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Q1 Marine minerals' role in future holistic mineral resource management

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Abstract: Deep marine mineral deposits are mineral deposits that have been formed outside the continental slope. Currently three main types of deposits are generally recognized: polymetallic manganese nodules, massive seafloor sulfides and cobalt-rich crusts. The authors argue that marine mineral resource management must be holistic. Holistic marine mineral management requires a clear understanding of the objectives to be achieved through mining and to assess and ensure a proper balance between costs, risks, potential gains and losses. For decades there have been substantial uncertainties regarding the short- and long-term impact of deep-sea mining on international society and the economy and, more recently, environmental issues have become central to the debate over mining the deep seabed. If deep-sea mining is to play a constructive role in the green transition towards more environmentally robust energy production and e-mobility, more ambitious interdisciplinary research is needed to provide the knowledge needed to devise a holistic approach to management of marine minerals. This includes completing thorough baseline studies in conjunction with geological exploration and devising new means of handling financial and technological uncertainties when making investment decisions and when developing regulatory frameworks.

Deep-sea mining (DSM) covers activities related to the understanding of, the exploration for and the exploitation of deep-marine mineral deposits. Although attempts have been made both in the Solwara 1 project in the Bismarck Sea and in the Atlantis II-project in the Red Sea, exploitation activities for deep-marine minerals are not currently being carried out commercially but are expected to take place in the not-so-distant future. Such activities will include mining on the seafloor, transport to the sea surface, monitoring of the activities mentioned and continuous remediation of mined areas as they are abandoned. Mineral processing is not currently expected to take place at sea, although size reduction and some pre-concentration is likely to be considered as subsea activities (Ochromowicz *et al.* 2021).

The deep sea is largely underexplored and so are the ecosystems, the geology, and the prospects of exploiting the abiotic, and potentially the biotic, resources present in the deep sea. These resources must be managed, and we argue that marine mineral resource management must be holistic. Such holistic marine mineral management requires a clear understanding of the objectives (e.g. employment, financial gain, supply of a market) to be achieved Q2 through mining and to assess and ensure a proper balance between costs, risks, potential gains and losses (Jackson and Christiansen 1993). It has long been understood that knowledge of the geology is only one part of the process to discover and develop mineral deposits in general and specifically marine mineral deposits. It involves the application of corporate-oriented modifying factors related to technical, financial and political decisions, environmental aspects, the development of mining-, processing- and transportation technologies and solutions, and the market (Jackson and Christiansen 1993; CRIRSCO 2019). More recently, however, additional emphasis has been put on the so-called ESGs, modifying factors that focus on the environment (E), social aspects (S) and governance (G) (Rogers and Serafeim 2019; Jowitt *et al.* 2020;

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Walker 2022). ESGs will play a major role in future business developments. This article touches upon some of these modifying factors.

1. Historical aspects of the demand for deep-sea minerals. To what extent have governments considered them to be a viable source of certain minerals of strategic and economic importance, and what political approaches have been proposed to manage marine mineral wealth?
2. Geological aspects related to the overarching mineral resource potential assessment and the more localized deposit characteristics decisive for the development of responsible mining and processing technologies.
3. Environmental aspects including a description of the relevant ecosystems. Ecosystem knowledge and the responsible management of ecosystems are keys in adaptive management.
4. Financial aspects related to the process of assessing the economic potential in this new potential industry, given all the uncertainties. Uncertainty management is a crucial part of proper management of abiotic and biotic resources.

Q3 Marine mineral resource management

Mineral resource management (MRM) is about exploiting the potential in a mineral deposit while making sure that none of the framework conditions that constrain the development are violated. This includes making sure that the environment is not harmed unnecessarily. MRM has been defined as the identification, optimization and realization of the value of a mineral deposit (Blaauw and Trevarthen 1987; Macfarlane 2006). The process of converting some exploration results into a resource and a reserve is crucial in MRM (CRIRSCO 2019). The mine plan bounded and constrained by controlling elements like the environmental management and monitoring plan (EMMP) (Jones *et al.* 2019) is developed and implemented as part of the management. The mine plan is an overview stating when the operation will extract what qualities and tonnages from where (Camus 2002). This includes the communication of the mine plan with all relevant stakeholders (Haugen and Ludvigsen 2015). From a (public) governance perspective rather than from a mining companies' perspective, MRM is linked to issuing exploration and exploitation permits, reviewing and approval of the mine plans, production, environmental follow-up and monitoring, and the processing of concession applications. For onshore mining, the modifying factors include environmental, economic, technological, geological, social and legal factors. These will be equally important for deep-sea mining operations. This requires a solid baseline and an adaptive management system (Hyman *et al.* 2021). A comparison between the management systems for petroleum resources on the Norwegian continental shelf and the management system currently under development for and by the International Seabed Authority (ISA) for marine minerals is made in Moses and Brigham (2021). Norwegian management of the petroleum resources on its continental shelf (Overland 2018) has been used as inspiration for the development of regulatory and legal frameworks for deep-sea minerals (e.g. for the Cook Islands) and is one of the management frameworks studied by ISA (Brekke 2019). The system is based on openness, data sharing and an actively involved public administration. Durden *et al.* (2017) and Jones *et al.* (2019) have reviewed generic management frameworks and suggest conceptual improvements to the existing systems to adapt them to deep-sea minerals. The work to finalize the international regulatory framework for deep-sea minerals is ongoing (Brekke 2021) and is expected to be finalized in 2023 after the Republic of Nauru in 2021 invoked the 'two-year rule' in the UN Convention on the Law of the Sea (Singh 2021). If the management and regulatory systems are not in place by mid-2023, ISA may be forced to process exploitation permit applications without a regulatory framework in place.

From supply security to sustainability: the changing parameters of holistic management

The mineral wealth of the deep seabed has been unknown and inaccessible throughout most of human history, with economic activity largely confined to the surface and the water column. By the late eighteenth and nineteenth centuries, technological advances increased the strategic and economic importance of mapping sea lanes, currents, and the seafloor (Andersen 2020). It was the British HMS *Challenger* expedition (1872–76) that first reported the existence of copious amounts of manganese nodules on the ocean floor. The lead scientists suggested that possibly other deep-sea regions could be covered by such nodules (Murray 1891). Subsequent oceanographic investigations showed that the minerals were unevenly distributed across the seafloor. For instance, sampling conducted during the Norwegian North-Atlantic Expedition (1876–78, Fig. 1) did **Q4** yield some pumice and mineral agglomerations, but largely marine clays as indicated in Figure 2. The expedition scientists concluded that the formation of manganese oxide nodules described in the *Challenger* reports did not seem to occur in these waters (Schmelck 1882). While the mapping of the

Fig. 1. 'Outdo the Brits?': In the wake of the *Challenger* expedition the Norwegian North Sea expedition used the combined sail and steamship 'Vøringen' to map the seafloor between Svalbard, Jan Mayen and the Faroe Islands. The expedition's task was promotion both of science and national prestige, and it aroused controversy by naming the area 'the Norwegian Sea' (Wille 1882).

ocean floor continued in the following decades, deep-sea minerals were treated as mere scientific curiosities.

The Second World War drastically expanded knowledge of the deep sea, but also underscored the dependency of modern industrialized societies on many minerals. US president Harry S. Truman was troubled by the world's rising demand of petroleum and other minerals (Fear 2015). To encourage exploration of the US continental shelf he declared it to be 'appertaining to the US', subject to its jurisdiction and control. The Truman declaration was a turning point in the development of the international law of the ocean, setting off a race to gain ownership and control over marine resources (Proclamation 2667 – Policy of the United States With Respect to the Natural Resources of the Subsoil and Sea Bed of the Continental Shelf | The American Presidency Project 1945). Concerns about resource scarcity were amplified by the Korean war (1950–53), as a superpower conflict appeared imminent. During the crisis, a US government panel on natural resources outlined an authoritative set of recommendations to secure the future supply of minerals. A novel and highly ambitious suggestion was to extract minerals from the ocean. The Commission suggested the technological challenges were surmountable, and that a deep-sea mining industry could be operational by the mid-1970s (United States. The U. S. President's Materials Policy Commission 1952; Vernon 1983).

The tensions of the early Cold War abated with the death of Stalin, and the advent of nuclear warfare seemingly reduced the requirements for large amounts of minerals to fight a new world war. Even so, the idea of mining nodules from the deep seabed stirred public imagination during the 1950s and 1960s. The mineral composition, accumulation rates and the sheer amount of manganese nodules became eagerly debated in academic writings, popular science books and military journals. In the latter, deep-sea minerals were promoted as a potential solution to concerns about the supply risk, e.g. for manganese supplied from Indian and African sources. It was speculated that a variety of other minerals, such as cobalt, nickel, antimony and even bauxite, could be extracted from the ocean in the future (Fitzgerald and Khan 1957; Bonatti and Nayudu 1965; Mero 1965; Rigterink 1965; Sparenberg 2019).

