species extinction as a consequence of DSM. Evidence also shows that the deep sea provides ecosystem services, which may be disrupted as a result of mining (Thornborough et al., 2019).

Methods to manage potential environmental impacts of DSM are nascent. Niner et al. (2018) argue that it would be 'impossible' for any DSM project to achieve 'no net loss of biodiversity', because industrial-scale remediation is not sufficiently developed, and because biodiversity offsets are unfeasible given current lack of data. Van Dover et al. (2014) suggest that the costs of restoring deep sea ecosystems could be two or three orders of magnitude greater than analogous restoration in shallow-water systems.

Compared to environmental risks, the social risks of DSM are less explored, and generally relate to issues of community consent to DSM. Filer and Gabriel (2018) point out that, unlike terrestrial mining, DSM involves no clearly delineated 'local community' to form the focal point of a so-called 'social licence to operate'. Aguon and Hunter (2018) argue for the inclusion of free, prior and informed consent as a precondition to DSM, consistent with the UN Declaration of the Rights of Indigenous Peoples. Broader analyses of potential socioeconomic impacts, or the social impacts of land-based components of DSM, have not been examined, except to estimate the commercial value of deposits (SPC, 2016; Hein et al., 2015).

Recent studies point to a concern that mineral exploitation will begin without establishing appropriate governance structures to manage environmental risks (Craik, 2020; Ardron et al., 2018; Cuyvers et al., 2018; Thompson et al., 2018; Zalik, 2018; Jaeckel et al., 2016, 2017). These studies largely focus on governance in international waters, and pre-date recent regulatory developments at the ISA (2019). They also give little attention to governance in waters within national jurisdictions. Petterson and Tawake (2019) provide an overview of the governance history of DSM in the Cook Islands, but their analysis pre-dates the most recent legislation passed in 2019.

Overall, extant literature on DSM indicates a nascent but burgeoning body of research into an emerging resource frontier. Against increasing market interest in developing DSM as an industry, the literature calls for the careful definition and management of ESG risks.

3. Deep sea minerals as complex orebodies

3.1. The concept of complex orebodies

The term 'complex orebodies' typically refers to subsurface geological conditions. In this context, the geological complexity of an orebody determines the risks of developing it. The more complex an orebody is, the greater the risk that the project would be unfeasible or uncommercial. More recently, researchers have argued for an expanded conception of complexity, to encompass ESG factors surrounding the orebody. Valenta et al. (2019), in their analysis of 308 undeveloped copper orebodies, demonstrate that the future supply will require navigating critical ESG factors surrounding projects. Lèbre et al. (2019) extend this

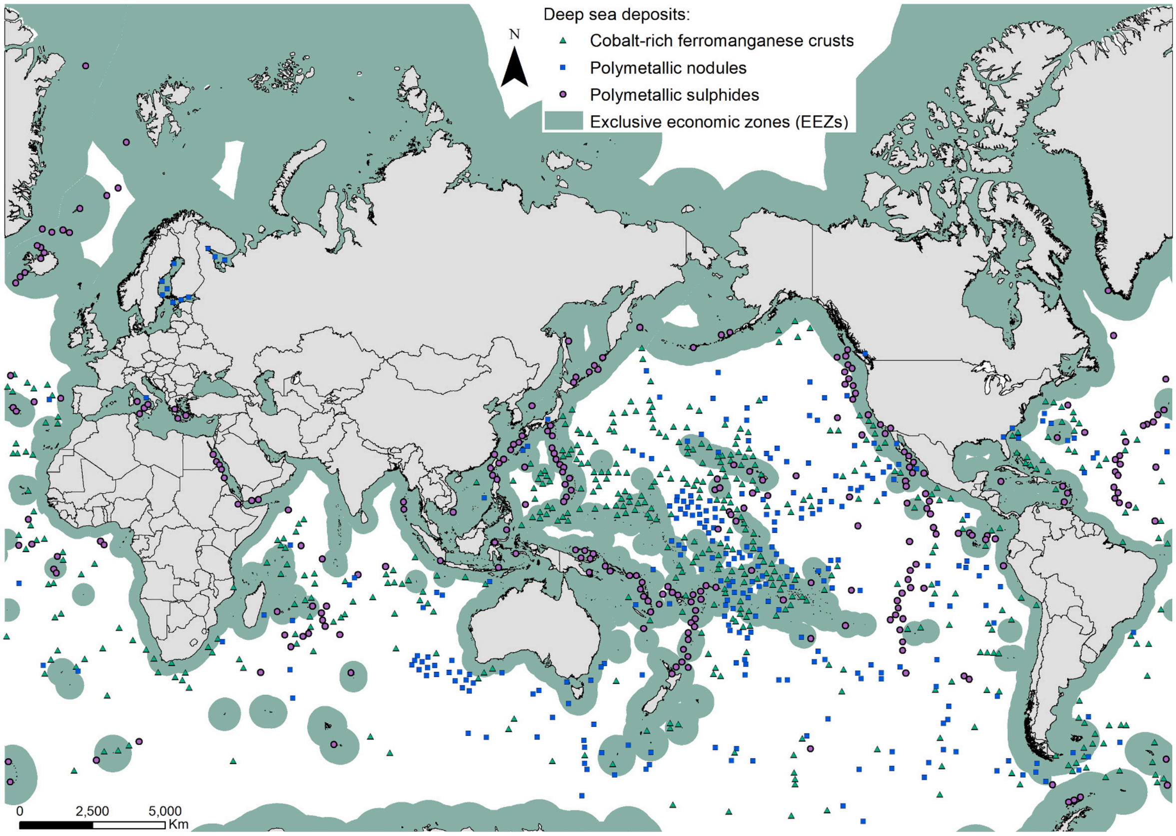

Fig. 1. Location of deep sea deposits and their spatial overlay with the exclusive economic zones (EEZs). EEZ boundaries from the VLIZ Maritime Boundaries Geodatabase (2019). An EEZ is a sea zone extending from a state's coast or baseline over which the state has special rights over the exploration and use of marine resources. Generally a state's EEZ extends 200 nautical miles out from its coast, except where resulting points would be closer to another country.

analysis to a global profile of mining 'source risks' – i.e. ESG factors local to the mine site that could adversely impede development and operation. They show that a large proportion of global reserves for iron (47%), copper (63%), and aluminium (88%) are subject to multiple and concurrent ESG risks. The key point is that the viability of mining projects depends not only on overcoming mineralogical complexity, but also complexities arising from ESG factors.

