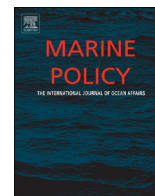




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## News from the seabed – Geological characteristics and resource potential of deep-sea mineral resources

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## ABSTRACT

Marine minerals such as manganese nodules, Co-rich ferromanganese crusts, and seafloor massive sulfides are commonly seen as possible future resources that could potentially add to the global raw materials supply. At present, a proper assessment of these resources is not possible due to a severe lack of information regarding their size, distribution, and composition. It is clear, however, that manganese nodules and Co-rich ferromanganese crusts are a vast resource and mining them could have a profound impact on global metal markets, whereas the global resource potential of seafloor massive sulfides appears to be small. These deep-sea mineral commodities are formed by very different geological processes resulting in deposits with distinctly different characteristics. The geological boundary conditions also determine the size of any future mining operations and the area that will be affected by mining. Similarly, the sizes of the most favorable areas that need to be explored for a global resource assessment are also dependent on the geological environment. Size reaches 38 million km<sup>2</sup> for manganese nodules, while those for Co-rich crusts (1.7 million km<sup>2</sup>) and massive sulfides (3.2 million km<sup>2</sup>) are much smaller. Moreover, different commodities are more abundant in some jurisdictions than in others. While only 19% of the favorable area for manganese nodules lies within the Exclusive Economic Zone of coastal states or is covered by proposals for the extension of the continental shelf, 42% of the favorable areas for massive sulfides and 54% for Co-rich crusts are located in EEZs.

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### 1. Introduction

Earth provides natural resources such as minerals and metals that are vital for today's society. At present, almost all of these resources are mined from ore deposits on land, which represents less than one third of Earth's surface. However, large, high-grade ore deposits are becoming more and more difficult to find, driving the mining industry to develop lower-grade sites where mining has greater environmental impacts, as well as to develop deposits in more remote areas or at greater depths. At the same time, future global demand for metals is expected to rise due to steady population growth, reaching 9.7 billion by the year 2050 [1], the economic growth of countries such as China, Brazil, and India, and the transition to a green economy. The population growth may also cause increasing land-use conflicts between the mining industry and the need to feed and house the growing population. In addition to the rising demand for metals, geopolitical concerns can also limit the availability of certain metal resources from land-based ore

deposits. This was evident over the past years with China lowering its export of "Rare Earth Elements" to global markets awakening the media and policy. China currently is responsible for about 95% of the total world REE production and therefore has almost complete control over that market. There is therefore a foreseeable risk of increasing resource supply shortages for some metals that are important to the economy [2,3], and a number of governments are looking for ways to ensure a secure supply of metals. Together with the development of new methods for mining on land and increased recycling, mining in the deep sea is viewed as a potential new avenue for the diversification of metal supply. The first two deep-sea mining licenses have been granted within the Exclusive Economic Zones (EEZs) of Papua New Guinea and Sudan/Saudi Arabia raising expectations that a new marine mining industry is about to emerge. At the same time, scientists and non-governmental organizations have raised concerns about the lack of a regulatory framework and environmental baseline studies and limited knowledge of the potential environmental impacts of deep-sea mining [4–9]. This paper provides an overview of the three primary deep-sea mineral commodities, the current status of exploration activities, and the global resource potential.

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## 2. Manganese nodules

### 2.1. Origin and distribution

Manganese nodules are mineral concretions that typically range between 1 and 12 cm in diameter and consist of manganese and iron oxides [10,11]. They occur widely on the vast, sediment-covered, abyssal plains at water depths of about 3000–6000 m, where sedimentation rates are lower than 20 mm per thousand years ( $\text{mm ky}^{-1}$ ). The manganese and iron minerals in these concretions form by a combination of hydrogenetic growth, in which the minerals precipitate from cold ambient seawater, and diagenetic growth, in which minerals precipitate from pore waters within the sediment [11]. The metals in seawater are concentrated by adsorption onto ultrafine particles of Fe and Mn-oxides (so-called nanoparticles or colloids) that are attracted to each other electrostatically in the water column. The Mn-oxide particles have a negative surface charge and so scavenge other trace metals as they form, especially positively charged ions such as Co, Ni, and Cu that are also present in seawater in trace concentrations. The Fe-oxide particles, in contrast, have a slight positive surface charge and they attract negative ions in seawater, such as the oxyanions of Mo, V, As, and some REE. Diagenetic precipitation within the sediment occurs under oxic or suboxic conditions from pore fluids that consist of seawater modified by chemical reactions within the sediment. Manganese nodules with mixed origin are more common than either of the two endmember types.

The ultimate source of the metals dissolved in seawater is erosion from the continents [12], but manganese is primarily derived from hydrothermal sources that are widely distributed throughout the global ocean. Over time, these particles, together with their sorbed trace metals, accumulate as nodules by accretion of concentric layers of the Mn- and Fe-oxides around a nucleus, which often consists of older nodule fragments, shark teeth, plankton shells, or rock fragments.

Hydrogenetic nodules grow at an extremely slow rate of about 1–10 mm per million years ( $\text{mm My}^{-1}$ ), while diagenetic nodules grow at rates of several hundred  $\text{mm My}^{-1}$ . Most nodules form by a combination of hydrogenetic and diagenetic precipitation and therefore grow at intermediate rates of several tens of  $\text{mm My}^{-1}$  [11]. Manganese nodule genesis and growth are affected by many environmental factors, especially (1) supply of biogenic, terrigenous and hydrogenetic material to the sediment and to the nodules; (2) deposition and reworking of sediments due to seafloor morphology; (3) bottom water composition and movement; and (4) bioturbation [11]. The presence of bacteria could indicate a biological role in the formation of the nodules, but this is not well understood. The very slow growth rates of hydrogenetic nodules suggest that bacterial mediation may not be a major factor in their formation. However, bacteria play a major role in sediment diagenesis, where manganese, nickel, copper, and other elements such as lithium are released into the pore fluids and then taken up during the formation and growth of the nodules.

The mineralogy of manganese nodules is rather simple and consists mainly of three manganese oxides: vernadite, todorokite, and birnessite as well as a number of non-crystalline Fe-oxyhydroxides [11].

The main prospective areas for manganese nodules are the global abyssal plains, which cover vast areas of the seafloor. Young oceanic crust ( $< 10$  million years) or areas with high sedimentation rates ( $> 1 \text{ cm ky}^{-1}$ ) are generally excluded from exploration [13–16], as are areas with a bathymetric relief of more than 300 m (Fig. 1A). Defined by these criteria, the global extent of the permissive areas for nodules exceeds 51 million  $\text{km}^2$ . This does not include vast areas north of  $80^\circ\text{N}$  and south of  $70^\circ\text{S}$ , where there is

no data on sediment thickness. [Note that prevailing weather conditions at these high latitudes may exclude them from future exploitation, regardless of the resource potential.] The search for nodules has been narrowed recently by closer consideration of the geological setting, sedimentation rates, and metal input to certain favorable areas [10]. These areas cover approximately 38 million  $\text{km}^2$  (Fig. 1B). Of this, the majority (81%) is located beyond the areas of national jurisdiction (referred to as “the Area”). The remainder is within EEZs (14%) or areas that are part of proposed extensions to the continental shelf (5%). Exploration of such large areas is a tremendous and time-consuming task.