During the 1960s and 1970s, many de-colonizing and developing countries asserted sovereignty over mineral endowments, demanded better terms of trade, and insisted on the right to nationalize foreign-owned mining assets. The establishment of producer cartels such as CIPEC (Conseil Intergouvernemental de Pays Exportateurs de Cuivre) and the IBA (International Bauxite Agreement) suggested that OPEC (Organization of the Petroleum Exporting Countries)

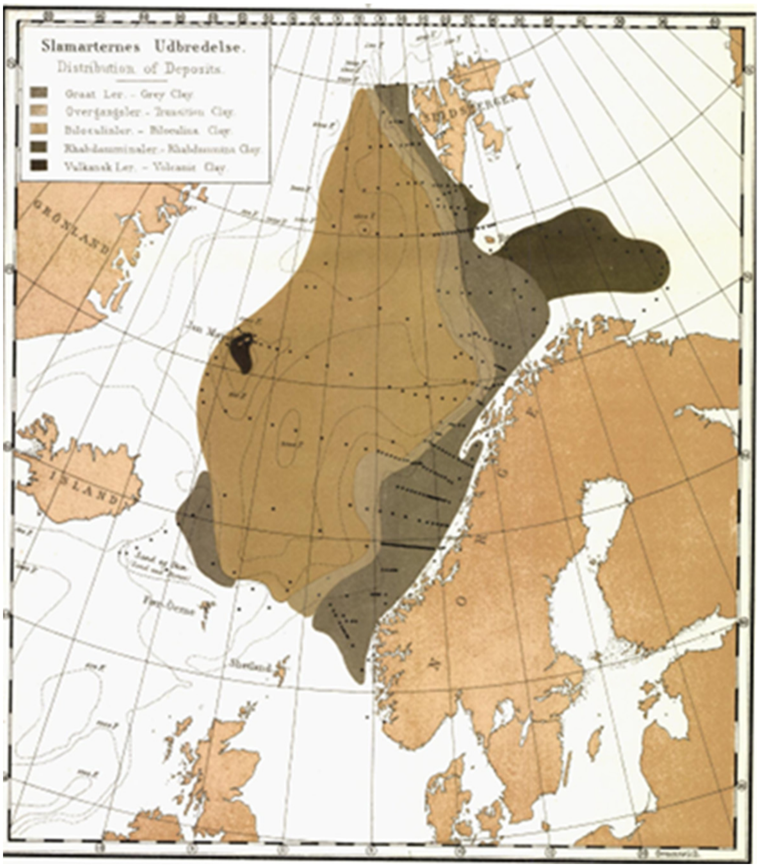


Fig. 2. Mud and clay. The deep seabed as it appeared in 1882. Distribution of deposits, as mapped by the Norwegian North Atlantic Expedition, 1876–78 (Schmelck 1882).

and the oil crisis had merely been the opening salvo in a struggle for global redistribution of economic and political power based on mineral resource (Litvak and Maule 1980). Third World assertiveness was perceived by consumer nations as a serious threat to future availability of minerals. Rising prices also sparked speculation about falling ore grades in land-based mining, rising energy costs and eventual exhaustion of mineral reserves (Meadows 1974).

As mineral supply insecurity rose during the 1970s, deep-sea minerals appeared to offer a spectacular solution. The Commission of the European Communities considered the risk of supply disruption as a 'real and serious threat' for Europe. But it was encouraged by UN reports suggesting that substantial shares of global demand for manganese (13%) and nickel (26%) soon could be mined on the ocean floor, and expectations ran high for the North Sea (Commission 1975). France and Germany also sought to mitigate their supply risk through national strategies for deep-sea mining, as did Japan (UN Department of International Economic and Social Affairs 1980; Koga 2018). The US minerals industry had also felt the threat of expropriation of their foreign investments, and eagerly eyed the possibility of mining minerals below the waters outside national jurisdiction. As the dominant political and economic power, and the most likely to access the resources, the US was at first ambivalent, and then outright hostile to the international regulation that was negotiated during the third Law of the Sea Conference (Bowsher 1983).

The 1980s cast doubts on the future of ocean mining. The demand and the concerns with supply security were still present. The global cobalt supply chains had been jolted by rebellion in Katanga, and similar risks were apparent also for other minerals. The Reagan administration's Cold Warriors believed they were fighting a 'resource war', afraid that their enemies could 'place their hands on our economic throttles and economic throats', cutting the supply of minerals necessary to produce everything from TV sets to supersonic jets and submarines (United States. Congress. House. Committee on Foreign Affairs. Subcommittee on Africa 1981). Promoters of deep-sea mining asserted that these minerals could be supplied from nodules, and that from an engineering perspective both mining and refining systems were realizable. Access to proven marine minerals was also touted as a potential weapon against 'capricious price inflation', cartelization or 'political' price hikes of the 1970s (Moore 1984). But the US' refusal to sign the Law of the Sea Convention, and its unilateral declaration of an Exclusive Economic Zone (EEZ) threw the legal order of the deep sea into disarray. This uncertainty made nodules less attractive as an investment object. The other, recently discovered, marine mineral deposit types could seem more likely to be realized. Cobalt-rich crusts offered the prospect of a new source of highly concentrated deposits of a strategic material in shallower waters, not subject to the legal limitations placed on the Common Heritage of Mankind in the Law of the Sea Convention (Johnson and Otto 1986).

By the late 1980s and the early 1990s, the prospects of the deep-sea mining industry plummeted. Raw material prices were stable or declining, and the New International Economic Order was politically dead in the water, thereby removing one of the risk factors from a consumer perspective. The triumph of western liberal capitalism was inscribed into the 1994 implementation agreement that finally gave birth to the International Seabed Authority (ISA). As long as global markets were awash with cheap raw materials, even the governments habitually concerned by import vulnerabilities, such as Japan, Germany, and the US, gave less attention to supply security as a problem (Radetzki 2006). As an expensive solution to the seemingly minor problem of supply security, expectations about the commencement of deep-sea mining were pushed far into the twenty-first century (Hoagland 1993).

As economic globalization enabled the growth of Chinese manufacturing, a new resource boom developed after 2004. The 'long boom' re-ignited concerns about competition for scarce metals; on the demand side China was able to outcompete western firms for the output of African producers. On the supply side, the disruption of Chinese rare earth deliveries to Japan after a clash over the Senkaku/Diaoyu Islands in 2010 rekindled fears of politically motivated embargoes (Kiggins 2015). As the US realized that its commercial and military supply chains for minerals were mutually dependent, it became a political priority to locate new sources and reduce its dependency on critical minerals (National Research Council 2008). In the circumstances of rising prices and with political support for exploration, the deep sea re-surfaced as a viable and attractive source of critical minerals.

The re-emergence of deep-sea mining in the 2000s during a period of high prices and renewed clashes over minerals bore a strong resemblance to its former glory days in the 1970s. But something had changed in the intervening decades. As the US Department of Energy noted in 2010, critical materials had become crucial components in the 'clean energy economy', amounting for 20% of global consumption of these minerals (US Department of Energy 2010). Similarly, the EU Commission had become increasingly worried about supply risks after 2008, furthermore it hoped that deep-sea mining could enable 'blue growth'. In 2012 Brussels anticipated that as much as 5% of the world's minerals, including cobalt, copper and zinc, could come from the ocean floor in 2020, rising to 10% by 2030. From virtually nothing it would create a €5 billion industry by 2022, rising to €10 billion by 2030 (European Commission 2012). To unlock this economic potential, the EU invested in several research projects to investigate the viability of deep-sea mining, while pushing the ISA to finalize its mining code (JOIN 2016). The ISA also saw a steep rise in interest from other countries. While it had issued only eight contracts for exploration by early 2011, the number had tripled by late 2015 (Dingwall 2020). The new aspiration of deep-sea mining promoters was that the blue economy could supply minerals for the green transition to a de-carbonized and sustainable future.

From an industry and government perspective, the green shift is potentially a boon for deep-sea mining. While it is still advocated as a solution to supply risks, cartel formation, price gouging and politically motivated embargoes (Pelaudeix 2018), the need for minerals for sustainable energy technologies has moved to the front and centre. For instance, in 2019 Norway enacted a specific law for deep-sea minerals on the Norwegian continental shelf, explicitly framed to secure a sustainable, socially and economically viable management regime (OED 2021). The hope that this new industry can mitigate the long-term loss of employment and revenues from oil and gas is underpinned by current estimates of vast mineral occurrences. The argument that deep-sea mining is necessary to solve the global sustainability crisis offers a different, and possibly more politically acceptable, argument than the previous emphasis on supply security. Yet the shift to sustainability as the main selling point of the industry is problematic. Although deep-sea mining was first seriously considered concurrently with the emergence of the global environmentalist movement during the 1970s and 1980s, at that time the scientific comprehension and political appreciation of deep-sea ecology was relatively slight. But by the 2010s, sustainability and biodiversity loss had emerged as global matters of concern, presenting new questions and challenges.

The ecological justification for deep-sea mining adds a new element to the political calculus. According to industry advocates, deep-sea mining is a responsible and necessary step in humanity's common quest to save the planet. But this shift also broadens the scope of the social, technological, and ecological considerations that come into play, placing new demands on regulators and miners. The parameters of holistic mineral management are expanded (Nilsson *et al.* 2021). For deep-sea mining to be seriously considered as a climate crisis mitigation measure and a means to implement the green transition, the budding industry will have to address a new set of modifying factors, thereby complicating investment decisions for companies and consortia (see the section 'Uncertainty quantification and **Q5** exploitation in new industries'). This requires us to deepen our knowledge of some of the most remote and inaccessible areas on the planet. Even today, 150 years after the nodules were first discovered, our understanding of deep-sea minerals and their natural environment is highly limited. While the consequences of deep-sea mining operations are not understood, what has become clear over time is that social, economic and ecological considerations also must be brought to bear in the development of any holistic mineral management strategy purporting to link deep-sea mining to sustainability (Haugan *et al.* 2020; Levin *et al.* 2020).