We characterise the complexity of DSM by assembling a profile of ESG risks. Our objective is to ascertain the extent to which deep sea mineral deposits exhibit characteristics of complexity in the sense described by Valenta et al. (2019). A secondary objective is to assess the extent of global-scale data available for the deep sea. Improved availability of multiple criteria datasets has increased the scope and quality of analysis that researchers can perform in understanding source risks in emerging resource frontiers (Northey et al., 2017; Graedel et al., 2015; Mudd et al., 2013); however, none of this existing work focused on DSM.

A geospatial overlay approach is applied, adopting the approach taken in Owen et al. (2020), Lèbre et al. (2019; 2020), and Valenta et al. (2019). The approach assembles the ESG risk profile associated with a spatial context. In effect, it provides a basis for analysing the ESG risks posed by mining to the local-level context, and conversely the risk the context can pose to mining development. This approach recognises that tension between mining and various ESG factors may restrain access to the orebody. The ESG risk profile is multi-faceted: having multiple ESG risks in the same location indicates heightened complexity. The ESG risk set applied to DSM comprised the eight indicators shown in Table 1.

Table 1
ESG risk set applied to deep sea mining.

Risk category	Category type	Data sources
Biodiversity	Environmental	Global Terrestrial Biodiversity dataset (Jenkins et al., 2013)
Waste	Environmental	Terrain Ruggedness Index (Amatulli et al., 2018); Aqueduct Water Risk Framework (flood occurrence) (Gassert et al., 2013); Global Seismic Hazard Assessment Programme (Giardini et al., 2003)
Water	Environmental	Aqueduct Water Risk Framework (Gassert et al., 2013)
Community	Social	S&P database (2019)
Land use	Social	Permanent Cropland (FAO, 2020); Population Density (World Bank and FAO, 2018)
Poverty	Social	Human Development Index (UNDP, 2019a)
Legal	Governance	S&P database (2019)
Permitting	Governance	Policy Perception Index (Stedman and Green, 2018); Ease of Doing Business Index (World Bank, 2020)[a]

[a] Note: the Ease of Doing Business Index has been criticised for encouraging deregulation practices at the expense of efforts to improve regulations: see Doshi et al. (2019); McCormack (2018).

3.2. *Applying the ESG risk framework to DSM*

This section applies the ESG framework to DSM. It uses a geospatial overlay approach to assemble an ESG risk profile for DSM. Each risk category (Table 1) is discussed in turn. Our analysis highlights gaps in the environmental data, and the need to consider social and governance risks that are material (though not unique) to DSM. The broader significance of these findings is discussed in section 5. In brief, this section signals a need to differentiate DSM as a new type of extractive industry, generating ESG risks and requiring data and analytical approaches not always easily translated from terrestrial mining.

3.2.1. Biodiversity

It is well established that terrestrial mining operations disturb and destroy natural and other habitats through land transformation, infrastructure development and pollution dispersion (seepage, dust, noise, vibration) both within and outside the mining lease. Mining also affects ecosystems and biota indirectly through transport corridors by enabling population movements and agriculture expansion (Bebbington et al., 2018). For DSM, these impacts are likely to include destruction or disturbance of seafloor ecosystems (Cormier, 2019), with consequential risks to ecosystem services (Thornborough et al., 2019). Waste disposal and sediment plumes caused by seafloor disturbance will also impact marine floral and faunal communities.

Current research indicates that seafloor biodiversity tends to be rich, endemic, and slow to recover (see section 2 of this paper). Understanding the impact of commercial-scale DSM will require detailed study of each site. In analysing faunal assemblages in the Clarion Clipperton Zone, an area rich in polymetallic nodules in the Pacific Ocean, Tilot et al. (2018) notes that nodules 'clearly provided a distinct habitat' for certain types of fauna, and that 'faunal communities particular to the nodule ecosystem may even be threatened with extinction' in the face of regional-scale DSM.

Global-scale spatial data is not available for benthic biodiversity. Marine protected areas may provide some proxy for areas of particular richness – but such areas are unlikely to indicate the location of endemic benthic populations (see Gill et al., 2017; Caveen, 2015; Edgar et al., 2014). Nonetheless, the coincidence of marine protected areas with deep sea deposits would indicate areas that carry additional environmental risk, as well as social and governance risks of operating an extractive industries in an area designated for conservation. Fig. 2 overlays the locations of marine protected areas (UNEP-WCMC and IUCN, 2020) with the locations of deep sea deposits (Mahapatra and Chakravartty, 2014). Approximately 13% of deep sea deposits coincided with marine protected areas, with most overlaps located in the Pacific.

3.2.2. Waste

For terrestrial mining, large amounts of mining waste (e.g., tailings, waste rock, and heap leach) require emplacement strategies and engineered structures to effectively contain polluting substances over the long term. Earthquakes and high precipitation leading to flooding are two factors that can raise concerns about the containment of hazardous waste and the prospect of structural failure (Oboni and Oboni, 2020; Rico et al., 2008). High variations in topography create challenges in the construction of terrestrial engineered structures.

For DSM, mining waste will vary depending on the method used for extraction. Polymetallic nodules are not connected to the seafloor, and can be 'scooped up', whereas ferromanganese crusts and seafloor massive sulphides require a method of mechanical detachment (Sharma, 2017; Yamazaki, 2017). Mineral processing methods for DSM have been discussed in the scholarly literature (Su et al., 2020; Das and Anand, 2017; Sen, 2017), although none are in commercial-scale operation. Wiltshire (2017) estimates that a commercially viable DSM project extracting polymetallic nodules or ferromanganese crusts would generate 1–3 million tons a year of tailings, with both land-based and ocean-based disposal possibilities. Available data on seismic hazard are exclusively terrestrial, which will allow assessment of ESG risks only for land-based components of DSM. The extent to which seismic hazards will affect DSM activities will require further research.