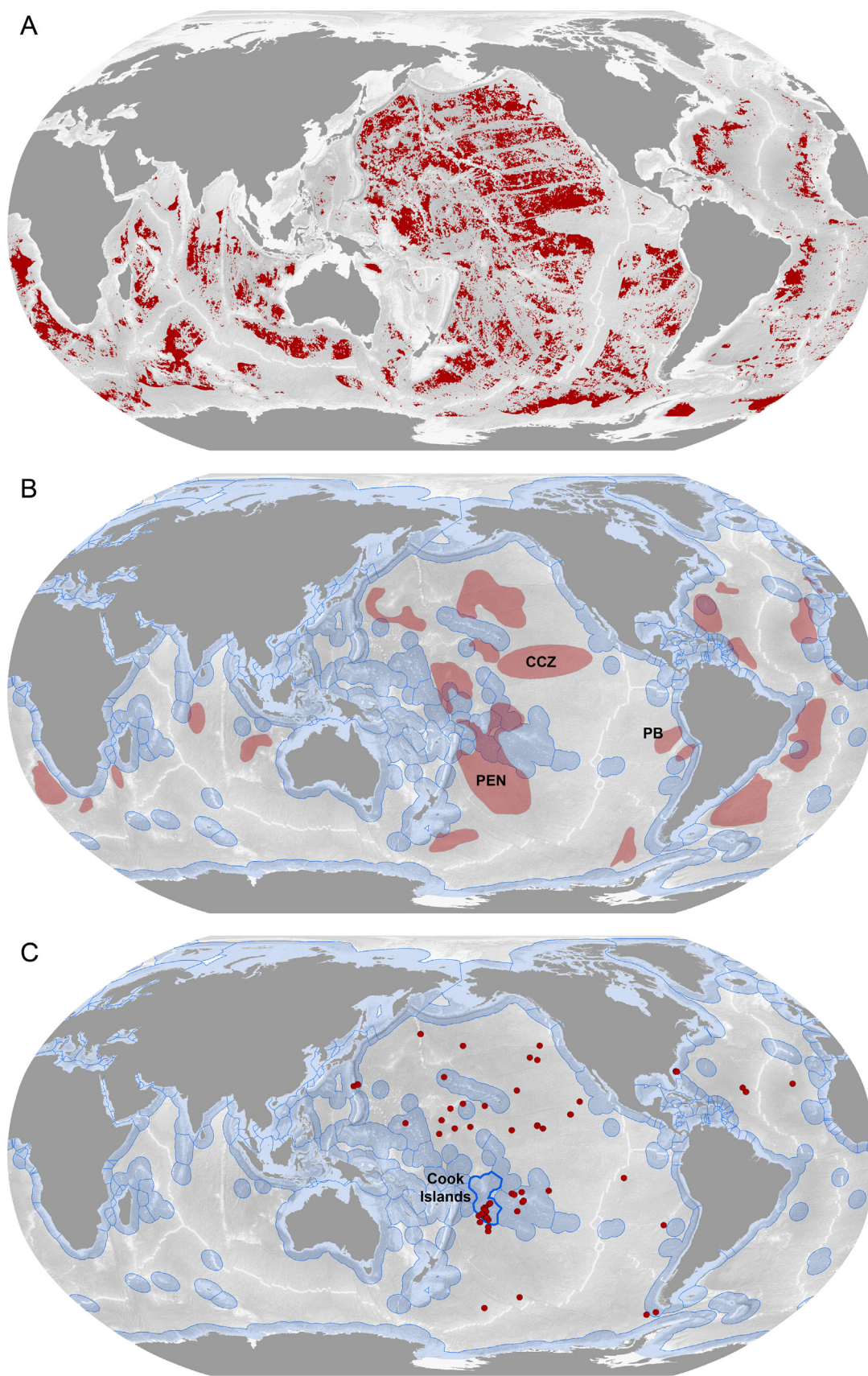
The greatest concentrations of metal-rich nodules that have been discovered so far occur in the Clarion-Clipperton Zone (CCZ) of the eastern Pacific Ocean, which extends from the west coast of Mexico to Hawaii between the Clarion and Clipperton fracture zones (Fig. 1B). Nodules are also known to be concentrated in the Peru Basin, near the Cook Islands, and at abyssal depths in the Indian and Atlantic oceans [11,17]. The area that is situated in international waters and is located between the Clarion and Clipperton fracture zones covers an area of 5.2 million  $\text{km}^2$  including an area of 4.2 million  $\text{km}^2$  of commercial interest [18]. Nodule densities in this area are rarely as high as 75 kg wet weight per  $\text{m}^2$  of seabed, but more commonly average less than 15 kg wet weight per  $\text{m}^2$  [11]. The highest concentrations of nodules (in terms of percentage of seafloor covered) are found between  $12$  and  $16^\circ\text{N}$  latitude and at water depths between 4100 and 4200 m [18].

The abundance of nodules in the CCZ is attributed to a number of factors. The combination of slow sedimentation rates and abundant animals living within the sediment itself, which cause bioturbation and the uplifting of the nodules, helps to keep them on the surface of the seabed. The flow of Antarctic Bottom Water through the CCZ also erodes and removes fine sediments, leaving abundant materials (such as fragments of broken nodules, mineral grains, and plankton shells) for the manganese and iron to nucleate around. This flow also keeps the bottom waters well oxygenated. The moderate surface-water productivity of the region provides the organic matter that the bacteria in the sediment use in diagenetic reactions, yet is not high enough to increase sedimentation rates. Finally, a semi-liquid bottom sediment layer provides abundant pore water to contribute to the diagenetic nodule growth.

### 2.2. Metal concentrations and resource potential

Manganese and iron are the principal metals in manganese nodules. The main metals of economic interest, however, are nickel, copper, cobalt, and possibly manganese and titanium [10,17]. In addition, there are traces of other valuable metals, such as molybdenum, REEs, and lithium that have industrial importance in many high-tech and green-tech applications and can possibly be recovered as by-products (Table 1). Rare earth element and platinum-group element (PGE) concentrations in nodules are lower than in ferromanganese crusts, so investigations of possible exploitation of marine resources for REE and PGE will likely focus on Co-rich ferromanganese crusts (see below, [11]).

The abundance of nodules and, therefore, the quantities of associated metals are moderately well known for the CCZ, the Central Indian Ocean Basin and the Cook Islands EEZ, but poorly known for other areas of the global ocean. A conservative calculation for the CCZ suggests that there are about 21,100 million dry metric tonnes of nodules in the region [18]. That would yield nearly 6000 million tonnes of manganese, which is more than the entire known land-based reserves for manganese [10,17]. Similarly, the amount of nickel (270 million tonnes) and cobalt (44 million tonnes) in those nodules would be three and five times



**Fig. 1.** (A) Locations of areas within the abyssal plains that are important for manganese nodule formation based on seafloor classification, seafloor age (older than 10 My), sediment thickness ( $< 1000$  m), sedimentation rate ( $< 1$  cm/1000 years), and water depth (between 3000 and 6000 m). Note the lack of data below  $70^{\circ}$ S and above  $80^{\circ}$ N. See text for details. (B) Areas with highest Mn-nodule potential based on seafloor morphology, age of the crust, and metal input as defined by [10]. Light blue areas delineate the Exclusive Economic Zones. Abbreviations: CCZ=Clarion-Clipperton Zone, PB=Peru Basin, PEN=Penrhyn Basin. (C) Location of manganese nodule samples in the International Seabed Authority (ISA) database with Co concentrations above 0.5 wt% ( $N=211$ ). Note the large number of Co-rich samples in the EEZ of the Cook Islands. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Table 1**  
Mean content of selected elements of manganese nodules in various locations (source [10,17]). Abbreviations: CCZ=Clarion Clipperton Zone; CIOB=Central Indian Ocean Basin).

	CCZ	CIOB	Peru Basin	Cook Islands
Mn (wt%)	28.4	24.4	34.2	16.1
Ni (wt%)	1.3	1.1	1.3	0.4
Cu (wt%)	1.1	1.0	0.6	0.2
Co (wt%)	0.21	0.11	0.05	0.41
Ti (wt%)	0.28	0.40	0.16	1.20
Mo (ppm)	590	600	547	295
Li (ppm)	131	110	311	–
REE+Y (ppm)	813	1039	403	1665