Ore deposit knowledge for marine mineral management

Deep-marine mineral deposits are mineral deposits that have been formed on the outer side of the continental slope in the deep oceans (Ecorys 2014) and are typically results of geological processes adjacent to the seafloor and in the ocean. Typically, three main types of deep-marine mineral deposits have been considered and explored in the world oceans (Ecorys 2014). These are defined by the mechanisms causing the formation of mineralizations on or in the seafloor (Hein *et al.* 2013), and include polymetallic manganese nodules (PMN), cobalt-rich manganese crusts (CRC), and seafloor massive sulfides (SMS). During the last decade, there has been a raise in awareness of the occurrences of deep-sea mud **Q6** (Kato *et al.* 2011; Takaya *et al.* 2018), which is typically enriched in rare earth elements (REE) and yttrium, and the marine phosphorite deposit with potential resources of heavy REE and yttrium (Hein *et al.* 2016). However, knowledge about the properties and extent of deep-sea muds is still limited, hence this deposit type will not be given detailed attention in this article.

In the section 'Mineral resource potential assessment' of this article, aspects of mineral resource potential estimation are presented using SMS deposits as case examples. Estimates of contained metal in PMNs and CRC have recently been published in Mizell *et al.* (2022).

Polymetallic manganese nodules

Polymetallic nodules are typically found as potato-shaped concretions (Fig. 3) distributed over large areas of seafloor sediments. The formation of PMN occurs typically on the vast deep oceanic plains, through precipitation of metals on to a nucleus, such as a shark's tooth or sand grain. Three main types of processes are responsible for the precipitation of manganese nodules: hydrogenetic, diagenetic and hydrothermal (Glasby *et al.* 2015). During formation of hydrogenetic nodules, metals are precipitated directly from the seawater; diagenetic nodules are the result of remobilization of elements in the sediment column. Hydrothermal nodules are formed from the discharge of hydrothermal (hot) fluids at the seafloor. Most PMN are

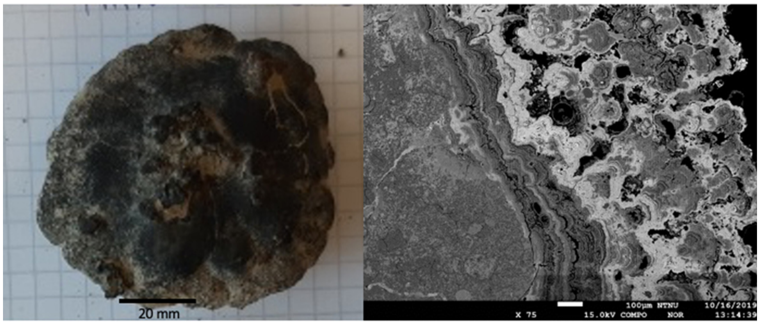


Fig. 3. Left-hand picture shows a manganese nodule from the CCZ. Right-hand picture shows SEM BSE image with the concentric layering in manganese nodules. Left side of the image is towards the centre of the nodule. Dark areas are light phases, bright areas are heavier phases. Image: A. Lang, NTNU.

formed through a combination of two or three of these processes, although the hydrothermal contribution is less frequent (Hein and Koschinsky 2014). Typical growth rates and metal contents vary between the different types of nodules. Although rarely found, the hydrothermal nodules show by far the fastest metal supply and precipitation. The diagenetic component of nodules allows faster formation of >100 mm Ma^{-1}, in comparison to the hydrogenetic nodules that typically show growth rates of 1–2 mm Ma^{-1}. Hence the increasing diagenetic component of the nodule may increase the growth rates significantly (Hein and Koschinsky 2014), averaging 10–100 mm Ma^{-1}. Another important contribution from the diagenetic component is the increased content of the commercially important elements, such as Mn, Fe, Cu, and Ni in these nodules. The hydrogenetic component on the other hand increases the content of Co and REE, for example. Hence, PMN of economic interest are mainly formed through combined hydrogenetic and/or diagenetic precipitation (Kuhn *et al.* 2017). Such variation in precipitation processes generally leads to variations in the content of valuable metals (Kuhn *et al.* 2017). Manganese nodules typically show concentric layering (Fig. 3), which is the result of precipitation and accretion around a nucleus. They also contain alternating layers with intimate intergrowths of very fine grained Mn- and Fe-oxides and -hydroxides with potentially economically interesting grades of critical elements (Glasby *et al.* 2015; Petersen *et al.* 2016). The typical content of valuable metals in PMN is summarized in Table 1, and includes Ni, Cu, Co as well as Mo, Li, REE and Ga (Hein *et al.* 2013). The largest area containing **Q7** PMN deposits known today is the Clarion Clipperton Zone (CCZ) in the Eastern Pacific Ocean. In the CCZ, the mixtures of hydrogenetic and diagenetic endmembers shifts towards a continuously increasing hydrogenetic proportion towards the central and western CCZ. As a result of increased hydrogenetic **Q8** influence in the formation of nodules, the central and western CCZ nodules show slightly increased cobalt and REE content. Similarly, characteristics of PMN from other areas are affected by the influence of the different genetic processes (Kuhn *et al.* 2017). There are also manganese nodule occurrences known in two other main areas of the Pacific Ocean (the Peru Basin, SE Pacific and the Cook Island region, SW Pacific), and in the central Indian Ocean Basin, and the Baltic Sea (Kuhn *et al.* 2017) **Q9** (Fig. 4).

Cobalt-rich manganese crusts

Manganese crusts are formed by precipitation and accretion by mainly hydrogenetic processes on to the sediment-free outcrops of seamounts (Glasby

Table 1. *Average content of selected elements in manganese crusts and polymetallic nodules*

	Fe (wt%)	Mn (wt%)	Ti (wt%)	Ni (ppm)	Cu (ppm)	Co (ppm)	Mo (ppm)	Zr (ppm)	Nb (ppm)	Li (ppm)	Y (ppm)	REE* (ppm)	Pt (ppb)	Ga (ppm)	Au (ppb)	Te (ppm)
Crust avg	20.7	19.6	1.0	3298	923	4406	425	566	51	12	186	2128	335	18	32	36
Nodules avg	6.4	28.9	0.3	12 389	9006	1195	568	306	16	179	88	632	58	32	3	3

Modified after Hein and Koschinsky (2014).
*Pm not included.

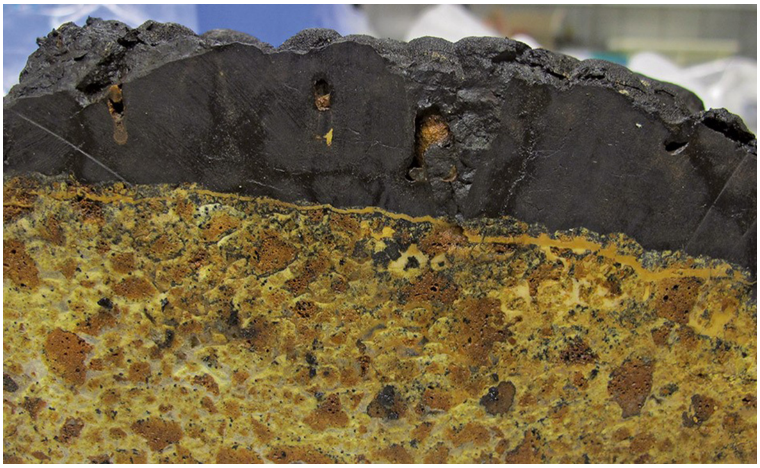


Fig. 4. Black crust of several centimetres thickness on top of substrate of volcanic rock. Sample by BGR from Louisville seamount chain SW Pacific (image after WOW3, World Ocean Review, 2014).

et al. 2015). Formation of manganese crust is seen in areas where the bottom currents are strong enough to keep sedimentation rates negligible. The precipitation and formation of crust takes place on the smooth rocky surfaces of seamounts (substrate) at water depths ranging from 400 to 7000 m (Hein and Koschinsky 2014). Precipitation is very slow and typical growth rates of the crust range from 1 to 5 mm Ma^{-1} (Mizell and Hein 2018). There are two main types of crust formations: (a) hydrothermal crusts, with less economical potential than (b) the cobalt-rich crusts, formed through hydrogenetic processes (Glasby *et al.* 2015).

Typical substrates to which crusts are attached can be basalt (Hein *et al.* 1999; Maciąg *et al.* 2019), breccia, phosphorite, limestone, hyaloclastite, and mudstone (Hein *et al.* 1999). Typical valuable constituents of CRC mineralizations are summarized in Table 1, and include Co, Ti, Ni, Cu, and Mn as well as Pt, Mo, Zr, Nb and REEs (Hein and Koschinsky 2014; Petersen *et al.* 2016). According to Hein and Koschinsky (2014), the ferromanganese crusts with the highest Co contents, are found at water depths between 800 and 2200 m. This coincides mostly with the Oxygen Minimum Zone (OMZ). However, it is not limited to the OMZ, as seen, for example, in the Atlantic and Indian oceans. Cobalt-rich crusts typically have a higher potential for economic contents of Co and REE than polymetallic manganese nodules (Hein and Koschinsky 2014).

