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Deep-ocean polymetallic nodules as a resource for critical materials

James R. Hein[1]✉, Andrea Koschinsky[2] and Thomas Kuhn[3]

Abstract | Deep-ocean polymetallic nodules form on or just below the vast, sediment-covered, abyssal plains of the global ocean. Polymetallic nodules primarily consist of precipitated iron oxyhydroxides and manganese oxides, onto which metals such as nickel, cobalt, copper, titanium and rare earth elements sorb. The enormous tonnage of nodules on the seabed, and the immense quantities of critical metals that they contain, have made them a target for future mining operations. Mining of polymetallic nodules has been spurred by the need for critical metals to support growing populations, urbanization, high-technology applications and the development of a green-energy economy. Nevertheless, an improved understanding of the affected ecosystems and their connectivity, as well as the environmental impacts of deep-ocean mining, is required before operations begin. Opportunities exist, however, to ensure that this new industry applies adaptive management to continually refine operations with the goal of environmental protection and invests in the development of green technologies for extractive metallurgy and mining. In this Review, we explore the chemical processes that control the concentration of critical metals in deep-ocean polymetallic nodules, discuss the mining and metallurgical techniques required, and highlight the opportunities and potential risks that are presented by this new industry.

Deep-ocean polymetallic nodules (also known as manganese nodules) are composed of iron and manganese oxides that accrete around a nucleus on the vast abyssal plains of the global ocean[1–6]. Polymetallic nodules vary in diameter from less than one to tens of centimetres and acquire economically interesting quantities of critical metals (metals that are essential to the security and economic wellbeing of a nation) from ocean water and/or sediment pore waters. As a result, the enormous quantities of these nodules — which are conservatively estimated to total 21 billion dry tons in the Clarion–Clipperton Zone[7,8] (CCZ; located in the northeast equatorial Pacific Ocean) alone (FIG. 1) — host considerable tonnages of critical metals that are essential for green energy, vehicles and infrastructure, as well as for new technology and military applications. This reservoir of critical metals has, therefore, triggered interest in new deep-ocean mining operations. However, the potential environmental impacts of such activities are of great concern and have hastened extensive research and evaluation in this area[9–11].

Polymetallic nodules were first discovered on the seabed at a depth of approximately 4,300–5,500 m during the 1872–1876 voyage of the HMS Challenger to study the deep ocean[12]. A number of nodules, which contained numerous shark teeth and cetacean ear bones, were collected from the western end of the CCZ nodule field[12]. Early hypotheses suggested that polymetallic nodules form by alteration of volcanic rocks and grains, especially glass, which are transformed into manganese carbonates and, finally, into oxides that are deposited from solution to form nodules on water-rich sediments[12–14]. However, later work — aided in part by the 1957–1958 International Geophysical Year — revealed the general source of the metals (seawater and sediment pore water) and the sorption processes that might be involved in the acquisition of minor metals by nodules[15–20].

Economic interest in the deep-ocean polymetallic nodules developed in the 1960s[15,16], which subsequently led to the formation of consortia in Germany, the United States, Canada, Japan, France, Belgium, Italy and the Netherlands in the 1960s and 1970s[21–23]. These consortia aimed to develop resource assessments and extraction technologies for polymetallic nodules in the CCZ[21]. Deep-ocean-mining initiatives were developed to the point of several pilot mining operations[21,24], although most commercial activities ceased by the early 1980s, owing to low metal prices on the global market. Nevertheless, scientific interest in polymetallic nodules continued and geological, oceanographic, environmental and geochemical baseline studies were undertaken[4,25–29]. The Deep Ocean Mining Environmental Study programme, for example, involved 12 National Oceanic and Atmospheric Administration

[1]U.S. Geological Survey, Pacific Coastal and Marine Science Center, Santa Cruz, CA, USA.
[2]Department of Physics & Earth Sciences, Jacobs University Bremen, Bremen, Germany.
[3]Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany.
✉e-mail: jhein@usgs.gov
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Key points

- Polymetallic nodules cover vast areas of the abyssal ocean floor and contain significant amounts of critical metals.
- The chemical and mineralogical compositions of polymetallic nodules are primarily controlled by their formation process.
- A unique characteristic of deep-ocean nodules compared to terrestrial deposits is the presence of multiple commodities in one deposit; for example, nodules from the Clarion–Clipperton Zone contain Mn, Ni, Cu and Co.
- Deep-ocean mining might avoid some of the environmental issues associated with terrestrial mining.
- The development of societies towards a more sustainable future cannot proceed without critical metals. Deep-ocean mining can not only deliver the metals necessary for this transition but can do so with a low carbon footprint.
- The precautionary approach, adaptive management and best environmental practices are essential to the development of a polymetallic nodule resource.

research cruises during 1975 and 1976, which integrated data from multiple disciplines to understand the distribution, formation and evolution of polymetallic nodules in three specific areas representative of the vast CCZ. The Deep Ocean Mining Environmental Study programme revealed that hiatuses in sedimentation, moderate to low primary productivity in surface water, Antarctic bottom-water flow and many other environmental conditions favour the formation of metal-rich nodules[25].