greater than the entire land-based nickel and cobalt reserves, respectively [17]. The amount of copper in the CCZ nodules is about 226 million tonnes and equals 30% of the global land-based reserves. When using these tonnages for comparison, it should be noted that approximately 0.9 million km<sup>2</sup> between the Clarion and Clipperton fracture zones have recently been designated as “Areas of Particular Environmental Interest (APEI)” and are thus now excluded from exploration and exploitation. The total area of the APEIs covers 1.4 million km<sup>2</sup>, but some parts are located beyond the area between the Clarion and Clipperton fracture zones and do not overlap with areas of commercial interest. Additionally, large areas within the CCZ are not suitable for exploitation as they are covered by seamounts or other topographic obstacles or they are simply areas with low nodule coverage. While the contained copper content in the CCZ is large, it is important to note that the land-based reserves include only those known deposits for which economic recovery is already assured; it does not include potentially large undiscovered or currently uneconomic resources. Although there has been extensive sampling of manganese nodules, detailed information about their geochemical compositions are not currently available from the ISA contractors. Moreover, information about the distribution of nodules globally is mainly limited to the publically available ISA sample database, which clearly shows a bias towards sampling in the Pacific high-grade area. Using proprietary data from its contractors, ISA has shown that, even in the CCZ, the nodules are unevenly distributed, with richer prospects in the central and northern parts of the CCZ and less attractive resources in the southern, south-western and eastern parts of the CCZ [18]. High grade CCZ manganese nodules commonly contain between 2% and 2.6% Ni+Cu [11,18–20]. Average grades between 2.2% and 2.3% Ni+Cu and cut-off contents between 1.2% and 1.7% Ni+Cu were reported earlier to be necessary for first generation mining operations [19,20]. However cut-off grades will depend on nodule abundance in the respective area, global metal markets, and other factors. Most early investigations neglect the possible recovery of minor elements as valuable components. Although the most favorable sites in the CCZ have already been licensed to contractors, manganese nodule resources around the Cook Islands are also still considered to be a viable resource based on their high Co-content (Fig. 1C), which commonly exceeds 0.5 wt% Co in individual samples. These are some of the highest reported Co concentrations from the ocean floor, and mean concentrations of Ti (1.2 wt%) and REE (total REE of 1665 ppm) have created additional interest for that area [17]. In August 2015, the Cook Islands decided to open a tender for 10 exploration blocks of 10,000 km<sup>2</sup> each encompassing the nodule occurrences in their EEZ.

### 3. Co-rich ferromanganese crusts

#### 3.1. Origin and distribution

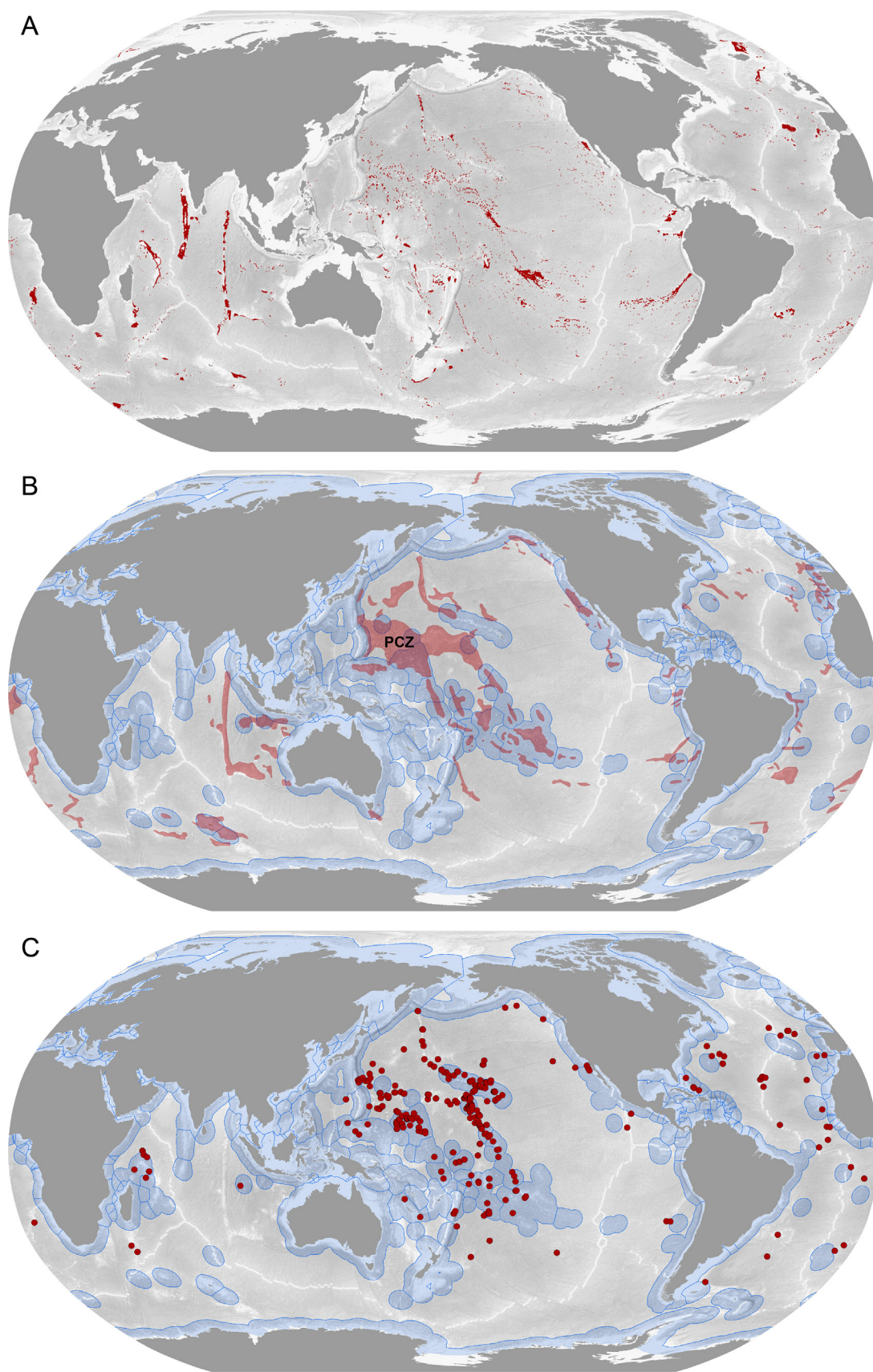
Cobalt-rich ferromanganese crusts precipitate onto nearly all rock surfaces in the deep oceans that, due to currents, are free of sediment. They form pavements of manganese and iron oxides on the flanks of volcanic seamounts, ridges, guyots, and plateaux in water depths ranging from 400 to 7000 m. Their thickness varies from less than 1 mm to about 260 mm [10]. Crusts with sufficient mineral content to be of economic interest commonly occur at depths of about 800–2500 m [10]. The global permissive area containing seamounts and guyots where economic Co-rich ferromanganese crusts may form covers 23 million km<sup>2</sup> [11].

Although ferromanganese crusts are common on large seamounts, regions like the PCZ also include large areas of the deep-ocean basins between the topographic highs that will not be explored for crusts. Using a combination of ocean floor topography, geomorphology, global seafloor spreading rate, age data, and global sedimentation data [13–16], a smaller area is defined that is most prospective for ferromanganese crusts (Fig. 2A). The approach considers the occurrence of seamounts, guyots and plateaus that peak between 800 and 3000 m water depth and are located in areas older than 10 million years old. Any areas with sediment thicknesses of more than 500 m or known sedimentation rates > 2 cm ky<sup>-1</sup> are also excluded. From this analysis, a much smaller area of 3.1 million km<sup>2</sup> is identified that is considered to be favorable for ferromanganese crusts globally. Only 1.7 million km<sup>2</sup> of this are located within the 23 million km<sup>2</sup> permissive area defined above [11]. The region with the greatest economic potential, the so called “Prime Crust Zone” (PCZ) covers 6.5 million km<sup>2</sup> in the western Pacific and contains the oldest seamounts, therefore providing more time to grow thick crusts ([11]; Fig. 2B). In contrast to manganese nodules, which mainly occur in international waters, the most favorable areas for Co-rich crusts are mainly located within the EEZs of coastal states (44%) or are included in proposals for extension of the continental shelf (10%). Only 46% are located in areas beyond national jurisdiction. The Atlantic Ocean, with the exceptions of the northeast and northwest continental margin areas, has fewer seamounts, and Co-rich crusts are commonly associated with hydrothermal activity at seafloor-spreading centers and have a lower economic potential [11].