Seafloor massive sulfides

SMS are mineralizations containing metals, such as Cu, Zn, Pb, Au, and Ag. SMS deposits are formed in various tectonic settings that are typically located on the boundary between oceanic plates (Hannington *et al.* 1998; Robb 2005). According to German *et al.* (2016), for example, slow spreading ridges have the potential to host the largest SMS deposits. According to Petersen *et al.* (2019), basalt-hosted deposits located at mid-ocean ridges are the most common type of deposits, while more than 30% of the discoveries are found in relation to subduction zones, in back-arc spreading centres, arc volcanoes or rifted arc settings. The economically valuable metals are deposited through precipitation of sulfide minerals in relation to hydrothermal black smoker systems (Hannington *et al.* 1998). The volcanic, chimney-like structures are present in any of the different settings related to SMS. These chimneys are formed through the discharge of high temperature hydrothermal fluids (typically 200–450°C) to the surrounding ocean bottom waters. The sudden temperature drop as the hot fluids mix with the seawater, together with changes in the pressure, leads to precipitation of minerals from the fluids. However, potential deposits are likely to comprise the feeder structures located immediately below the seafloor, the mound consisting of precipitated minerals and collapsed chimney structures (Fig. 5). Additionally, sediments covering the ocean floor in the immediate vicinity to the chimney or assemblage of chimneys could be enriched in the valuable metal minerals. Typically, valuable metals of SMS deposits are Cu, Zn and Au. Table 2 lists the main metals and their average contents according to tectonic setting of formation. The ratio between Zn and Cu is defined by the temperatures of the hydrothermal fluids, Cu being the element precipitating first, at higher temperatures. This leads to a typical distribution of Cu and Zn in the deposit, with the Cu-dominated part

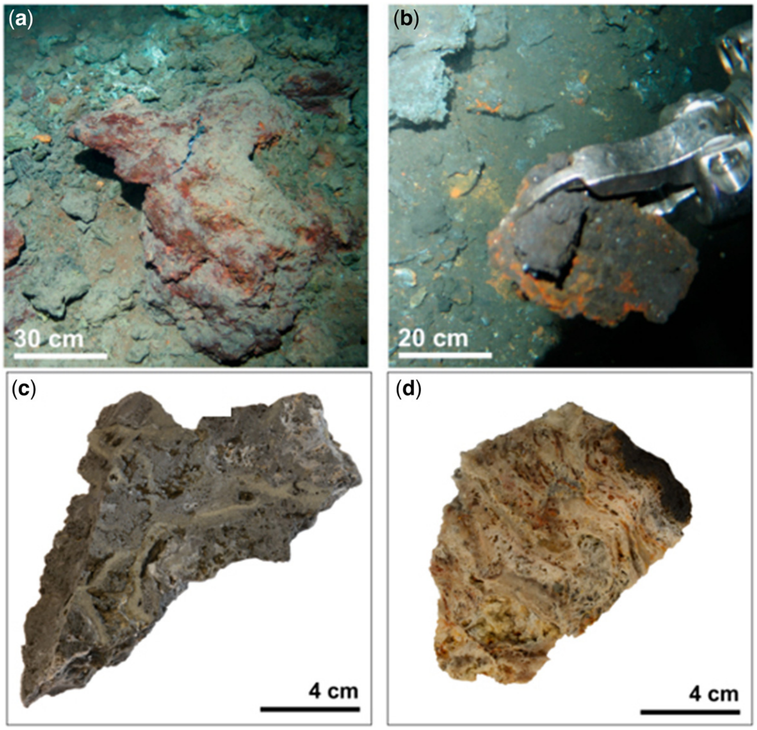


Fig. 5. Picture (**a**) and (**b**) show fragments of hydrothermal vent materials in collapsed chimney fragments on the seafloor; (b) shows grab sampling of a vent fragment using ROV grab. Cut fragments of (**c**) black smoker and (**d**) white smoker end-member specimens; (c) contains lenses and finely disseminated sulfide minerals. Illustration after Snook *et al.* (2018).

of the deposit closer to the hot feeder structures or chimneys, and the Zn-dominated parts of the deposits more distant from the hot feeder structures or related to lower temperature chimneys. The black smoker typically contains abundant (black) sulfides, while the white smokers rather consist of (white) sulfate. Figure 5 shows black and white smoker specimens.

The characteristics of PMN, CRC and SMS deposits can be summarized as PMN and CRC being typical two-dimensional deposits, defined by lateral distribution (Mizell *et al.* 2022). The depth of such deposits is limited, with the distribution of the nodules on the top of the sediment-covered seafloor while covering vast areas at the size of small continents. PMN deposits are typically measured in

Table 2. *Overview of average concentrations of selected metals in SMS deposits related to their tectonic settings*

Setting	N	Cu (wt%)	Zn (wt%)	Pb (wt%)	Fe (wt%)	Au (ppm)	Ag (ppm)
Sediment-free MOR	51	4.50	8.30	0.2	27	1.3	94
Ultramafic-hosted MOR	12	13.4	7.2	<0.1	24.8	6.9	69
Sediment-hosted MOR	3	0.8	2.7	0.4	18.6	0.4	64
Intra-oceanic back arc	36	2.7	17	0.7	15.5	4.9	202
Transitional back-arcs	13	6.8	17.5	1.5	8.8	13.2	326
Intracontinental rifted arc	5	2.8	14.6	9.7	5.5	4.1	1260
Volcanic arcs	17	4.5	9.5	2	9.2	10.2	197

N, number of deposits included in the calculations. Concentrations in wt%, except Au and Ag reported in ppm. Data from (Petersen *et al.* 2016).

abundance of nodules given as kg m^{-2}. CRC deposits on the other hand are also limited towards depth, as the thickness of crusts is typically a few centimetres, up to 26 cm on older seamounts (Hein *et al.* 2013). SMS-type deposits are the only deposits that have a significant vertical extension, although there are still only a few deposits that have been drilled towards depth, where Solwara 1 has a maximum vertical extension of *c.* 30 m below seafloor (Lipton 2012) and TAG approximately 100 m below seafloor (Hannington *et al.* 1998).

Mineral resource potential assessment

Mineral resource potential assessment is about quantifying yet-to-find mineral resources (Singer and Menzie 2010). How much will you find if you explore thoroughly? The potential is preferably given as a range rather than one number. It finds its use in exploration strategy development, in public governance and is a key in proper mineral resource management. The following contribution focuses on SMS, but the methodologies will in the future be further developed to take the specificities of the deposit types presented in the section ‘Ore geology’ into account.

Several attempts have been made to assess the yet-to-find resources on the ocean floor (Hannington *et al.* 2010; Cathles 2011; Singer 2014; Juliani and Ellefmo 2018; Ellefmo *et al.* 2019*b*). All these contributions have focused on SMS. The assessment results vary significantly in terms of tonnage of both potential ore and metal which is not a matter of optimism v. pessimism (Barriga *et al.* 2013), but rather due to different regional perspectives and focus. All assessments spin off by asking five basic questions.

1. Where and what represents the permissible tracts (favourable areas or the play) for potential hydrothermal SMS resources?
2. What are the chances that hydrothermal SMS resources exist?
3. If hydrothermal SMS resources exist, how many accumulations will be found if the areas are explored thoroughly?
4. What is the expected size distribution of accumulations?
5. What types of metals and what grades will the accumulations have?

Methodologies to answer these questions include the 3-Part assessment (Singer and Menzie 2010) which takes a mineral system approach that looks at (metal- and energy) source, effective migration/hydrothermal flow, trapping mechanisms and preservation. This is comparable to the petroleum system approach (Wendebourg 2020). However, the 3-Part assessment should be combined with mineral prospectivity modelling approaches (Nykänen 2008) as was attempted in the MAP-project (MAP 2020). Ellefmo *et al.* (2019*b*) assessed the marine mineral resource potential inside the Norwegian jurisdiction along the Arctic Mid Ocean Ridge (AMOR), specifically along the Knipovich Ridge and Mohns Ridge. A large potential with significant uncertainty was confirmed, spanning the sample space defined by the results from the different attempts to assess the yet-to-find resources cited above. The risk factors were assessed on a regional or a play ‘level’ and a prospect level. The play level risk quantifies the probability that the play or the permissive tract is effective and that there is, somewhere within the play boundaries, at least one occurrence that satisfies the minimum tonnage and grade. The risk on the prospect level says something about the probability that a specific hydrothermal manifestation contains massive sulfides that correspond to the given minimum values and that this will be found if the play is thoroughly explored. The play probability has been set to 0.9 for unconfirmed plays based on the rather restrictive criteria used in the definition of them and to 1 for plays confirmed by a positive identification of an active or inactive hydrothermal field. The criteria used included the presence of crossing faults, flat-topped, conic, and cratered volcanos, axial volcanic ridges (AVR), fault scarps, detachment faults, oceanic core complexes and favourable geodynamic conditions. The prospect risk has been set to 0.43 based on the ratio between the number of black smoker sites to the total number of hydrothermal manifestations (Hannington *et al.* 2013).

Figure 6 shows the Mohns Ridge and Knipovich Ridge on the boundary between the Norwegian and the Greenland Sea. A selection of sites of interest, including Loki’s Castle, is shown in the same figure.

Aggregation of the potential in multiple plays

Since the work for the regional assessment along the AMOR was finished, exploration cruises have made discoveries that were not included in the analysis. Further, Ellefmo *et al.* (2019*b*) did not take the different play types into account. Along the AMOR one could at least differentiate between three play types:

- plays associated with Oceanic Core Complexes (OCC);
- plays associated with a sedimentary rock setting;
- plays associated with a sediment-free, or basalt-hosted setting.