For ocean-based disposal, modelling will be required to understand the impact of DSM wastes, as well as the extent of sediment plumes generated by seafloor and sea surface activity (Clark, 2019; Yamazaki, 2017). Fig. 3 shows a spatial overlay between ocean currents (NOAA, 2019) and deep sea deposits (Mahapatra and Chakravartty, 2014). A

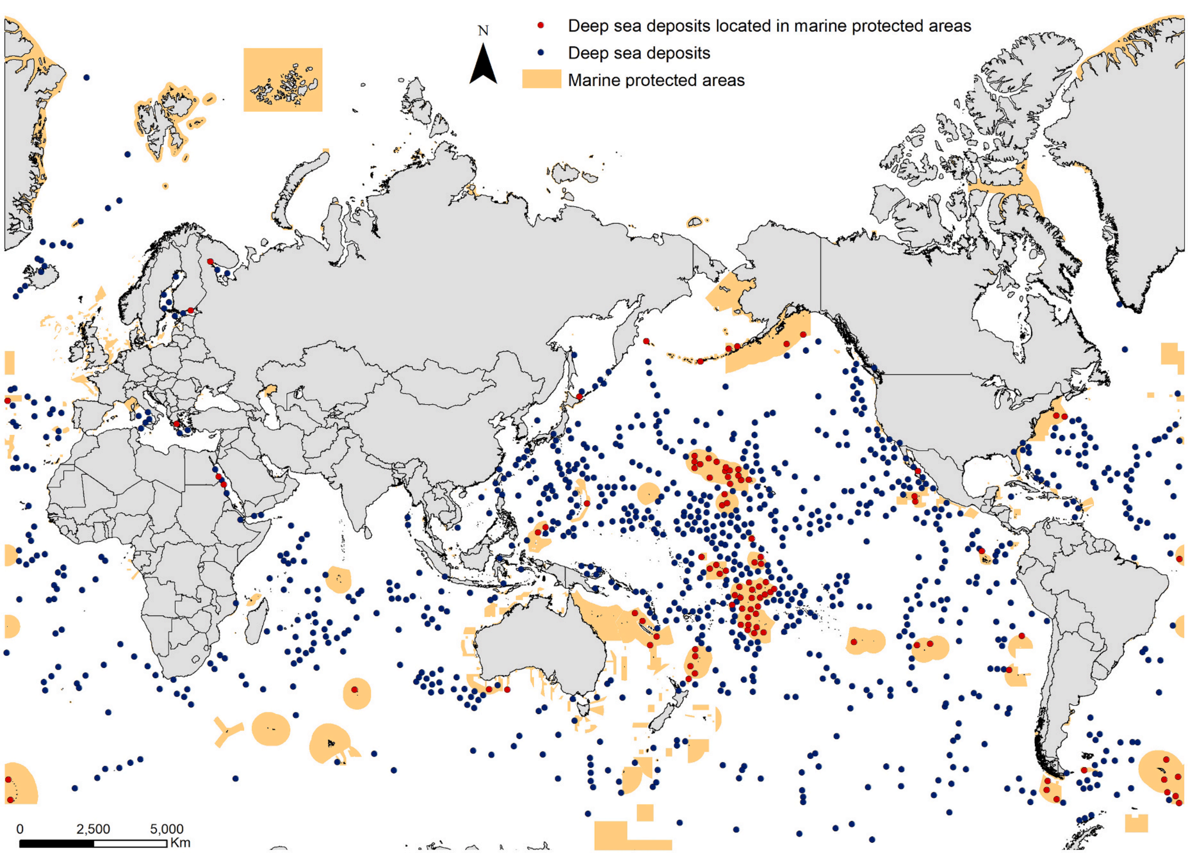

Fig. 2. Deep sea deposits located in marine protected areas. A spatial overlay of deep sea deposits (Mahapatra and Chakravartty, 2014) and marine protected areas (UNEP-WCMC and IUCN, 2020) resulted in 13% of deep sea deposits being in conflicts with the protected areas. The majority occurred in the Pacific Ocean.

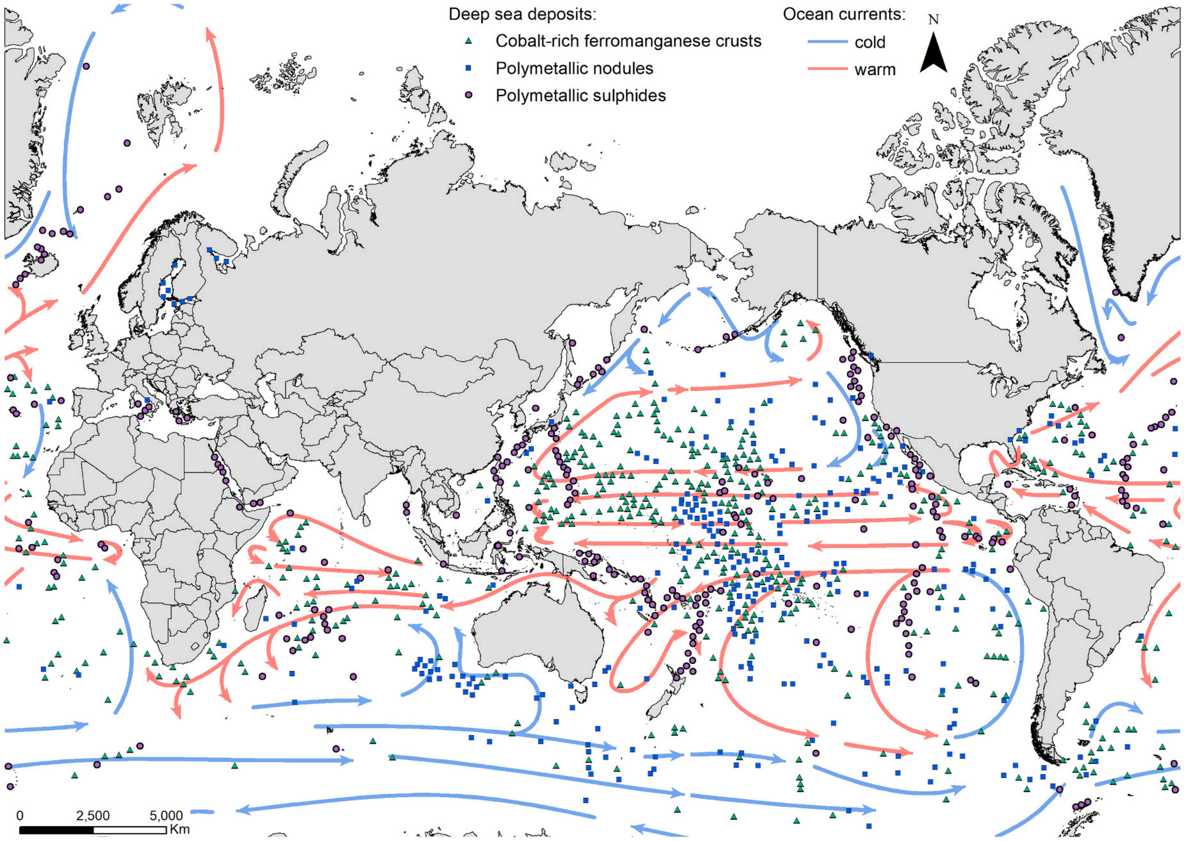

Fig. 3. Deep sea deposits (Mahapatra and Chakravartty, 2014) located in global network of ocean currents (NOAA, 2019). Ocean currents indicate the general flow of global ocean circulation. They transport heat from warm equatorial seas to colder polar waters. The system consists of warm surface currents (in red) and cold deep ocean currents (in blue). It is apparent that majority of the deposits is located in warm currents of the Pacific, Indian and Atlantic oceans. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