Most of the manganese and iron oxides in the Pacific are hydrogenetic. Hydrothermal crusts are less common, except near active volcanic arcs and hot-spot volcanoes. Generally, the crusts are thicker on older seamounts. As for nodules, a range of different elements that dissolved in seawater is adsorbed onto the manganese and iron oxides that make up the crusts. However, they have slower growth rates than nodules (75% grow at 1–5 mm My<sup>-1</sup>) and an enormous specific surface area (average 325 m<sup>2</sup> cm<sup>-3</sup> of crust), which partly accounts for the higher grades [21]. Cobalt-rich ferromanganese crusts have a simple mineralogy and are composed predominantly of the manganese oxide vernadite and a variety of non-crystalline iron oxyhydroxides [11]. The crusts also contain minor amounts of detrital minerals, such as quartz and feldspar, and most thick crusts (greater than about 60 mm) also contain a layer enriched in phosphorous [11].

#### 3.2. Metal concentrations and resource potential

The metals adsorbed include cobalt, nickel, copper, and titanium, as well as the minor elements molybdenum, tellurium, platinum, zirconium, niobium, bismuth, and the REEs. This makes Co-rich ferromanganese crusts a potential resource for some of the metals used in emerging high-tech and green-technology



**Fig. 2.** (A) Locations of seamounts, guyots, and oceanic plateaus that are important for the formation of ferromanganese crust based on seafloor classification, seafloor age (older than 10 My), sediment thickness ( $< 500$  m), sedimentation rate ( $< 2$  cm/1000 years), and water depth (peaks between 800 and 3000 m). Note the lack of data below  $70^{\circ}$ S and above  $80^{\circ}$ N. See text for details. (B) Area with highest ferromanganese crust potential based on morphology, age of the crust, and metal input as defined by [10]. Light blue areas delineate the Exclusive Economic Zones. Abbreviations: PCZ=Prime Crust Zone. (C) Location of ferromanganese crust samples from the ISA database with Co concentrations above 0.5 wt% (N=465). Note that most Co-rich ferromanganese crust samples lie in the western Pacific. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Table 2**  
Mean content of selected elements of ferromanganese crusts in various regions (source [11]). Abbreviation: PCZ=Prime Crust Zone.

	PCZ	South Pacific	Atlantic	Indian
Fe (wt%)	16.9	18.1	20.9	22.3
Mn (wt%)	22.8	21.7	14.5	17.0
Ni (wt%)	0.42	0.46	0.26	0.26
Cu (wt%)	0.10	0.11	0.09	0.11
Co (wt%)	0.67	0.62	0.36	0.33
Ti (wt%)	1.16	1.12	0.92	0.88
REE+Y (wt%)	0.24	0.16	0.24	0.25
Bi (ppm)	43	22	19	30
Mo (ppm)	461	418	409	392
Nb (ppm)	52	59	51	61
Pt (ppm)	0.5	0.5	0.6	0.2
Te (ppm)	60	38	43	31
Zr (ppm)	548	754	362	535

applications. Iron and manganese are major constituents of ferromanganese crusts and occur in approximately equal amounts (Table 2). Cobalt is a minor element, but of greatest economic interest, being present at concentrations that commonly exceed 0.5 wt% Co. The manganese oxide vernadite has a particular affinity for the adsorption of Co and other rare metals and is more abundant in crusts than in nodules. This explains the generally higher concentrations of Co in crusts [10]. Tellurium (Te) is also of potential economic importance, and is present at concentrations of about 50 ppm, up to 205 ppm [10]. The trace element platinum may occur at concentrations up to 3 ppm in individual samples [22], although high average grades would generally be less than 0.7 ppm. Other platinum-group elements (PGE) are much less concentrated in the crusts. The high concentrations of the rare metals tellurium and platinum are attributed to adsorption mainly onto Fe-oxyhydroxides, which are more abundant than in nodules. The REE are similarly concentrated by Fe-oxides, and average REE concentrations in crusts from many parts of the global oceans range from 0.16 to 0.25 wt% (total REE; [10]). However, small areas can yield total REE concentrations as high as 0.7% and individual samples contain more than 1%. Further metals of interest as potential by-products of future ferromanganese crust mining include molybdenum, bismuth, niobium, and zirconium [10].

As for nodules, there are limited publicly available data on crust compositions in the most prospective areas. The ISA sample database is used to show the global distribution of the most Co-rich samples (> 0.5 wt% Co; Fig. 2C). However, little is known about the abundance of ferromanganese crusts in most areas of the global ocean. The thickest crusts with the highest concentrations of cobalt have been found at the rims of terraces and on broad saddles near the summits of seamounts [23]. One estimate of the quantity of crusts in the central Pacific region has been given at 7533 million dry tonnes, containing about four times more cobalt, three and a half times more yttrium, and nine times more tellurium than the entire land-based reserves of these metals [10].

## 4. Seafloor massive sulfides

### 4.1. Origin and distribution

Seafloor massive sulfides (SMS or black smoker) deposits form on and below the seabed from high-temperature hydrothermal fluids emitted by volcanoes along ridges, island arcs, and in rifted back-arc basins behind active subduction zones (Fig. 3A). The deposits form as a consequence of the interaction of seawater with a heat source (magma) in the sub-seafloor at active volcanic centers such as those of the global mid-ocean ridges. During this process,

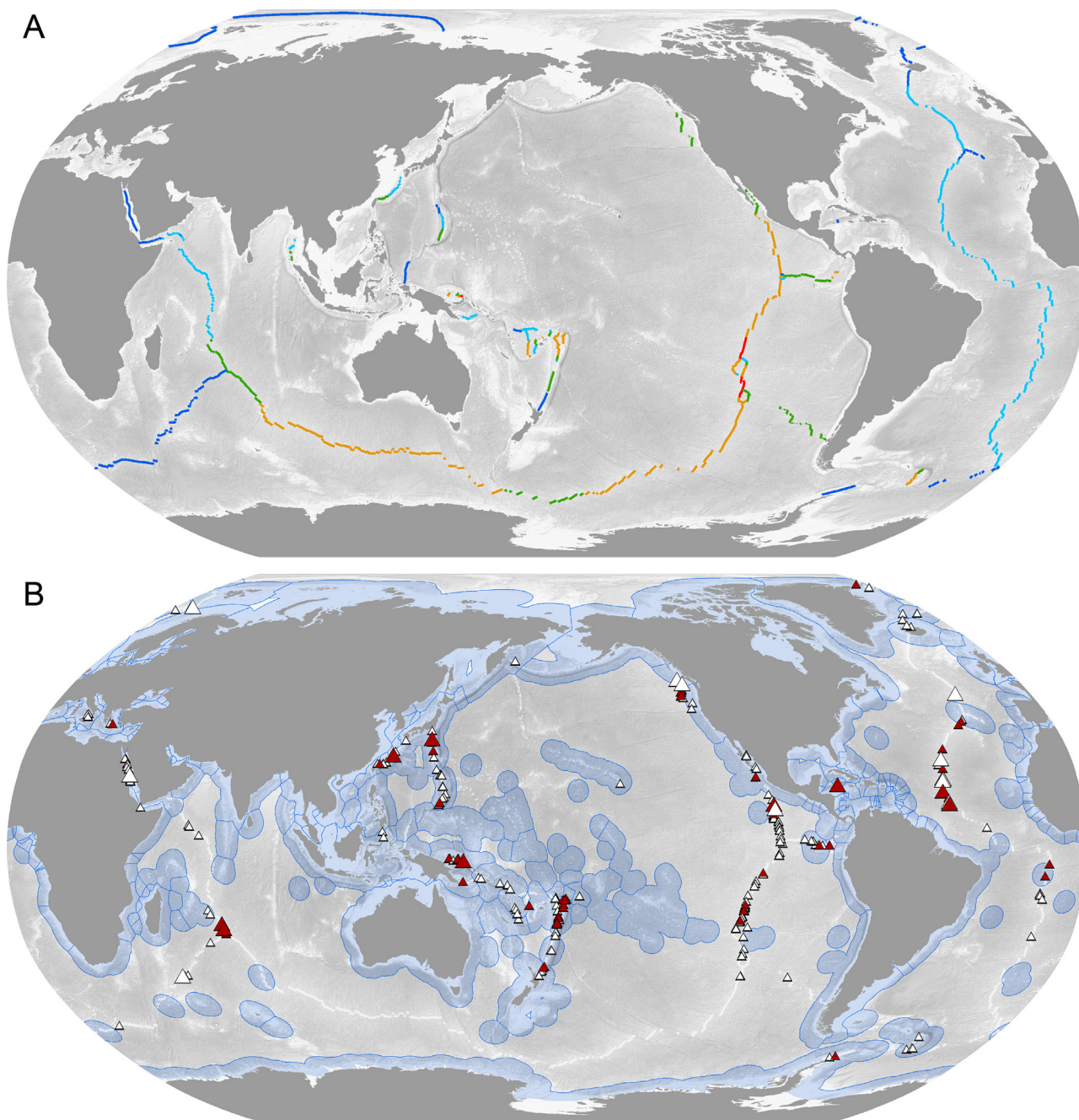
cold seawater penetrates through cracks in the seafloor, reaching depths of several kilometers into the crust, and is heated to temperatures above 400 °C [24]. The chemical reactions that take place during this process result in a fluid that is hot, slightly acidic, reduced, and enriched in dissolved metals and sulfur that are leached from the surrounding rock. Due to the lower density of this now mineral-rich, hot fluid, it rises rapidly to the seafloor, where most of it is expelled into the overlying water column at “chimney-like” vents. The dissolved metals precipitate when the fluid mixes with cold seawater, and a high proportion of the metals are expelled from the vent as “smoke”, forming a dispersing hydrothermal plume. Much of the particles in these plumes are then deposited as fallout in proximal marine sediments. The remainder of the metal precipitates as metal sulfides and sulfates at the vent site, producing black and white smoker chimneys and mounds. The subseafloor magma may also be a source of ore metals, particularly at sites where seafloor massive sulfides deposits are forming in close association with subduction-related volcanic centers. Metal-enriched fluids that are exsolved from the magmas locally mix with ordinary black smoker fluids to produce spectacularly rich sulfide deposits at the seafloor [25–27].