The OCC play is associated with ultramafic rocks and with deep-reaching oceanic detachment faults that may facilitate hydrothermal flow (Sharkov 2012). The OCC plays are indicated in the

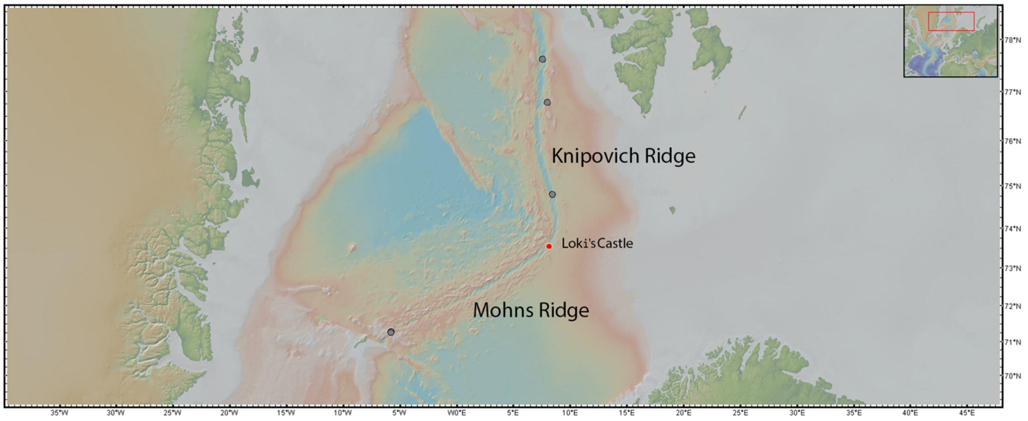


Fig. 6. The more than 1000 km long Mohns Ridge and the Knipovich Ridge along the Arctic Mid Ocean Ridge (AMOR). The active hydrothermal site Loki's Castle shown in red (Pedersen *et al.* 2010). A small selection of other sites of interest (active confirmed venting or water column indications) in grey. Source: GeoMapApp ver. 3.6.6 and Interridge Vents Database ver. 3.4 (Beaulieu and Szafranski 2020).

bathymetric data through the identification of breakaway rides and corrugations and lineations. The sediment-hosted play is associated with sedimentary rocks on the ocean floor and hydrothermal flow along fault structures (Robb 2005). It may contain both exhalative and replacement sulfide mineralizations. The Bent Hill site at the northern Juan de Fuca Ridge in the Pacific is an example of this deposit type (Bjerkgård *et al.* 2000). The sediment-free play is normally associated with axial volcanic ridges and crossing faults (Tivey 2007). They form semi-circular mound-shaped structures on the ocean floor and exhibit internal variations both laterally and with depth. Loki's Castle belongs to this sediment-free, basalt-hosted play type.

Ellefmo *et al.* (2019*a*) investigated an area around Loki's Castle (see Fig. 6). Figure 7 is an enlargement of the area where Loki's Castle is situated on the northernmost AVR, AVR1. The area contains geological settings that can be associated with all the three play types.

Sites of interest that may form on or in association with the different plays would have significantly different geochemical, mineralogical and tonnage characteristics (Fouquet *et al.* 2010; Lusty and Murton 2018). Ellefmo *et al.*(2019*a*) modified grades presented in Hannington (2013), Lusty and Murton (2018) and Cherkashov (2019) based on the ratio between surface samples and core drilling at TAG (Petersen *et al.* 2000) and Solwara 1 (Lipton 2012). This is to accommodate for the sampling bias that is introduced when a grade statement is based on surface samples only. Their representativeness for the interior of the mineralization is highly uncertain. These modified grades were combined in a Monte Carlo simulation framework with the mineralization/deposit density (sites per km^2) and the tonnage models to produce an aggregated resource potential assessment of the area (Fig. 7). The adjusted grades are given in Table 3 and the play areas and the predicted number of yet-to-find sites of interest are given in Table 4.

In Table 4, a correlation between prospective area and deposit density (number of deposits per km^2) is used where the median deposit size is considered (Singer and Menzie 2008). The highly skewed tonnage distribution with a minimum, a median and a maximum of 1700, 73 000 and 23×10^6 t, respectively, is thoroughly presented and discussed in Ellefmo *et al.* (2019*b*). A small area will, following the formalism presented by Singer and Menzie (2008), have a higher deposit density. Table 4 also includes information about the number of confirmed sites in the different play types within the relevant areas. The areas from the respective plays are shown in Figure 7, where the prospective area of the 'sediment-hosted' play is restricted to the axial valley.

Figure 8 shows the aggregated results of the analysis in metric tonnes of metals. The results from the three play analyses (OCC, sediment-hosted and sediment-free) have been merged into one plot and summarized in the embedded table. It shows a total mean potential for all three plays of 273 000 t of metal (Zu, Cu, Ag, and Au combined). The grade distributions showing the relative importance of the elements are given in Table 3. The resource diagram shows the composition probability curve for the total *in-situ* metal potential (metric tonnes) and indicates the relative importance of the three play types inside the area. Each bar indicates the significance of each play type for the given probability. The very large, unlikely scenarios (bottom bars) are

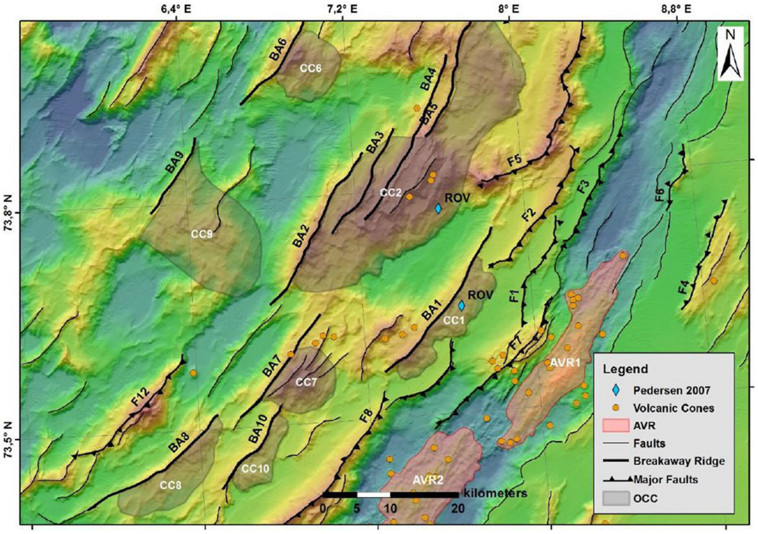


Fig. 7. The different plays and their respective areas are indicated. The sediment-hosted play area included in the analysis is restricted to the axial valley coloured in a bluish tone. Figure from Reimers (2017).

Table 3. *Adjusted grades of Cu, Zn, Au and Ag per play*

	Cu wt%	Zn wt%	Au ppm	Ag ppm
Sediment-free MOR	1.3	2.5	0.4	27.6
Ultramafic MOR (OCC)	4.0	2.1	2.0	19.8
Sediment-hosted MOR	0.3	0.9	0.1	19.5

Original grades have been adjusted based on the ratios between surface samples and drill core samples from the TAG and the Solwara 1 sites.

Table 4. *Area per play and associated number of undiscovered and confirmed deposits/sites of interest*

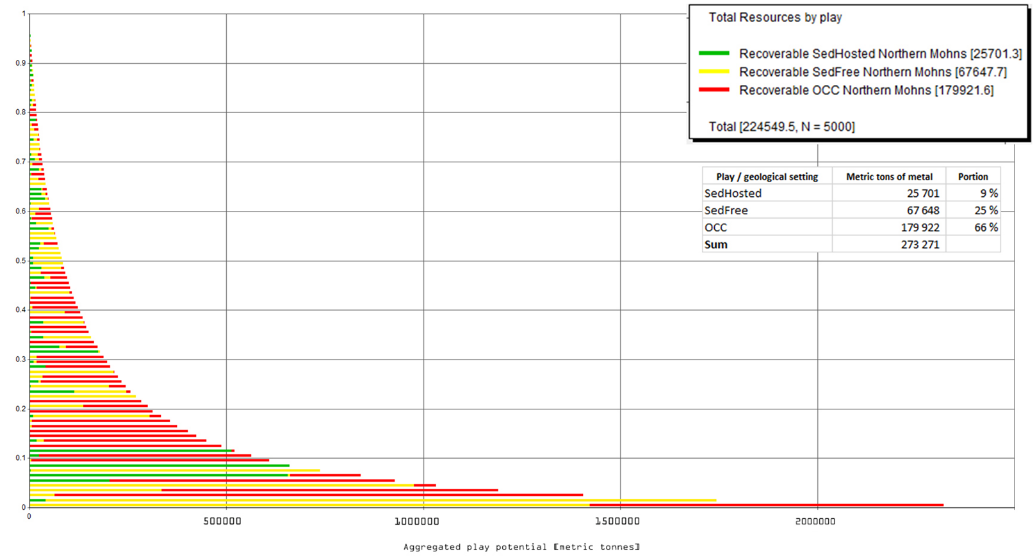
	Area (km^2)	P90	P50	P10	Confirmed sites
Sediment-free MOR	324	1	3	9	1
OCCs	1115	2	6	16	0
Sediment hosted	466	1	4	11	1 (?)

mostly made up of the OCC and the sediment-free plays (red and yellow respectively) and occur when these plays show a significant potential in the Monte Carlo simulation framework. The sediment-hosted play shows a relatively small potential in this analysis, mostly due to the significantly lower grades (Table 3).