question arises as to the cumulative impacts of DSM projects. Terrestrial mining contaminants can accumulate in river sediments for hundreds of years after closure, with downstream deposition sites becoming more contaminated than the original mine sites (Coulthard and Macklin, 2003). Ocean currents can flow for thousands of kilometres, driven by density and temperature gradients, and have a key ecological role (Amatulli et al., 2018). Modelling ocean currents to assess environmental impacts of DSM will be labour-intensive (Billett et al., 2019). As such, scientific knowledge of the impact of DSM wastes is likely to be developed incrementally on a project-by-project basis, limiting the ability to accurately predict individual and cumulative impacts of prospective DSM operations. The long-term, cumulative interaction between ocean currents and DSM wastes and sediments will require significant research.

3.2.3. Water

Terrestrial mining activities typically have high freshwater requirements and withdraw water from local catchments, sometimes competing with existing water uses. Baseline freshwater scarcity and high seasonal variations in freshwater availability are contextual risk factors for water management at mine sites. The extent to which DSM will draw down on freshwater supplies is presently unknown, although minerals processing will require some measure of water. For a large number of mining operations, part of the mineral processing occurs on-site, meaning that spatial data can be used to determine likely areas of tension between prospective water users. Where DSM operators ship raw materials for processing in other jurisdictions, these same considerations would apply, leading to a more diffuse risk footprint.

Similarly, in order to understand the potential for competition among water users, extensive mapping is required showing areas used for commercial fishing as well as international shipping routes and routes of submarine cables. Potential conflicts between DSM and international shipping routes are shown in Fig. 4. Using a spatial join tool in ArcGIS, this figure overlays the ISA's data on the deposits (Mahapatra and Chakravartty, 2014) and commercial shipping routes (Halpern et al., 2008). An estimated 52% of deposits are in potential conflict with commercial shipping routes. While shipping routes currently co-exist with extractive industries (e.g. offshore petroleum projects), shipping routes can also be seen as an indicator of broader geopolitical interests (see e.g. Huang et al., 2015; Blunden, 2012; Cafruny, 1985). ESG risks would arise where DSM affects international political interests.

Fig. 5 presents an extent of potential conflicts between DSM and routes of submarine cables and telecom terminals (data provided by Global Bandwidth Research Service, 2018). Based on a proximity analysis (using the ArcGIS tool 'Near'), we found out that 1% of the deposits are in less than 1 km proximity to the submarine infrastructure. Another 20% of the deposits are located in the distance between 1 and 50 km from the infrastructure.

3.2.4. Community

Social acceptance (broad-scale and localised) is highly coveted by the mining industry (Hall et al., 2015). Delays in the project construction phase and disruptions at operations are costly to the proponent (Franks et al., 2014). This indicator, as used by Valenta et al. (2019), captures returns on keyword searches that strongly suggest oppositional attitudes or activities in relation to mining projects. In terrestrial mining, gauging social acceptance is already a problematic exercise, involving unsettled conceptual and practical questions such as whose acceptance matters, the degree of consensus required to claim acceptance, and what weight should be given to the acceptance (or otherwise) of various actors (see

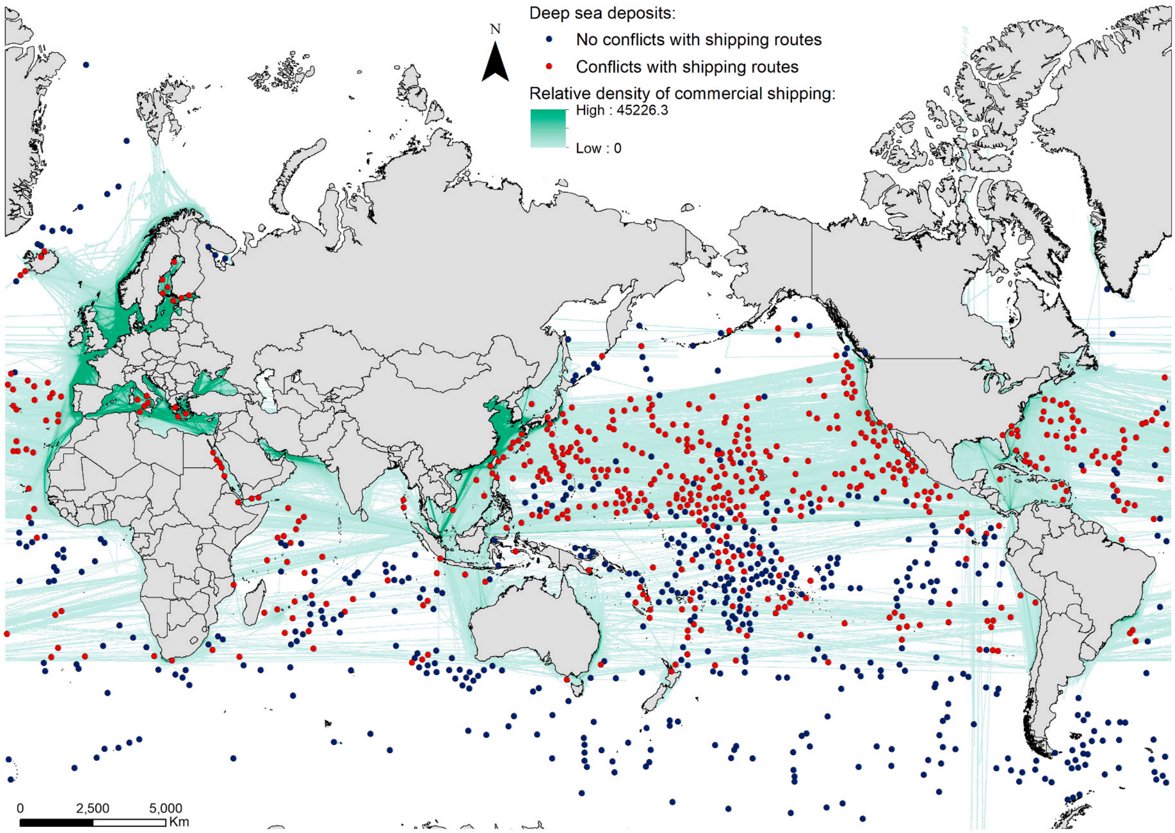

Fig. 4. Potential conflicts between deep sea deposits and commercial shipping routes. Overlaying dataset on relative density of commercial shipping (Halpern et al., 2008) and deep sea deposits (Mahapatra and Chakravartty, 2014) revealed that 52% of deposits are in areas with identified shipping routes. Over 1% of the deposits are located in the highest relative density of the shipping routes (over 1000).