The minerals forming the chimneys and sulfide mounds include iron sulfides, such as pyrite, as well as the main minerals of economic interest such as chalcopyrite (copper sulfide) and sphalerite (zinc sulfide). The precious metals gold and silver may also occur in elevated concentrations, together with non-sulfide (gangue) minerals, which are predominantly sulfates and silicates. A large number of minor elements can be incorporated in the massive sulfides often as a consequence of processes related to the geological setting of the sulfide occurrence [24].

Since black smokers were first discovered, more than 340 high-temperature hydrothermal sites have been identified in all oceans, indicating that this type of mineralization is widespread (Fig. 3B). The currently active black smoker deposits are restricted to the young, volcanically active parts of the ocean, including the spreading centers of the mid-ocean ridges and back-arc basins (combined strike length of 67,000 km) and on active submarine volcanic arcs (total length of 22,000 km). Accordingly, most of the known sulfide occurrences (60%) have been found along global mid-ocean ridges, with 25% occurring in back-arc basins and 15% along submarine volcanic arcs. Very few sites (1%) have been observed at intraplate volcanoes, such as Hawaii. Most of the known or suspected active deposits (59%) occur in areas beyond national jurisdiction, dominated by the mid-ocean ridges; 39% are located within the EEZs of coastal states, and 2% are in areas included in proposals for extensions to the continental shelf. However, an important consideration is that almost all currently known deposits occur with the volcanically active (neovolcanic) zones of the ridges and back-arc spreading centers; there is at present little knowledge of the occurrence and distribution of older deposits that may be located far off-axis from these locations and potentially buried by deep marine sediments.

At intermediate- to fast-spreading mid-ocean ridges (spreading rates > 40 mm yr<sup>-1</sup>), high-temperature venting occurs mainly in the axial zones of the spreading centers and is associated with basaltic volcanism [24]. At slower spreading ridges (spreading rates < 40 mm yr<sup>-1</sup>), however, long-lived detachment faults may divert fluid flow away from the ridge axis and the associated sulfide deposits can be found many kilometers away from the ridge axis [28–33]. For example, the Petersburgskoe site on the Mid-Atlantic Ridge is located 16 km west of the ridge axis [34]. Older deposits undoubtedly exist much farther from the ridge axis, but exploration is still limited to areas close to the ridge axis. Currently, however, we do not know the fate of deposits that are transported away from the ridge axis by seafloor spreading.

Sulfide deposits that form at subduction-related volcanic arcs



**Fig. 3.** (A) Locations of mid-ocean ridges and back-arc spreading centers important for the formation of seafloor massive sulfides. Colors denote the spreading rate of each segment. Dark blue=ultra-slow spreading (<20 mm/yr); light blue=slow spreading (20–40 mm/yr); green=intermediate spreading (40–60 mm/yr); orange=fast spreading (60–140 mm/yr); red=ultra-fast spreading (>140 mm/yr). (B) Location of high-temperature seafloor hydrothermal systems and associated seafloor mineralization, where red color indicates occurrences with economically interesting metal concentrations (average grade of the deposit is either > 5 wt% Cu, > 15 wt% Zn, or > 5 ppm Au) and large symbols indicate occurrences with size estimates above 1 million tonnes. Using these criteria, only a few occurrences of economic interest have been identified. Note that geochemical analyses are commonly only available for surface samples that are not representative for the entire occurrence. A quantitative resource assessment for seafloor massive sulfides is only available for two occurrences (Solwara 1 and Solwara 12, both within the EEZ of Papua New Guinea; [56]). Light blue areas delineate the Exclusive Economic Zones. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and back-arc basins are broadly similar to those at mid-ocean ridges [35,36]. However, the geology and tectonic setting influence the composition of the hydrothermal fluids and, by extension, the mineralogy and chemical composition of the associated sulfide deposits. These differences are related to variations in source-rock composition as well as variable input of magmatic volatiles and metals into the hydrothermal systems [24]. Unlike the deposits at mid-ocean ridges, which are regularly spaced along the ridge, depending on spreading rate, many of the arc-related SMS occurrences are more closely associated with discrete volcanic centers

with variable spacing related to deeper crustal controls on magmatic activity along the plate boundaries.

The total number of vent sites that exist along the ridges and volcanic arcs is not known, although several attempts have been made to infer their abundance based on heat flow measured plume sources. Early estimates based on Earth's heat flow indicated that at least one black smoker would be required every kilometer along the global mid-ocean ridges in order to explain the heat flux. However, clustering of the hydrothermal systems means that heat may be removed by just a few thousand

hydrothermal fields [37,38]. The distribution of active hydrothermal plumes along the spreading axis and over volcanic arcs has also been used to infer similar abundance values [39–41]. It should be noted, however, that the latter approach only considers active hydrothermal fields and visual observations of well-studied sulfide occurrences indicate that there are more inactive sites than active sites [42,43]. Initial estimates of the abundance and distribution of known sulfide deposits in well-studied areas indicate that between 1000 and 5000 large sulfide deposits may exist on the modern seafloor, which is consistent with other estimates [42].

If a favorable area for recently active deposits is considered, 20 km to either side of the global mid-ocean ridges and back-arc spreading centers, the area that should be explored for SMS deposits is more than 3.2 million km<sup>2</sup>. Of this, 58% is located in the “Area”, 36% within EEZs, and 6% in areas included in proposals for extensions to the continental shelf.

#### 4.2. Metal concentrations and resource potential

In contrast to manganese nodules and ferromanganese crusts, the chemical composition of seafloor massive sulfides is highly variable and not all elements contained in the sulfides are of commercial interest [36,43]. For example, SMS deposits along the East Pacific Rise and, to some extent, those along the Mid-Atlantic Ridge are primarily composed of iron sulfides that currently have no economic value (Table 3). In contrast, sulfide occurrences in the southwest Pacific have high concentrations of copper (Cu) and zinc (Zn), which make them more economically attractive [36]. Valuable metals such as gold and silver are trace constituents of the sulfides but can be highly enriched in some deposits, reaching concentrations of several tens of parts per million (ppm) for gold and several hundred ppm for silver (Table 3). Other trace elements such as antimony (Sb), bismuth (Bi), cadmium (Cd), gallium (Ga), germanium (Ge), indium (In), tellurium (Te), and thallium (Tl), are normally contained in SMS in low quantities (ppm), but can be significantly enriched in some deposits, especially those that form at volcanic arcs (Table 4). Weathering of old SMS on the seabed has upgraded the metal concentrations in some deposits by leaching of metals and sulfur and concentrating metals in new minerals at higher grades (e.g., secondary copper-rich sulfides, secondary gold [24]).