The approach shows that the play associated with OCC has the largest potential. This is primarily due to higher expected grades given in Table 3 but is naturally also a function of the larger area relative to the other two play types (Table 4). Further, it can be deduced from Figure 8 that a prerequisite for the area to realize a potential larger than 10^6 t of metal, is that the sediment-free and the OCC plays combined and 'at the same time' contain a significant amount of metal. Further it can be concluded that the play methodology enables a hierarchical approach where multiple plays are combined with a robust risking of plays, prospects, and segments. A preliminary conclusion from this work is that the splitting of the analysis into three distinct different play analyses that are aggregated gives a better understanding of the relevant mineral systems and thereby a better understanding of the uncertainty associated with the different inputs and the outcome. Future work will further elaborate on this notion.

Updating the unknown

A mineral resource potential estimate as presented in Ellefmo *et al.* (2019*b*) and in the previous section 'Aggregation of the potential in multiple plays' must be updated as new information is made available. New information may reduce or increase complexity and hence change the epistemic uncertainty. Since the work that went into Ellefmo *et al.*



Play / geological setting	Metric tons of metal	Portion
SedHosted	25 701	9 %
SedFree	67 648	25 %
OCC	179 922	66 %
Sum	273 271	

Fig. 8. Aggregated play potential for the three play types given in metric tonnes: (1) the sediment-hosted play in green bars; (2) the sediment-free or basalt-hosted (axial volcanic ridge) play in yellow bars; and (3) the oceanic core complex play in red bars. Y-axis gives the probability of exceeding the corresponding play potential.

(2019*b*) was executed, several research cruises have been completed and new occurrences have been confirmed. This would, in effect, update the probability that the play is effective, setting the play probability to 1 (confirmed) if some or more than the newly discovered occurrences fall within the defined plays. If they fall outside the plays, the play boundaries or the play definitions must be updated. Figure 9 shows the central part of the Mohns Ridge (see Fig. 6 and map inset in Fig. 9 for spatial reference) with sub-plays and newly confirmed sites of interest (NPD 2018; Stensland *et al.* 2019).

Table 5 states the play risk before and after the discoveries as well as the number of occurrences within the play areas. This number of known occurrences is considered when the play-specific potential is estimated.

Play 3 and play 5 have been updated due to the findings of the Fåvne and Aegir active sites. Play 9 is ‘only’ confirmed by water column data and the play risk is therefore updated to 0.95.

Figure 10 summarizes the results from the analysis for the play analysis before and after risk update. For the blue points plotted on the orange bisector line, the potential before and after risk update is identical. Points plotted above, indicate that the potential after update is larger than before update. One can see that the potential in plays 3, 5 and 9 has increased slightly due to the lower risk.

Figure 11 presents the percentiles of the aggregated resource potential before and after risk update. The orange dashed line is the first bisector line where the before and after potentials are identical. Due to the high uncertainty in the input variables, the last percentile included in this representation (the P0.5) is affected the most. The maximum metal in the ground after update is slightly lower than before the update, indicating that the potential estimate has been more or better constrained. In addition, we can see that the P25 and P50 are slightly above the first bisector line, indicating a higher 25 and 50 percentiles. The potential has increased and the uncertainty in the estimate has decreased.

The role of ecosystem knowledge in environmental and resource management

One of the crucial aspects of MRM in the context of exploration and exploitation of potential mining areas is environmental assessment. Areas with high marine mineral resource potential (e.g. PMN, CRC and SMS deposits) are unique ecosystems harbouring highly diverse and specialized deep-sea communities (Boschen *et al.* 2013; Schlacher *et al.* 2014; Morgan *et al.* 2015; Vanreusel *et al.* 2016). These ecosystems are considered as hotspots of biodiversity and biota associated with mineral deposits and have adapted over long timescales to the given and often extreme environmental conditions. Due to the limited accessibility of deep-sea habitats, our

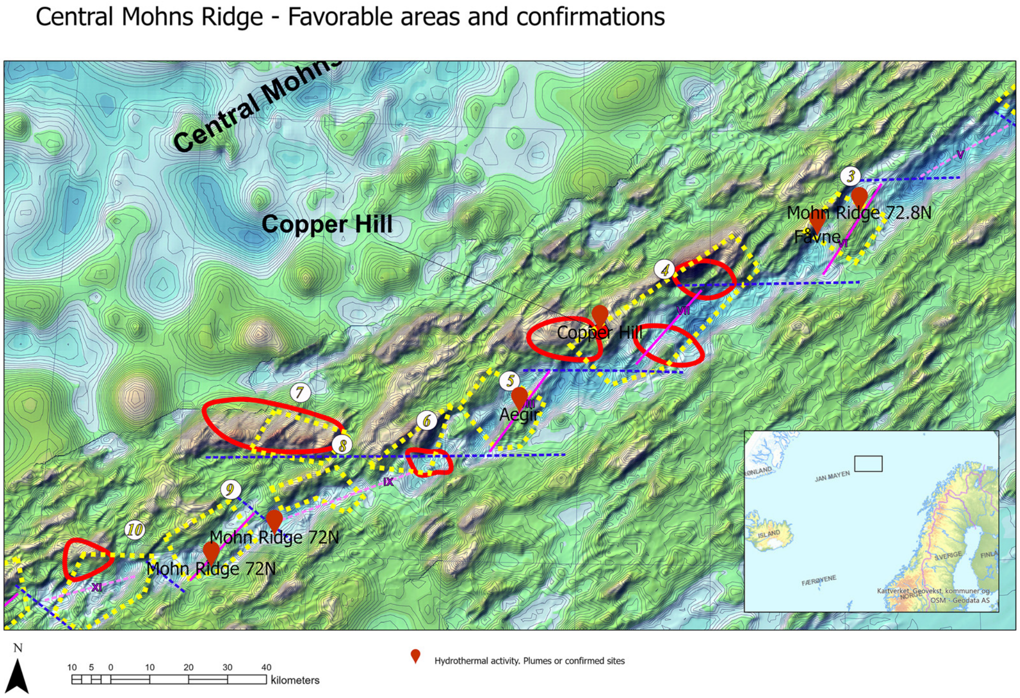


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Fig. 9. Central Mohns Ridge with favourable areas/plays and confirmed occurrences.

Table 5. *Play risk before and after confirmation and the number of mapped sites of interest inside the play*

Play	Play risk before	Play risk after	Number of mapped features
3	0.9	1.0 (Fåvne)	1 (2?)
4	1.0	1.0	1
5	0.9	1.0 (Aegir)	1
6	0.9	0.9	0
7	0.9	0.9	0
8	0.9	0.9	0
9	0.9	0.95 (72N, plume)	(1)
10	0.9	0.9	0

The name of the occurrence responsible for the risk update is in parentheses. The updated risk of play 9 is fixed at 'only' 0.95 since the site has not been positively confirmed with a remotely operated vehicle (ROV) but rather only in the water column.

knowledge of these ecosystems is still very limited and the few studies that exist provide only snapshots in space and time rather than a comprehensive understanding of these complex ecosystems. Any anthropogenic activity and physical disturbance have thus a high potential to harm benthic, pelagic and bentho-pelagic communities substantially (Pedersen *et al.* 2010; Christiansen *et al.* 2020) resulting in long-lasting damage, habitat degradation and biodiversity loss (Vonnahme *et al.* 2020). The biodiversity crisis caused by climate change, habitat loss/fragmentation, pollution and (over-) exploitation of marine resources is one of the major global challenges. However, marine biodiversity and especially deep-sea biodiversity is considered as one of the major knowledge gaps to date. In addition, our knowledge about distribution ranges, life-history dynamics (e.g. reproduction, growth, and mortality rates), adaptive/recovery potential of deep-sea organisms and the ecosystem services such communities provide are not well understood yet.

Mineral deposits with substantial exploitation potential are PMN, CRC and SMS deposits. So far, mineral deposits are a non-utilized resource, but the first exploration licences have been issued (e.g. to Nautilus Minerals Inc. for SMS deposits off the coast of Papua New Guinea), raising concerns among deep-sea biologists and environmentalists due to the risk of substantial loss in biodiversity and ecosystem services (Van Dover 2011).

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As indicated in the section 'Ore geology', vast areas with PMN are found in the abyssal plains (>4000 m depth) in the Pacific and Indian Ocean with a high density and diversity of associated biota ranging from microbial communities to

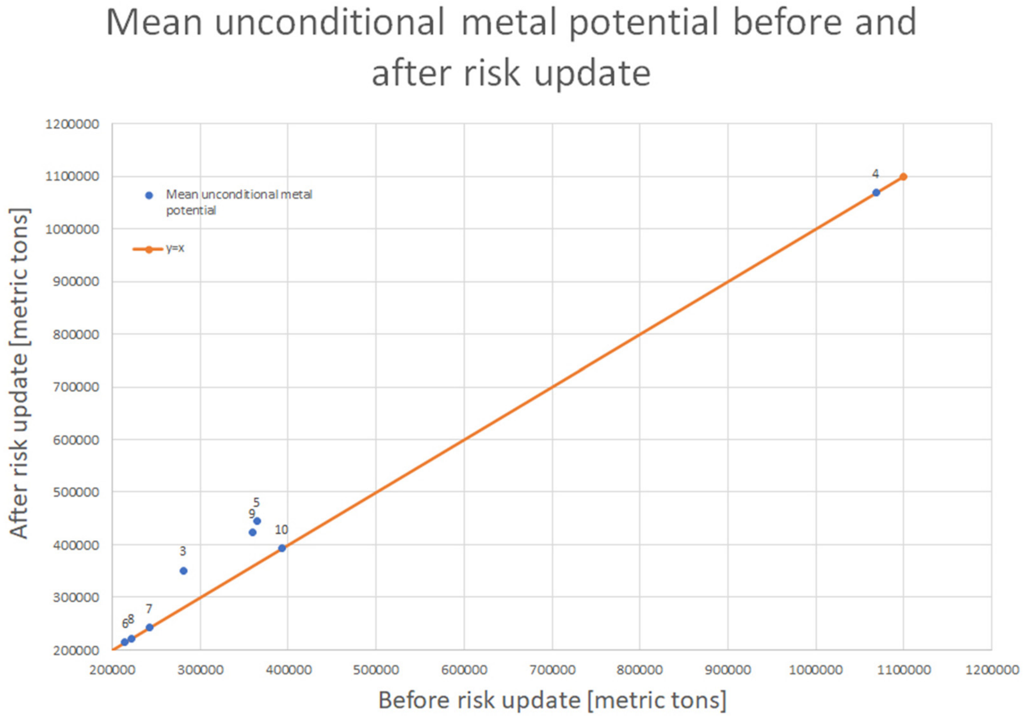

Fig. 10. The mean unconditional metal potential in the different sub-play before and after risk update. Point number corresponds to play number in Table 5.