Owen, 2016; Parsons et al., 2014; Owen and Kemp, 2013). How social acceptance could practically translate into regulation is also unclear (van Putten et al., 2018).

Navigating social acceptance and conflict around DSM is likely to be more amorphous than for terrestrial mining. As Filer and Gabriel (2018) note, terrestrial mining sites typically have landowner or land user groups to focus discussions about project acceptability. In contrast, opposition to DSM will likely arise from a wider and more diverse group of stakeholders, who have less well defined relationships to the mine site. The rights of indigenous peoples with respect to ocean areas adds complexity to this issue. Land tenure systems (whether customary or formal) may not extend to the deep ocean, notwithstanding cultural values associated with the ocean. While the principle of free, prior and informed consent is generally accepted as a norm in terrestrial mining (Buxton and Wilson, 2013), how this principle is given effect in DSM has not yet been tested (Aguon and Hunter, 2018).

3.2.5. *Land use*

With the exception of major land reclamation projects, the supply of land is fixed. The development of large-scale mining projects requires extensive tracts of land to accommodate pits, processing and plant infrastructure, laydown areas, transport and power corridors, camp accommodation and for the storage of waste. Valenta et al. (2019) used the land use category to indicate the presence of people and the main land uses on which their livelihoods depend, understanding that mining may collide with these activities. Our assumption is that DSM will not generate the same extent of terrestrial land use disturbance; however, the need for ports, worker accommodation, and processing facilities in at least one jurisdiction indicates that some of the same types of land use competition will be replicated across the overall mineral supply chain. This brings into frame many of the significant challenges terrestrial mining projects have faced with respect to engaging, and later managing, customary and hybrid systems of land tenure.

3.2.6. *Poverty*

The social and economic conditions of communities affect their capacity to respond to changes brought about by major projects, including resource extraction projects (Lodhia, 2018). Valenta et al. (2019) used Human Development Index (HDI; UNDP, 2019a) to capture poverty conditions at the national scale, rather than at a project-scale, and took HDI as an indicator of the host society to adjust to economic shocks, such as rapid inflation in general goods and services, or in the domestic housing and land markets. DSM poses cognate risks where commercial extraction leads (directly or indirectly) to revenue flows to host States. Poverty-based indicators will be needed to assess underlying vulnerability. We suggest to complement HDI with Multidimensional Poverty Index (UNDP, 2019b) and World Bank's Poverty and Equity Data (World Bank, 2020) to include more dimensions of poverty to ESG risk considerations.

3.2.7. *Legal*

Mining projects routinely experience legal disputes throughout their lifecycle, resulting in costly delays to operation or permitting. Similar to the community indicator described above, in Valenta et al. (2019), the keyword return for legal issues was used to signal potential costs and or delays at critical stages of project development. DSM, where many of the technological, social, environmental, and governance issues have not been actively tested in any jurisdiction, should be considered a likely candidate for future legal action. We note also that diplomatic challenges may arise where DSM is developed in international waters. In particular, the ISA is established by UNCLOS, but not all nations are signatories to UNCLOS – the USA is notable in this regard (see Glasby,