At intermediate- to fast-spreading mid-ocean ridges, the source rock is relatively homogenous mid-ocean ridge basalt (MORB), whereas at slower spreading ridges tectonic processes expose mantle rocks at the seafloor that appear to contribute to enrichments in copper and gold in associated sulfide occurrences [44]. Deposits that are hosted by sediment have lower than average metal-grades due to the dilution by non-ore material. At volcanic arcs and back-arcs, such as in the western Pacific, the source rocks are more variable in composition, and this is directly reflected in the composition of the massive sulfides, which are often higher in copper, zinc, lead, silver, and gold (Table 3). Water depth is also an important factor influencing the composition and economic

**Table 4**

Range and mean concentration of selected trace metals in seafloor massive sulfide samples in parts per million (ppm; source GEOMAR). Note that these elements are not routinely measured for seafloor massive sulfides and therefore the number of analyses varies considerably.

Element	N	Range (ppm)	Mean (ppm)
Antimony	3396	< 1–43,500	510
Bismuth	1840	< 1–2000	12
Cadmium	3549	< 1–6300	392
Gallium	1483	< 1–3700	58
Germanium	934	< 1–918	29
Mercury	2252	< 1–95,000	104
Indium	1471	< 1–592	18
Selenium	2278	< 1–9700	115
Tellurium	1374	< 1–431	5
Thallium	1549	< 1–1600	38

potential of seafloor massive sulfide deposits [24]. The majority of mid-ocean ridge sites are at 2–3 km water depth, where pressure prevents the boiling and cooling of the hydrothermal fluids. In contrast, on many arc volcanoes (90% shallower than 1500 m water depth), the hydrothermal fluids generally boil before reaching the seafloor, depositing metals in inaccessible subseafloor stockwork mineralization.

The bulk compositions also vary greatly at the deposit scale and even hand-specimen scale, mainly reflecting strong gradients in fluid temperatures [24]. Copper-rich minerals (chalcopyrite and isocubanite) typically line the high-temperature upflow zones and fluid conduits. The outer parts of the deposits consist of minerals that are rich in iron (pyrite, pyrrhotite, and marcasite), or zinc (wurtzite, sphalerite). These are usually deposited at slightly lower temperatures as the hydrothermal fluid mixes with seawater. As a result of this heterogeneity, the sampling of black smoker chimneys, which commonly show high concentrations of copper, is not representative of the bulk compositions of the deposits. Many published grades of sea-floor sulfide deposits are strongly biased due to sampling of high-temperature chimneys, which are easier to recover than sub-sea-floor mineralization. Unfortunately, with the exception of a few deposits that have been drilled scientifically through the Ocean Drilling Program (ODP or IODP) or by commercial or scientific projects, little is known about the interiors of most seafloor massive sulfides deposits (see below). Due to lack of information about the important subsurface component of deposits, it is difficult to estimate the resource potential of most seafloor massive sulfides, except perhaps by comparison with land-based analogs.

Geochemical data for seafloor massive sulfide occurrences are currently available for 142 sites, but only 34 deposits are represented by more than 50 samples, almost always taken from the surfaces of the deposits. About 60% of the deposits (91 of the 142 with some data) have average metal concentrations in the sampled material of either > 5 wt% copper or zinc or > 5 ppm gold (red triangles in Fig. 3B). A number of minor elements may also be present at sufficient concentrations to improve economic viability

**Table 3**  
The mean metal content of seafloor massive sulfide deposits with respect to their tectonic setting (source GEOMAR). Note that the concentration of the trace metals gold and silver is given in parts per million (ppm). N=number of deposits for which chemical data is included. Abbreviations: MOR=Mid-Ocean Ridges.

Setting	N	Cu (wt%)	Zn (wt%)	Pb (wt%)	Fe (wt%)	Au (ppm)	Ag (ppm)
Sediment-free MOR	51	4.5	8.3	0.2	27.0	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
Intraoceanic back arc	36	2.7	17.0	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	2.0	9.2	10.2	197



if they can be recovered, in particular Ag, Cd, In, Ga, and Ge (Table 4). Information on minor elements is also important for environmental baseline studies, in particular the toxic trace elements such as antimony (Sb), arsenic (As), cadmium (Cd), mercury (Hg), and thallium (Tl) that may occur at high concentrations in selected samples or deposits. For example, some samples from the Calypso vent field near White Island (New Zealand) have > 1 wt% Hg [45]. Regulations defining baselines and tolerances for the release of toxic elements into the marine environment during mining have not yet been considered anywhere near to the degree that they are in land-based mining operations.

While the number of discoveries of seafloor massive sulfides occurrences is steadily increasing, most deposits are small in size compared to land-based analogs [40]. Most seafloor hydrothermal vent systems are highly inefficient and lose much of their metal load to hydrothermal plumes, where they are dispersed from the vent sites. The largest deposits form where sediments allow for efficient trapping of the metals due to precipitation below the sea floor (such as the deposits at Middle Valley, Guaymas Basin, and Okinawa Trough) or where hydrothermal activity lasts for long periods of time, as with sulfide mineralization related to large detachment faults [24]. Based on information about the age of the sulfides and the underlying volcanic crust, it appears that tens of thousands of years (even hundreds of thousands) are needed to form the largest known deposits. However, some of the largest deposits, such as those along the central Mid-Atlantic Ridge, have relatively low metal grades [34,46] (Table 3). An important, but perhaps unique, exception is the brine pool deposits in the Atlantis II Deep of the Red Sea, by far the largest metal deposit (90 Mt) on the modern seafloor [47]. However, these deposits form in a unique geological setting where the ore material is deposited as unconsolidated metal-bearing muds instead of massive sulfide.

Sizes of most seafloor massive sulfide deposits vary from a few tonnes to > 20 Mt of sulfide material [42,48]. However, reliable size estimates are very rare because drilling information is needed to infer the tonnage of massive sulfide occurrences. Such data exist for only very few sites (Table 5). In most cases, the sizes of deposits are estimated from visual observations of the surface area that is covered by hydrothermal precipitates. Individual chimneys can vary in size from only a few centimeters to up to 45 m in height. Over time, these collapse and the sulfide debris accumulates as a mound that forms a substantial part of the total tonnage of a sulfide deposit. The deposits also grow by precipitation of metals within the mound, as early-formed sulfides are dissolved by the high-temperature hydrothermal fluids and reprecipitated at the

cooler outer margins of the deposit. Such mounds are often zoned, with the surface being more Cu- and Zn-rich than the core (e.g., the TAG, Middle Valley, PacManus, and Palinuro deposits, which have all been drilled) [49–53]. Drilling results from the large TAG mound, which measures 200 m in diameter and 45 m in height, indicate 2.7 million tonnes of massive sulfide averaging 2 wt% Cu plus 1.2 million tonnes of stockwork at 1% Cu [54]. During Ocean Drilling Program (ODP) Leg 139, drilling at Middle Valley intersected massive sulfide accumulations and subsequent drilling of the Bent Hill and ODP mounds at Middle Valley during Leg 169 indicated a total tonnage of between 10 and 15 million tonnes [50]. Only small amounts of massive sulfides have been recovered during the recent IODP-Leg to Iheya North in the Okinawa Trough [55]. Data from extensive commercial drilling of the Solwara-1 deposit near Papua New Guinea indicates a deposit size of 2.5 Mt [56]. A number of deposits was drilled by small lander-type drilling platforms that provide important chemical information for the upper few meters of the deposits, but insufficient for resource estimates [31,51–53,56,57–59].