meio-, macro- and megafauna assemblages in undisturbed nodule areas (Gollner *et al.* 2017, 2021; Vonnahme *et al.* 2020). Based on benthic disturbance experiments simulating mining operations in the deep sea, some groups like mobile megafauna show a good recovery potential (Gollner *et al.* 2017) while the majority of biological processes and groups, especially sessile epifauna, remain affected over decades, showing only slow, if any, recovery rates (Vanreusel *et al.* 2016; Jones *et al.* 2017; Vonnahme *et al.* 2020). A mechanical removal of nodules results in habitat destruction, thus affecting seafloor integrity. By destroying the biologically highly active sediment surface layer, the associated fauna as well as remineralization and bioturbation processes are severely affected by mechanical disturbance with long-lasting consequences for the recovery of deep-sea biota (Vonnahme *et al.* 2020).

Deposits of CRC are found at seamounts (submarine volcanoes) in all oceans at depths between 400 and 4000 m. Fauna and biological activity associated with CRC are poorly investigated so far. The few studies that exist indicate that habitats with CRC deposits are very heterogeneous, with a large variety and patchy distribution of biota, e.g. crinoid and octocoral communities (Morgan *et al.* 2015). Many organisms associated with CRC are slow-growing species with long life cycles and thus especially prone to mechanical disturbance (Schlacher *et al.* 2014). Due to the distinct role as hotspots in marine biodiversity, nursery grounds and refuge, seamounts *per se* are considered as habitats that are especially vulnerable to anthropogenic pressure related to deep-sea bottom fishing and mining. Thus, strict environmental guidelines, biological status assessments and conservation measures need to be developed before any CRC exploitation can be considered.

SMS deposits at hydrothermal vent fields are found at depths between 100 and 4000 m along mid-ocean ridges that differ in seafloor spreading velocity and magma supply. Vent communities are characterized by a high biodiversity consisting mainly of molluscs (Archaeogastropoda, *Bathymodiolus* spp.), arthropods (copepods, shrimps, crabs), and annelids (e.g. *Rifta pachyptila*) that colonize different zones around the vents according to temperature and fluid gradients (Vrijenhoek 2010; Galkin 2016). Most SMS communities are gathered around active sites. Active sites are usually not considered as targets for mineral extraction due to the acidity and high temperature of spewing fluids, instability of active mounds and lower mineral potential due to

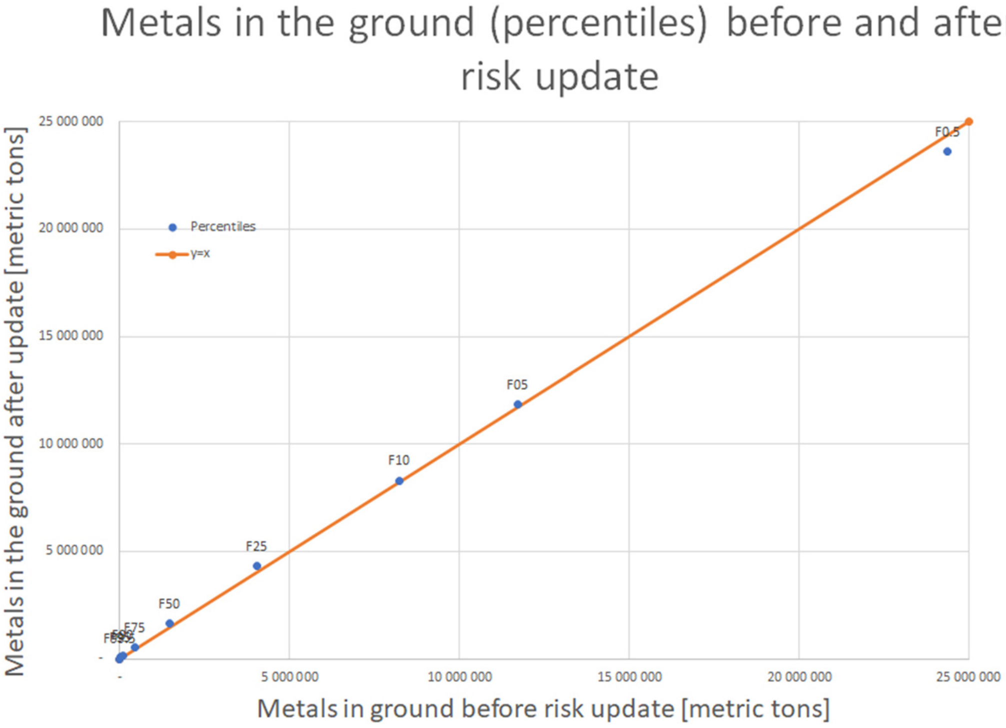

Fig. 11. Percentiles describing the aggregated potential distribution. Due to the high uncertainty in the input variables, the last percentile included in this presentation is affected the most. The P0.5 metals in the ground after update is slightly lower than before the update, indicating that the potential estimate has been more or better constrained. The P25 and P50 are also affect slightly indicating a larger potential after update, indicating that the estimate is more constrained (lower uncertainty).

immaturity of active deposits. However, inactive sites with less diverse and abundant fauna and mature mineral deposits are targeted. To date, our knowledge on potential anthropogenic impacts related to the exploitation of inactive sites and subsequent alterations such activities cause for biota at active sites close by ($<$10 km) have not been studied yet.

While the East Pacific Ridge (EPR) is characterized as a fast-spreading area with high magma supply, the mid-Atlantic ridge (MAR) is considered as a slow-spreading area with less magma supply. The degree of seafloor spreading velocity and magma supply affect the colonization pattern of vent communities with shorter distance ($<$10 km apart from each other) between vent communities at EPR and larger distances at MAR sites ($>$100 km apart from each other). The distance between vent communities considerably affects the stability, dispersal and (re-) colonization rates after disturbance from natural (e.g. volcanic eruptions, plate tectonics) and anthropogenic drivers (e.g. research, mining). Communities from slow-spreading areas with less frequent eruptive events and larger distance between vent communities (including e.g. Loki's Castle vent field at the ultra-slow spreading Arctic Mid-Ocean Ridge) are usually considered as more stable and prone to disturbance than those from fast-spreading areas that show higher resilience and faster recovery rates (Pedersen *et al.* 2010; Beaulieu *et al.* 2015; Gollner *et al.* 2015; Mullineaux *et al.* 2018).

SMS deposits are of interest for mining industries, e.g. along the MAR and the Indian ridge. In Norwegian waters, the major focus was so far on the exploration of four active vent sites with SMS deposits along the Kolbeinsey Ridge, Mohns Ridge and Knipovich Ridge at the AMOR while most knowledge on biological status is available for the Jan Mayen Vent Field and Loki's Castle where a unique benthic fauna is documented (Olsen *et al.* 2016). Active and inactive vent sites harbour different biological communities (Boschen *et al.* 2013). However, for most vent fields, especially the inactive ones, comprehensive studies on community structure and ecological status are missing, thus pointing at considerable knowledge gaps and the needs for thorough mapping and ecosystem assessment (Boschen *et al.* 2013; Olsen *et al.* 2016). Vents are non-permanent structures of different ages ranging from newly established to old vent systems (>20 000 years of age). While they are considered to have a high turnover on geological timescales, they serve as stable, undisturbed environments in a biological sense. With age, vents usually become cold and less active, but the temporal overlap of old and newly established vent fields is crucial since the old, less-active vents serve as stepping stones for the colonization of new vent fields (Smith *et al.* 1989; Tandberg *et al.* 2013). A prerequisite for a successful colonization of new vents is that suitable habitats need to be reachable within a given temporal window of the pelagic life-stages of vent fauna that are advected by currents. To date, one of the major knowledge gaps in the context of deep-sea mining is how resilient these communities are and on which timescales recovery and adaptation to changes in environmental conditions will happen. As long as a high degree of uncertainty related to these fundamental questions exists, concerns about deep-sea mining activities raised from researchers, environmentalists and society need to be taken serious and mitigation measures need to be implemented.

When considering the exploitation of a potential deep-sea mining area, it is thus fundamental to perform thorough, scientifically sound, and independent Environmental Impact Assessments (EIA) (Jones *et al.* 2019). EIA should be performed in concert with geological exploration to gain a comprehensive understanding on the geobiology of a given area, long before permit issuance can be considered, by taking regional to large spatiotemporal scales and the connectivity between systems into account.