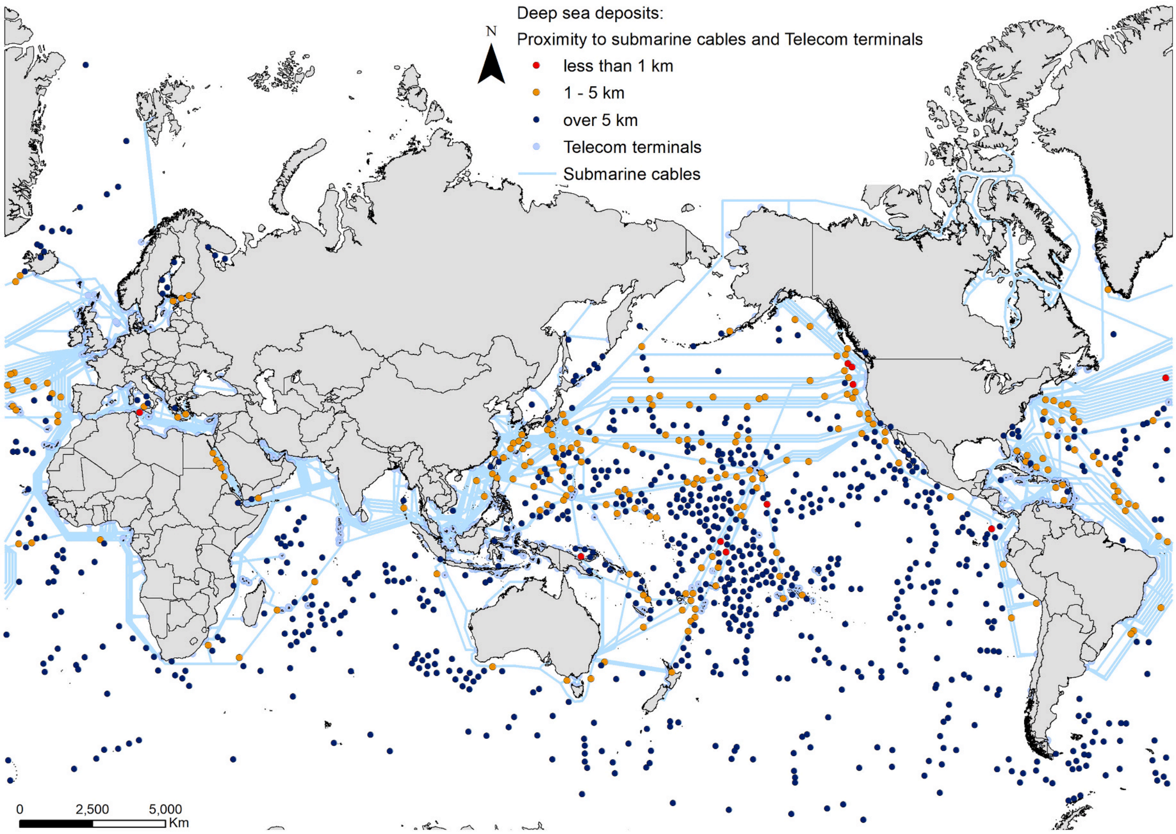

Fig. 5. Deep sea deposits and their proximities to submarine infrastructure. Analysing a dataset of submarine cables and Telecom terminals (Global Bandwidth Research Service, 2018) and its proximity to deep sea deposits (Mahapatra and Chakravartty, 2014), we found out that 21% of the deposits are in a proximity shorter than 50 km to this infrastructure.

2002).

3.2.8. *Permitting*

In Valenta et al. (2019), this indicator combines two global rankings on policy perception: Policy Perception Index (Stedman and Green, 2018) and Ease of Doing Business (World Bank, 2020). The combined score is taken as a measure of the country's overall stability in terms of entering, executing, modifying and exiting commercial arrangements. In their research, Valenta et al. argued that the combined score was an effective proxy for how a given jurisdiction manages disputes relating to development of large extractives projects, their timeliness, transparency and the extent to which stakeholders consider the process to be fair and reasonable. These same questions are regarded as being relevant to the development and permitting of sea bed mining projects.

4. Regulatory responses to DSM governance

The foregoing highlights that DSM faces some cognate ESG risks with terrestrial mining, but also differentiated risks. While the general character of some of these risks can be articulated, a nuanced and detailed risk profile requires as-yet unavailable data about the receiving environments that would host DSM activities. DSM activities are themselves a source of uncertainty. Since no commercial-scale extraction of deep sea minerals is currently taking place, there are no DSM technologies or project designs that have been implemented where researchers can fully appraise the effects of the industry once in production.

In the face of these combined uncertainties, how can regulators meaningfully govern for DSM? This section outlines two sets of DSM regulations, respectively developed by the ISA and the Cook Islands. We use these examples to illustrate the difficulty facing regulators in devising suitable governance architectures for DSM. These mechanisms use generic governance processes largely drawn from terrestrial mining governance structures, with few mentions of technologies, activities, or impacts specifically associated with DSM.

4.1. *International Seabed Authority Mining Code*

UNCLOS establishes the ISA as the responsible agency over mineral resources in international waters. The ISA has issued 30 exploration contracts, over half of which (16) are for polymetallic nodules in the Clarion Clipperton Zone, Pacific Ocean (ISA, n.d.-a). There are no contracts for commercial-scale production ('exploitation') of deep sea minerals.

The ISA is in the process of developing the Mining Code, which collectively refers to 'the whole of the comprehensive set of rules, regulations and procedures issued by the International Seabed Authority to regulate prospecting, exploration and exploitation of marine minerals in the international seabed Area' (ISA, n.d.-b). To-date, regulations have been issued for prospecting and exploration for polymetallic nodules (2000, updated in 2013), seafloor sulphides (2010), and cobalt-rich crusts (2012). Regulations for exploitation are currently being developed.

The ISA's Assembly and Council (effectively a legislature and executive respectively) are advised on technical matters by the Legal and Technical Commission (LTC), which comprises 30 individuals elected by the Council on the basis of their expertise in DSM. The LTC is responsible for developing DSM regulations, and for reviewing work plans, supervising DSM activities, and assessing environmental impacts of mining.

The ISA's draft regulations on DSM exploitation (ISA, 2019) are more detailed than the three regulations on prospecting and exploration. They are also more recent in their development, notwithstanding their present draft status. For these reasons, the draft exploitation regulations provide a useful example of the ISA's approach to DSM governance, and the attention given to ESG risks.

The bulk of the ISA draft regulations establish procedures for granting of contracts to exploit deep sea minerals. Part II sets out the approvals process, Part III the rights and obligations of contractors (i.e. mine operators), Part V the review process for work plans, Part VI closure planning, and Part VII financial terms. These provisions largely aim to establish the commercial relationship between the contractor and the ISA, and represent efforts to manage risks associated with DSM governance: the 'G' component of ESG risks.

Part IV of the draft regulations is dedicated to 'protection and preservation of the marine environment'. The ISA and contractors have a general obligation to 'plan, implement and modify measures necessary for ensuring effective protection for the Marine Environment from harmful effects in accordance with the rules' (reg. 44). The precautionary approach, 'best available techniques', 'best environmental practices', and 'best scientific evidence' are to be applied.

What constitutes 'best' is not substantively defined, only expanded upon. For example, 'best environmental practices' means 'the application of the most appropriate combination of environmental control measures and strategies, that will change with time in the light of improved knowledge, understanding or technology, taking into account the guidance set out in the applicable Guidelines'. What 'best' means in an industry that has yet to begin is not explained.

The draft regulations require the ISA to develop a set of environmental standards, which set out (among other items) 'environmental quality objectives, including … biodiversity status, plume density and extent, and sedimentation rates'. No such standards are available, acknowledging the regulation is still in draft stage.

Mining operators are required to submit an Environmental Impact Statement (EIS) (reg. 47) alongside applications for project approval. Annex IV provides general guidance on the structure of an EIS, and recommends that EISs cover the biological, physical, and chemical environment of the proposed operations.

The regulations require operators must have 'reasonable regard for other activities in the Marine Environment' (reg. 31, 13). Such other activities are to be characterised in the EIS, which is also expected to cover fisheries, marine traffic, tourism, and marine scientific research (Annex IV). Operators must exercise 'due diligence' to avoid damage to submarine cables and pipelines (reg. 31).

Human remains and 'objects and sites of an archaeological or historical nature' are also to be assessed in the EIS. If found, the ISA is to be notified immediately (reg. 35). The wording of this provision suggests a focus on tangible cultural heritage, to the exclusion of intangible cultural heritage. Indigenous peoples are not mentioned in the regulations.