Current mining scenarios for multi-year exploitation of seafloor massive sulfide deposits require an annual mining rate of up to 2 million tonnes of sulfide ore from a single deposit. However, only few deposits in the largest size class (top 10%) are thought to exceed 2 million tonnes in size [48]. Large deposits approaching this size have been found in most of the settings where seafloor hydrothermal activity occurs, including the mid-ocean ridges (Galapagos, TAG, Alvin Zone, Krasnov, Zenith, Puy de Folles, and Semyenov sites), sedimented ridges (Middle Valley), intraoceanic back-arc basins (North Fiji Basin), volcanic arcs (Myojin Knoll), and rifted arcs in transitional or epicontinental environments (Izena Cauldron, Solwara 1). However, most estimates of size are not based on drilling results and typically are based only on visual estimates of the surface area multiplied with an estimated thickness of the occurrence. Seafloor accumulations such as those at Middle Valley may be of special economic interest. Such hydrothermal systems are difficult to find but clearly more efficient in retaining the metal sulfides within proximity to the vent site, with the potential to form very large deposits. By contrast, most deposits on the intermediate and fast spreading ridges are very small because the hydrothermal discharge is episodic on relatively short time scales of only 10s to 1000s of years [60,61]. As noted above, the protracted history of hydrothermal venting at sites like TAG on the slow-spreading Mid-Atlantic Ridge was a major factor in the large size of the deposit, a consequence of deep-seated magmatic activity followed by long periods of cooling and release of heat from depth. Therefore, slow- to ultra-slow spreading ridges seem to host larger sulfide deposits on average than those along the faster spreading segments because the stable structural environment with relatively slow rates of spreading allows long-lived hydrothermal circulation [42,44]. Additionally, exposure of mantle rocks is common under these conditions and currently available data suggest that deposits associated with these rocks have higher than average Cu and Au contents [44]. The only deposit with sufficient drilling and other information to define a resource is the Solwara 1 deposit in the Eastern Manus Basin of Papua New Guinea, for which the first ever SMS mining license was granted in 2011 [62]. However, ongoing exploration results have not yet identified another deposit in the region of sufficient size and grade for mining [24,36].

Notwithstanding the limited information on the tonnage and the lack of data from the interiors of the deposits, a preliminary comparison of 340 known occurrences, suggests that probably no more than ten would be of sufficient size and grade to sustain multi-year exploitation within a single mining license [63]. However, it is possible that smaller, economically interesting deposits could be combined into a single mining operation, making mining

**Table 5**

Seafloor massive sulfide occurrences for which size information is available based on drilling information. Abbreviations: ODP=Ocean Drilling Program; ROV=remotely-operated vehicle.

Deposit	Location	Size	Drilling tool/vessel	Reference
Atlantis II	Red Sea	90 Mt	Coring	[47]
Middle Valley	Juan de Fuca Ridge	10–15 Mt	ODP-drill ship	[50]
TAG	Mid-Atlantic Ridge	4 Mt	ODP-drill ship	[49,54]
Izena	Okinawa Trough	3.4 Mt	Lander-type	[57]
Solwara 1	Bismarck Sea	2.5 Mt	ROV-based	[56]
Solwara 12	Bismarck Sea	0.2 Mt	ROV-based	[56]
Fryer, Pika	Mariana Trough	Small	Lander-type	[58]
Iheya North	Okinawa Trough	Small	IODP-drill ship	[55]
Logatchev	Mid-Atlantic Ridge	Small	Lander-type	[31]
PacManus	Bismarck Sea	Small	ODP-drill ship	[51]
PacManus	Bismarck Sea	Small	Lander-type	[52]
Palinuro	Tyrrhenian Sea	Small	Lander-type	[53]
Suiyo	Izu-Bonin Arc	Small	Lander-type	[59]

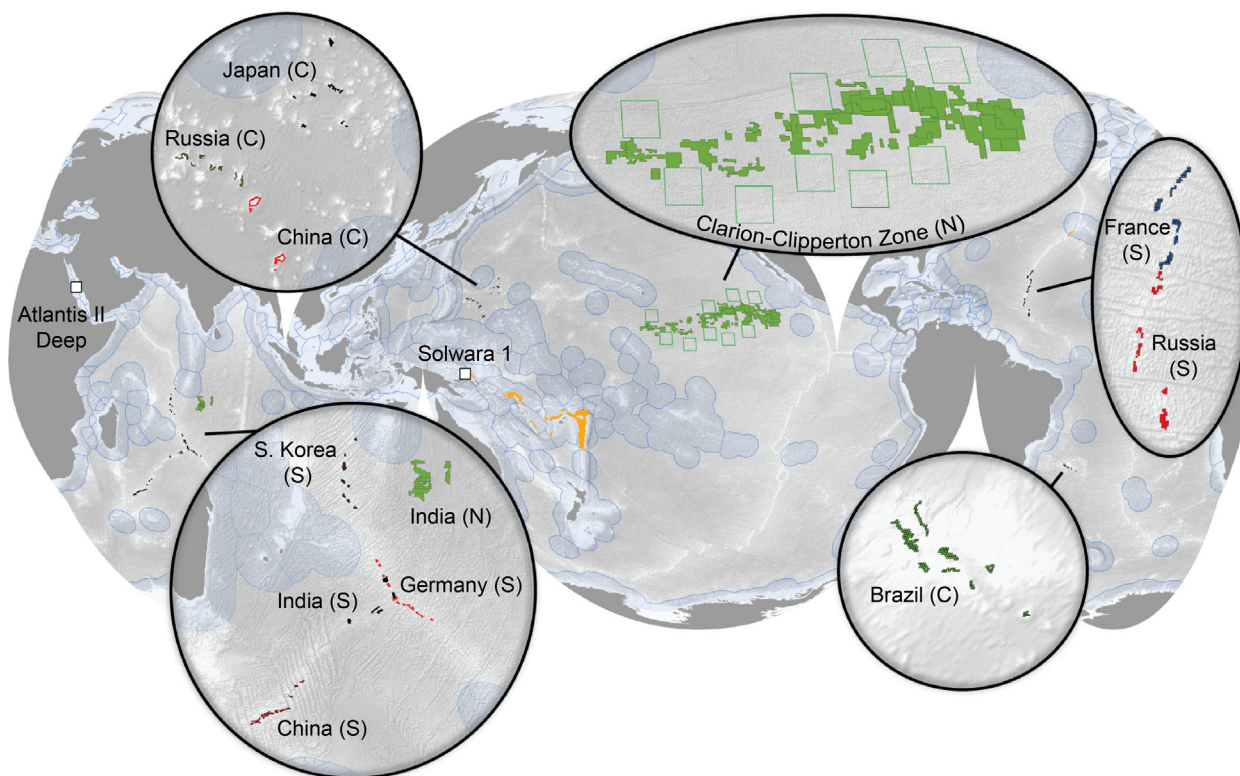
of clusters of smaller SMS deposits potentially viable. Current exploration for seafloor massive sulfides is performed using tools developed for the discovery of geochemical anomalies associated with hydrothermal plumes in the water column and geophysical anomalies associated with the deposits or their altered host rocks. The search for hydrothermal plumes only detects young and hence small deposits. The discovery of older and larger deposits (e.g., away from the ridge axis and covered by sediments) clearly demands new exploration technologies.

## 5. Current exploration and mining activities

Since 2002, twenty-seven exploration contracts have been approved by the International Seabed Authority for areas beyond national jurisdiction (the “Area”; Fig. 4). Seventeen contracts are for manganese nodule exploration, of which 14 have been signed and 3 are pending signature. Most (16) are located in the Clarion-Clipperton Zone, covering 1.171 million km<sup>2</sup>, and one is in the Central Indian Ocean (77,000 km<sup>2</sup>). Of the 17 contractors, 8 are government bodies while the remaining 9 are commercial entities sponsored by states. In the first 9 years of licensing, until 2011, only national governments applied for exploration contracts in areas beyond national jurisdiction, but since then only commercial entities backed by state parties have made applications. Four contracts for the exploration of Co-rich ferromanganese crusts in “the Area”, covering 3,000 km<sup>2</sup> each, have been granted to national governments since 2013. Three contract areas are located in the Prime Crust Zone of the western Pacific and were signed by China, Japan, and Russia. The Brazilian contract area is located on the Rio Grande Rise in the southwestern Atlantic. Combined, these four contract areas cover 12,000 km<sup>2</sup>, less than 1% of the most

favorable area. Six contracts for exploration of seafloor massive sulfides have been approved in areas beyond national jurisdiction since 2011, covering 10,000 km<sup>2</sup> each (Fig. 4). All 6 contractors are national governments: representatives of the states of China, Russia, South Korea, France, India, and Germany. Four contract areas are located in the Indian Ocean, the remaining two in the central Atlantic. The contract for India has not yet been signed. Overall these six sulfide exploration contracts cover 15% of the spreading center length beyond national jurisdiction (6,000 km of the 39,000 km of mid-ocean ridges and back-arc spreading centers in the “Area”) but only 3% of the favorable area along the spreading center defined here as an area including 20 km to both sides of the spreading axis. In total, these 27 approved exploration contracts cover an area of 1.24 million km<sup>2</sup>. Because of the staggered granting of the licenses and the 15-year tenure, they will gradually expire over the next 15 years. Although the 6 pioneer contracts for nodule exploration will expire in 2016, the regulations that would allow mining have not yet been ratified. The affected contractors will have to decide whether they want to start mining or apply to extend the exploration contract for another 5 years. As a full mining system is not yet ready and no pilot tests have been undertaken, it is likely that the early contractors will apply for extensions.