Deep-sea mining as a potential future business venture on the NCS: uncertainty quantification and exploitation

On 1 July 2019 the Norwegian Seabed Minerals Act entered into force (NPD 2021*b*). This Act is intended by the Norwegian authorities to 'facilitate exploration for and extraction of mineral deposits on the Norwegian Continental Shelf in accordance with societal objectives' (NPD 2021*a*). Along with this, the Norwegian Government has decided to initiate an opening process for mineral activities on the Norwegian Continental Shelf (NCS) and tasked the Norwegian Petroleum Directorate (NPD) to map the most commercially interesting mineral deposits (NPD 2021*b*). Companies are now strategically positioning themselves to exploit this resource potential (Energi24 2021).

From the corporate perspective, deep-sea mining represents a potential business venture with both a high potential up- as well as downside. A key takeaway from a recent report (Rystad 2020) evaluating the potential of deep-sea mining on the NCS is that marine minerals are 'in the money', with a projected income significantly higher than the estimated cost of extraction. However, committing resources to deep-sea mining at this stage entails a great deal of risk. When assessing investment opportunities and developing entry strategies, companies are confronted with various sources of uncertainty and risk factors as many of the determining modifying factors are highly uncertain at this point. Uncertainties span from regulatory to market, environmental impact, and technological uncertainties. Future demand for, supply and therewith, prices of the relevant metals are highly uncertain. The regulatory framework is not established and whether and when technologies will allow for mining activities on the ocean floor with a sufficiently low environmental impact is unknown. This emphasizes the need for an in-depth focus on mineral resource management.

Establishment of a new deep-sea mining value chain on the NCS will require substantial investment in technology and infrastructure. Many of these investment outlays will have to be made years before companies might earn potential revenues. These investment options show similarities with other strategic investment problems like joint ventures or research and development. It is well established that the value of many strategic investments does not derive so much from direct cash inflows, as it does from the options to invest in future growth (Smit and Trigeorgis 2007). However, the investment and project assessment tools predominantly used as the basis for corporate investment decision-making by mining and other commodity companies are still widely based on static discounted cash flow (DCF) analysis and net present value calculation. These traditional methods do not, however, provide the flexibility for strategic decision-making on new business ventures in deep-sea mining.

The traditional DCF approach is based on an implicit assumption that management is passive. In reality, however, if expected events are not realized, management can actively revise future decisions to capitalize on better-than-expected developments or retreat to limit losses from adverse market developments or competitive moves (Smit and Trigeorgis 2007). To assess the value of such strategic investment options, real options tools present an important complement to the traditional techniques. Compared to traditional valuation methods, the real options approach encourages proactive strategic management and presents decision makers with a more proactive response to uncertainty. The real options approach is more dynamic than traditional approaches. It is capable of incorporating not only the value of flexibility and growth opportunities but also of competitive strategies in an uncertain environment (Smit and Trigeorgis 2007).

Real options analysis applies valuation models originally developed for financial securities to the area of corporate investment decisions. Options are financial derivatives that give buyers the right, but not the obligation, to buy or sell an underlying asset at an agreed-upon price and date. Real options differ from financial options contracts since they involve real (i.e. physical, 'underlying') assets and are not exchangeable as securities. A real option is an economically valuable right to make or else abandon some choice that is available to the managers of a company. In other words, a real option gives a firm's management the right, but not the obligation to undertake certain business opportunities or investments. It is referred to as 'real' because it typically references projects involving a tangible asset (such as machinery, buildings, or inventory), instead of a financial instrument. These assets must be managed as part of the mineral resource management process.

A complexity inherent to real options is that many different uncertainties can affect their value. These can be classified into exogenous and endogenous uncertainties. Exogenous uncertainties are those that are outside the control of the decision maker. Examples are market prices of, for example, metals or other commodities which usually can be hedged with market instruments. Endogenous uncertainties include technological uncertainty that might be solved through further learning-type investment (Trigeorgis and Reuer 2017). Other examples are uncertainty in resources in place or future production profiles. These are often estimated based on expert judgements. Early applications of real options valuation and standard models are well suited for exogenous uncertainties. Here the standard financial economics approaches to option pricing can be applied. In recent years research extended the modelling approaches and analysis to additionally account for endogenous uncertainties (Smith and Nau 1995; Smith and McCardle 1998; Brandão *et al.* 2005; Oriani and Sobrero 2008).

From a macroeconomic point of view, deep-sea mining could be viewed as a development option for economic growth (Baker and Beaudoin 2013). Norway has long benefitted from its position in oil and gas. But with this industry under pressure from environmental concerns, deep-sea mining could contribute to economic development. Rystad (2020) estimates, in their most constructive scenario, that this industry could create annual revenues worth USD 20 billion, together with employment for up to 21 000 full-time equivalents. These estimates are related to the NCS. Having a large export potential, the parallels to the oil and gas industry are evident. As the industry is in its infancy, creating a leading local business could be the key to a high revenue export industry (Rystad 2020).

Without proven technology and pre-existing infrastructures, investors may, however, prefer to wait due to the regulatory uncertainty, large capital costs, and many other uncertainties. Given the urgency of the energy transition and the need for radical technological solutions, finding the optimal timing that assures that future opportunities are realized, and at the same time stranded assets are avoided, is crucial.

Despite the belief that marine minerals extraction could help to enable the green transition, it is crucial that the industry itself will be sustainable. Paulikas *et al.* (2020) concluded that, compared to onshore mining, offshore mining of nodules would reduce the environmental footprint by more than 90%. To date, no such study has been performed for SMS mining. However, before granting any exploration and extraction licences to body corporates on the NCS, the NPD will complete an impact assessment to understand if it is possible to carry out responsible mineral activities and simultaneously protect the ocean environment (Norwegian Ministry of Petroleum and Energy 2021). How the governmental restrictions and licences will be regulated will have a major impact on the evolution of a deep-sea mining industry. The decision concerning the opening of the NCS for licence application is currently planned for Q2 2023 (GCE Ocean Technology 2021).

Crossing discipline boundaries

Uncertainties abound regarding the potential impact of deep-sea mining on society, the economy, and the environment. These range from disruption of cultural practices in coastal communities, through the future state of metal markets to the cumulative effects of disruption to the marine environment. Deep-sea mining not only spans the boundaries between the marine and terrestrial environments, but also between nature and culture (Koschinsky *et al.* 2018). For onshore mining, large amounts of work and investment are needed to obtain the social licence to operate since societies are widely spread, cultural heritage sites are numerous and sacred land needs to be protected. This may be different offshore, but here the ecosystems are unique and to a large extent unknown and their importance for functions and services is uncertain. An interdisciplinary approach is needed to identify and describe the problems, but also to devise potential solutions, and ultimately to decide whether there is a path forward for deep-sea mining (Koschinsky *et al.* 2018).

Interdisciplinary work is therefore imperative in education and in industrial operations to achieve responsible mining needed for a future sustainable development (Binder *et al.* 2017; Koschinsky *et al.* 2018). The interdisciplinary approach has been defined as an integration of knowledge and competencies from different disciplines that enables to **Q17** reach a higher goal and a distinction between a unidisciplinary, a multidisciplinary and a transdisciplinary approach has been made (Peek and Guikema 2021). The latter includes most co-operation and data and information transfer across discipline and scientific boundaries and a potential development of new worldviews, domains and sets of methodologies. In geoscience, geometallurgy is often labelled as interdiscipline integrating a vast range of geosciences including mathematical geosciences (van den Boogaart and Tolosana-Delgado 2018). The inter- **Q18** disciplinary approach (Peek and Guikema 2021) will enable the involved stakeholders to comprehend smaller nuances in the understanding and use of concepts like uncertainty, value, and risk. This may, if managed well and focusing on interaction and positive dialogue, render it possible to reach goals not possible if a unidisciplinary approach was used. van der Bles *et al.* (2020) emphasize the importance of communicating uncertainties, of which there are many in deep-sea mining, spanning from technological, geological, biological, legal to social uncertainties.

This article has taken a broad perspective on deep-sea mining and the overall management of mineral resources and the environment. It advocates the need for a holistic perspective where the vast mineral deposits on the ocean floor may play a future role in meeting the demand for metals and minerals to support the transition towards a greener energy production and e-mobility. For marine mineral deposits to play a role, an interdisciplinary or even a transdisciplinary approach is taken where all modifying factors are included and assessed by including both natural and social sciences and technological aspects. These modifying factors have been exemplified in this contribution by factors related to environmental concerns and social aspects, to ore geology and resource assessment and to risk and financial aspects. The social aspects are of uttermost importance. Geological, technical and to some extent ecological risks may be calculated. Social or political risks are arguably more difficult to assess due to the subjective aspects of these risks and failing to understand and to assess them thoroughly may cause significant costs and may turn over a project before it has properly started. Successful attempts to quantify social and political risks have been made using the Grey-TOPSIS model (Li *et al.* 2021). Risk is the effect of uncertainty on your objectives and both risks and uncertainties in all relevant modifying factors must be managed. In the introduction to this contribution, it is stated that ‘holistic marine mineral management requires a clear understanding of the objectives to be achieved through mining, to assess the proper balance between costs, risks, potential gains and losses’. We have touched upon some of the factors that need to be balanced. Whether our society will manage to balance these factors in the future to ensure responsible mining for sustainable development remains to be seen and will depend on our ability to communicate across boundaries.

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