4.2. Cook Islands

The EEZ of the Cook Islands covers nearly 2 million square kilometres. It contains the largest and densest field of seabed polymetallic nodules globally. Hein et al. (2015) estimate the Cook Islands EEZ contains a total of 12.1 billion wet tonnes of nodules, representing a globally significant accumulation of cobalt, nickel, and rare earth elements (REEs). SPC (2016) estimated a potential royalty benefit to the Cook Islands at USD 47 million per annum, over a modelled 20 year mine life (taking into account likely capital and operating costs, as well as recoveries associated with reasonable mining and processing scenarios). In addition to nodules within the EEZ, the Cook Islands also holds an exploration contract in the Clarion Clipperton Zone.

Interest in DSM in the Cook Islands dates back at least as far as the 1970s, during which oceanographic minerals research began (Petterson and Tawake, 2019). Driven by increasing commercial interest in the Cook Islands' deep sea mineral resources, the Cook Islands government passed the Seabed Minerals Act 2009. This legislation established the Seabed Minerals Authority, a statutory authority tasked with managing the prospective DSM industry in the Cook Islands. The Cook Islands government invited tenders for exploration licences in 2015, but no applications were received.

In 2019, a new Seabed Minerals Act superseded the 2009 version. The 2019 Act provides for the continuation of the Seabed Minerals Authority, and sets out processes for the awarding of seabed mining permits and licences. At time of writing, the policy position of Cook Islands government is to continue pursuing DSM (SMA, 2019, 2014). The Cook Islands Seabed Minerals Authority invited Kung (2019) to review the draft Bill, which the following observations extend.

The Seabed Minerals Act 2019 requires all licences to be made 'in the national interest', which includes consideration of environmental and social risks (section 69). Procedurally, the Act defers to the Environment Act 2003 for environmental protection in seabed mining – no permit or licence is to be issued unless Environment Act requirements are satisfied (section 90). The Environment Act sets up a generic process which for environmental impact assessment (EIA) – there is no EIA process designed for seabed mining.

An attempt to adapt the EIA process to DSM is evident in the Seabed Minerals Act. For example, the National Environment Service, which oversees EIAs in the Cook Islands, and the Seabed Minerals Authority must consult each other to determine licencing conditions (section 90). Schedule 2 obligates permit- and licence-holders to 'collect and analyse environmental data, in accordance with any guidelines issued by the Cook Islands Government, and in any event sufficient to enable comprehensive' EIA. No guidelines are available to the public at time of writing.

Mirroring the ISA draft regulations, schedule 2 also requires permit- and licence-holders to 'apply the precautionary approach, and employ best environmental practice including best available technology, in accordance with prevailing international standards'. What constitutes such best practice is not defined.

Social impacts are within the scope of the EIA under the Environment Act; the Seabed Minerals Act does not otherwise address potential social impacts in detail. There is a duty on the Seabed Minerals Authority to hold public consultation in relation to any licence application (section 66). This provision creates a procedural right for the public comment and to have such information considered in the project approval process. It does not establish substantive rights to approve or reject a proposed project. The draft version of the Act required licence holders to obtain the free, prior, and informed consent of marine or coastal users. The finalised version has had this requirement removed.

As with the ISA regulations, the majority of the Seabed Minerals Act relates to governance. Part 2 establishes various bodies responsible for carrying out the responsibilities laid out in the Act. Part 3 relates to cadastral matters, while Part 4 sets up detailed approval processes for permits and licences. Part 5 relates to duties and responsibilities of permit- and licence-holders, and includes the environmental obligations outlined above. Part 7 relates to enforcement powers, and Part 8 to the interaction between the Cook Islands and the ISA.

5. Discussion

5.1. The effect of uncertainty in DSM governance

Our research highlights major gaps in data necessary to understand the ESG risks of DSM. The gaps in environmental data for the ocean floor (e.g. biodiversity, waste, water) create uncertainties that will necessitate time- and labour-intensive research, conducted in challenging research contexts beneath the ocean. Such uncertainties are likely to spill into social risks where people oppose their countries' foray into DSM (see e.g. Doherty, 2019).

These uncertainties are translating into defects in emergent DSM governance architecture. The ISA and Cook Islands regulations establish governing bodies, define licensing systems, and set out processes for permitting and approvals. Both the ISA and the Cook Islands adopt generic EIA processes as the primary mechanism for understanding the environmental and social risks of DSM. Substantive standards that relate to environmental and social protections – which would require reckoning with as-yet uncertain ESG risks – receive comparatively light coverage. The generality of both sets of regulation reflects the state of knowledge about how DSM impacts will manifest and to what extent mitigations are available and/or feasible for regulators to consider crystallising into law.

This is not to say that requiring EIA is unusual. Many jurisdictions globally require EIA as a prerequisite to mining, and conditions attached to a mining licence are often drawn from EIA findings. As Clark (2019) notes, EIA is a well-established process that would be well employed in assessing prospective DSM projects. The problem lies in applying EIA methodologies to a frontier industry with scant environmental data on the status quo, and with no functional precedent in terms of project design. EIAs for terrestrial mining can typically draw on experiences of similar projects in similar environmental contexts (e.g. open-pit copper mines in high-rainfall, tropical environments). Neither type of similarity is available for DSM. In particular, DSM proponents will need to be prepared to commission environmental studies that are significantly more complex, time-consuming, and costly than those typically commissioned for terrestrial mining. Regulators in turn require institutional capacity – expertise, availability, support staff, information systems, etc. – to oversee these studies, and to ensure that they are critically reviewed ahead of approval decisions. Policy decisions about acceptable thresholds of environmental risk will need to be made on the basis of scientific evidence (see Levin et al., 2016). Notwithstanding the generic nature of the EIA processes established, how EIA is practically conducted for DSM is likely to be vastly different from EIA for terrestrial mining.

The broader point is that the wholesale importation of governance architectures from terrestrial mining to DSM results in regulations that appear to align with international expectations of mining governance. But such regulations do not recognise the effort and expertise required either to meaningfully translate terrestrial mining governance structures to DSM, or to create new governance structures tailored to DSM.

5.2. Applicability of terrestrial mining knowledge to DSM

Some knowledge from terrestrial mining can be readily transferred to DSM. Technical aspects of geological sampling and mineral processing, for example, are unlikely to differ greatly from those used currently in terrestrial operations, notwithstanding that extracting deep sea minerals will require novel technologies. Research related to the potential ESG risks of terrestrial mining, however, will require further development if they are to be immediately compatible with DSM. The potential biophysical aspects of DSM, whether on a cumulative sector scale or a project-by-project basis, are largely unknown or untested.