The intensity of exploration in the EEZs of coastal states cannot be easily established because many countries do not make their contracts public. There are also some strong national exploration programs, namely by Korea, France and Japan, within their EEZs in the western Pacific [57,64]. Some Pacific Island States regard deep-sea mining as a potential way to generate revenue and are therefore interested in establishing regulations and governance structures [65]. Approximately 650,000 km<sup>2</sup> of seafloor are covered by exploration contracts within EEZs of coastal states. At least



**Fig. 4.** Locations of global exploration licenses for manganese nodules (N), Co-rich ferromanganese crusts (C) and seafloor massive sulfides (S for licenses within “the Area”, orange for licenses within EEZs). The locations of the only two deep-sea mining licenses (Atlantis II Deep in the Red Sea and Solwara 1 in Papua New Guinea) are indicated by the white squares. The location of the “Areas of Particular Environmental Interest” (size of 400 km by 400 km each) in the CCZ is provided as rectangles with a green outline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



two commercial companies (Nautilus Minerals Inc. and Neptune Minerals) have been granted exploration tenements in several countries of the Western Pacific and applications are pending for several offshore areas in Italy, New Zealand, Japan, and Portugal. Two deep-sea mining licenses have been issued by national governments, both for seafloor massive sulfides. *Nautilus Minerals Inc.* was granted a mining license by the government of Papua New Guinea in 2011 for the Solwara-1 project in the Bismarck Sea. The governments of Saudi Arabia and Sudan in 2010 granted a 30-year mining license to a consortium of *Diamondfields International Ltd.* (Canada) and *Manafa International Trade Company* (Saudi Arabia) for the Atlantis II project in the Red Sea. Mining has not yet started in either project, but “ground-breaking” at Solwara-1 is currently projected to start in early 2018 [66].

## 6. Future directions

Marine mineral resources such as sand, gravel and placer deposits are already mined in shallow water environments (i.e. < 500 m) throughout the globe and are continuing as a viable economic activity. However, there are a number of different motivations among those interested in an emerging deep-sea mining industry. These include not only economic considerations but also geopolitical and strategic considerations. Manganese nodules and Co-rich ferromanganese crusts are clearly vast resources, and mining them could impact global supply of certain metals (Table 6). Some deposits could potentially be mined for profit, and the technological barriers to the development of mining systems capable of efficient and reliable operation in deep-sea environments are rapidly being overcome. Technologies for mining Mn-nodules are, in principle, available and several hundred tonnes of Mn-nodules have been collected from the seabed in the past [67]. However, a complete mining system capable of reliable long-term operations has not yet been realized and is unlikely in the short term (i.e. within the next 5 years). Also, the exploration for Co-rich ferromanganese crusts is still in its infancy and the technologies to

assess and recover crusts have not been built or tested. Therefore, seafloor massive sulfides are likely to be the first mineral resource to be mined, driven by commercial interests in Papua New Guinea and by strong domestic interests in Japan. Most of the known deposits are, however, small and mining them will likely have little impact on global metal supply. It should be noted that larger deposits may exist on the modern seafloor and new technologies to explore for them away from the ridge axis and/or under sediment cover are currently being developed. As a result, there is still considerable interest in exploration of SMS both within the EEZs of coastal states and in the “Area”. The technology for mining sulfide deposits is currently being built and the first deep-sea tests were recently performed by Japan in their coastal waters [61].

Whether deep-sea mining will be a viable activity in the future depends largely on its environmental impacts, which have yet to be fully assessed. It is important to note that the impacts will be different for the mineral types addressed here. While mining for manganese nodules would cover several hundreds of km<sup>2</sup> per year and for Co-rich ferromanganese crusts several tens of km<sup>2</sup> per year for a single mine site, future mining in the Solwara 1 SMS project in Papua New Guinea would cover an area of less than 0.2 km<sup>2</sup> (Table 6). Ecosystems associated with active vents sites may recover more quickly due to the inherently instable environments with frequent volcanic eruptions and cyclic hydrothermal activity. Ecosystems in the abyssal plains may never recover to the original species richness and distribution due to the substantial loss of hard substrate. The potential impacts of manganese nodule mining have been investigated on various scales (see [11] and references therein) and are currently the focus of two major research programs, the EU-FP7 funded project “MIDAS” and the JPI-Oceans initiative “Ecological Aspects of Deep-Sea Mining”. For SMS, the most comprehensive study of potential mining impacts is reported by the environmental impact assessment of Nautilus Minerals for its Solwara 1 deposit (see [www.cares.nautilusminerals.com](http://www.cares.nautilusminerals.com)). As deep-sea mining is not yet occurring, the process of defining the mining regulations by the ISA [68] provides the opportunity for NGOs and scientists to contribute and shape the regulations before

**Table 6**  
Characteristics of deep-sea mineral resources.

	Manganese nodules	Co-rich ferromanganese crusts	Seafloor massive sulfides
Geological Setting	Sedimented abyssal plains	Upper flanks of old volcanic seamounts	Oceanic spreading centers and young island arc volcanoes
Characteristics	Potato-sized nodules on soft sediment	Up to 25 cm-thick crusts on hard substrate	Ten to hundreds of meter wide mounds
Water depth of greatest economic potential	3000–6000 m	800–2500 m	1000–5000 m
Favorable area (“Area”, EEZ, ECS)	38 million km <sup>2</sup> (81%, 14%, 5%)	1.7 million km <sup>2</sup> (46%, 44%, 10%)	3.2 million km <sup>2</sup> (58%, 36%, 6%)
Dimensions	Large 2-D deposits	Large 2-D deposits	Small 3-D deposits
Main metals of interest	Nickel, Copper, Manganese, Cobalt	Cobalt, Nickel, Manganese, Copper	Copper, Zinc, Gold, Silver
Other commodities	Molybdenum, Lithium, Titanium	Titanium, REEs, Platinum, Molybdenum, Bismuth	Cadmium, Gallium, Germanium, Indium, Antimony
Resource estimate	21,100 million tonnes in the Clarion-Clipperton-Zone	7533 million tonnes in the Prime Crust Zone	600 million tonnes in the neovolcanic zone of mid-ocean ridges
Grades	(Clarion-Clipperton) 2.4 wt% Cu + Ni 0.2 wt% Co 28 wt% Mn	(Prime Crust Zone) 0.5 wt% Cu + Ni 0.7 wt% Co 23 wt% Mn	(Occurrence median) 3 wt% Cu 9 wt% Zn 2 ppm Au 100 ppm Ag
Grade distribution	Homogeneous on regional scale	Homogeneous on regional scale	Very heterogenous on regional and local scale
Footprint of 2 mio tonne mining activity on the seafloor	150 km <sup>2</sup>	25 km <sup>2</sup>	< 0.2 km <sup>2</sup>
Knowledge base for resource estimate	Good in the CCZ	Poor	Poor
Resource potential	High	High	Small
Global impact of mining on metal markets	High <sup>a</sup>	High <sup>a</sup>	Low

<sup>a</sup> Depends on rate of establishment of mines; with a phased approach, these designations would change.

mining actually starts. Comprehensive environmental impact assessment, mitigation strategies, baseline studies, as well as long-term monitoring need to be implemented into the regulations not only in order to do it right, but also to get the social license to mine.

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