Some social and governance risks of DSM may be developed further by analogy to terrestrial ESG issues. For example, in terrestrial mining, land use conflicts arise when developers seek access to land over which individuals or groups have pre-existing use or ownership rights. Contestation over land rights in mining is well documented (e.g., Rugadya, 2020; Nyame and Blochler, 2010; Akpan, 2005; Hilson, 2002; McLeod, 2000). There is potential for DSM to drive similar types of access, ownership, and usufruct conflicts, given: (a) the location of deep sea deposits – which are at times relatively near-shore; (b) their proximity to major shipping lanes, marine cables, ocean currents and protected areas (Figs. 2–5); and (c) their likely need for on-shore infrastructure such as ports and processing facilities. As for terrestrial mining, competition over access to waterways, ports, fishing areas, and land-based infrastructure will form part of the overall risk proposition. Many of the details required to make an assessment of project-based risk are effectively unavailable for DSM, in part due to the lack of clarity surrounding what DSM project design will require, and in part because the biophysical context in which these project dimensions will be placed have not been characterised against activity-based risks. The composition of these risks, and the influence that market demand (i.e. price) will have in moderating the magnitude and effects of these conditions, is largely unknown due to the infancy of the industry.

Similarly, indicators that provide country-level resolution of social and governance factors, such as the Human Development Index (UNDP, 2019a), Policy Perception Index (Stedman and Green, 2018), or the Ease of Doing Business Index (World Bank, 2020), are relevant for drawing macro-level comparisons between potential DSM jurisdictions. The degree to which these factors affect, or are affected by, sector-scale activities remains unknown. As such, even where terrestrial mining knowledge provides a basis for further ESG risk analysis, knowledge development specifically for DSM is likely to be piecemeal – gained on a study-by-study or project-by-project basis.

5.3. Future development of DSM constrained by ESG risks

The commercial viability of DSM and terrestrial mining projects alike depend on numerous variables. These include commodity prices, ore grade, and projected tonnages, against the costs of extraction, processing, royalties and taxation, permitting and approvals, and risk management (SPC, 2016). Although extant studies indicate tonnages and grades available in some deep sea deposits (Hein et al, 2013, 2015), there remain key uncertainties in terms of the technologies required for extraction, their capital and operating costs, and the cost of managing ESG risks.

What is not clear is the extent to which the risks of developing DSM can be offset by increases in price. As Valenta et al. (2019) discuss, some risks are price-sensitive; for example, risks associated with ore grade could be largely offset by increases in market price. Others are indirectly price sensitive, such as risks of deploying costly technological advances. Social, environmental, and political risks tend to be resilient to price factors – and across the sample of complex orebody projects examined by Valenta et al. (2019), a significant majority exhibited combinations of risk factors that were price-insensitive, or not directly price-sensitive. In the context of terrestrial mining, both Valenta et al. (2019) and Lèbre et al. (2019) contend that high levels of concurrent ESG risk could, in some circumstances, result in the existence of a subset of mineral deposits which are essentially unavailable for future mineral supply regardless of commodity price.

For DSM, key ESG risks have not been effectively identified or characterised due to the infancy of the industry, the inapplicability of existing approaches to ESG risk assessment, and the unavailability of data to inform such assessment. This creates governance dilemmas for nation states seeking to expedite the resource opportunities available to them, and commercial dilemmas for investors wanting greater levels of assurance around the identification and management of project-based risks.

This is not a challenge unique to DSM. Studies on ESG risks of terrestrial orebodies, and on risks associated with global supply chains in general, all face the paucity of good quality, high resolution, and up-to-date global data (West, 2020). Lack of data limits results accuracy, and introduces challenges related to the representativeness and relevance of available indicators and measures, which constrain studies' scopes (Schrijvers et al., 2020). When the phenomena assessed are inherently qualitative, as it is the case for some types of social risks, far greater effort is required to characterise the interface between the project and its host setting. While data quality is acknowledged as a limiting factor for the evaluation of risks in terrestrial orebodies, it is clear that these difficulties will be more extensive for DSM.

6. Conclusion

In this article, we have highlighted that market pressures will likely drive future resource development into a new frontier of mining. Based on an emerging thread in the academic literature on source risks to global metal supplies, we have made a case for describing DSM as a novel type of complex orebody. Recent re-conceptualisation of the term 'complex orebody' retains the long-standing geological viewpoint, and adds other non-geological factors to illustrate the breadth of situated risks that can make an ore body complex. A consensus is rapidly forming around the growing importance of social and environmental conditions in resource development projects and the mutually detrimental consequences that can follow when these conditions are not given proper attention. To date, this thinking has been applied primarily to terrestrial resource projects. We call for a further extension of the term to include DSM due its inherent complexity, and because the associated risk factors will have a pronounced effect on the development of sea bed minerals and metals.

As we have shown, however, direct application of the complex orebodies assessment framework to DSM is also problematic. As a nascent activity, DSM remains only partly defined in terms of the technologies that will be deployed in the resource extraction process, and in terms of intersection between project activities and the natural environment. Our analysis suggests significant gaps in knowledge necessary to assess the ESG risks of DSM, and more fundamentally to identify what constitutes a comprehensive ESG risk set. Such knowledge is pre-requisite to evidence-based resolution of debates about the net impacts of DSM. That is, a clearer understanding of the ESG risks of DSM is necessary in order to critically assess the claim that DSM presents lower ESG risks than continuing to supply metals from terrestrial sources (see Paulikas et al., 2020b; Hein et al., 2020).

The scientific and technological uncertainties of DSM are reflected in recent efforts of state and non-state actors to put in place industry-ready legislation. Our review of efforts by the ISA and Cook Islands respectively demonstrates the limits imposed by the present knowledge base and how these limits are shaping what will eventually become test rules for the governance of DSM. These formative regulations are generic in their treatment of the sector, with few specific mentions of technologies, activities or impacts that are likely to be associated with mining the ocean floor. We call for clearer regulatory acknowledgement of DSM as a distinct extractive industry type, and for more focused efforts to govern DSM development with its unique features in frame.

Credit author statement

Anthony Kung: Conceptualization, Investigation, Writing – original draft. **Kamila Svobodova:** Formal analysis, Visualization, Writing – review & editing. **Eléonore Lèbre:** Writing – original draft. **Rick K. Valenta:** Writing – review & editing. **Deanna Kemp:** Writing – review & editing. **John R. Owen:** Conceptualization, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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