Over the following four decades, research continued throughout the central Pacific and provided new insights into, for example, the complex surface-chemical processes that allow for the acquisition of remarkably large metal contents and the local, regional and global environmental controls on the formation of alternating, micrometre-scale, Fe-rich and Mn-rich laminae[1,2,10,24,30–43] (FIG. 2).

Research activities were controlled by exploration contracts with the International Seabed Authority, which was created based on the United Nations Convention on the Law of the Sea as an independent agency to administer mineral resources in areas beyond national jurisdictions (ABNJ; that is, all areas oceanward of the exclusive economic zones — 200 nautical miles from the coastline of coastal or island nations). Originally, research was predominantly undertaken by national agencies, until 2010, when private companies became involved and a polymetallic-nodule-mining industry was born. These exploration activities are ongoing today and polymetallic-nodule mining is likely to begin in earnest in the mid-to-late 2020s.

In this Review, we outline the chemical properties and formation characteristics of polymetallic nodules, before evaluating their economic significance and potential for future deep-ocean-mining. We also highlight the environmental and ecological significance of this developing industry and offer an overview of the opportunities and challenges that still remain. A comprehensive review of deep-ocean polymetallic nodules and their resource potential is critical, as these nodules provide an important natural laboratory for understanding chemical sedimentology and associated geochemical processes. In addition, deep-ocean polymetallic nodules represent a resource for critical elements (including Ni, Cu, Mn, Co, Mo, Ti, Li and rare earth elements, plus yttrium, or REY), which require secure and diverse sources to aid transition from a petroleum-based-energy world to a low-carbon future.

Nodule formation and coverage

Deep-ocean polymetallic nodules, composed of alternating Fe-rich and Mn-rich laminae, are predominantly formed on the sediment-covered floor of the global ocean, at water depths of approximately 3,500–6,500 m (FIG. 2a). In the following sections, we review the principle formation mechanisms of deep-ocean polymetallic nodules and outline how their chemistry and mineralogy (and, therefore, ore grade) define different types of potential ore deposits.

Nodule characteristics and formation. Deep-ocean polymetallic nodules have been subdivided based on their size (small, <4 cm diameter; medium, 4–8 cm; and large, >8 cm)[1,38,44], shape (spheroidal, discoidal, botryoidal or polyshape)[1,30,45] and seafloor density (from tens up to a thousand nodules per square metre; FIG. 2a displays a region of the central CCZ covered by medium-sized nodules with a nodule density of ~20 $kg\,m^{-2}$)[1]. Polymetallic nodules form on, or just below, the sediment surface of the abyssal ocean by two principle processes, hydrogenetic and diagenetic precipitation[4,46,47]. Both processes require a nucleus (for example, a shark's tooth) around which hydrogenetic and diagenetic layers can precipitate[6,28,30,47] (FIG. 3).

Hydrogenetic precipitation is driven by the oxidation of dissolved Mn^{2+} and Fe^{2+} in oxygen-rich ocean waters and subsequent accretion of Mn^{4+} and Fe^{3+} oxide colloids around a nucleus[32,47,48]. X-ray diffraction reveals that these precipitates are composed of amorphous ferrihydrite (FeOOH) and cryptocrystalline Fe-vernadite (δ-MnO_2), which possess positive and negative surface charges, respectively[1,32,48]. Hydrogenetic layers form at very slow rates of a few millimetres per million years, which requires negligible sedimentation, as well as oxic conditions, on the ocean floor and in the underlying sediment[1,4,7,24,30,34,39].

Diagenetic precipitation, on the other hand, occurs within the pore space of deep-ocean sediments[4,46]. Oxidation of organic matter in deep-ocean sediments results in the reduction and dissolution of Mn oxides and release of associated elements (Ni, Cu, Li, among others)[1,4,36]. Owing to concentration gradients in the sediment, these metals diffuse upwards and, on contact with oxygen-rich ocean water, are reoxidized, leading to the precipitation of 7-Å and 10-Å Mn oxides (disordered phyllomanganates)[1,2,4,36]. Diagenetic layers, which grow at a few tens of millimetres per million years, require slightly higher sedimentation rates (<10 $mm\,kyr^{-1}$) than hydrogenetic layers, reflecting climatically induced variations in surface-water biological productivity, as well as suboxic conditions on the ocean floor and in the underlying sediments[1,4,7,46,47].

Note, phyllomanganates are sometimes referred to in the literature as buserite and birnessite[49,50], but those names correctly refer to ordered rather than disordered phyllomanganates. Mn oxides in deep-ocean

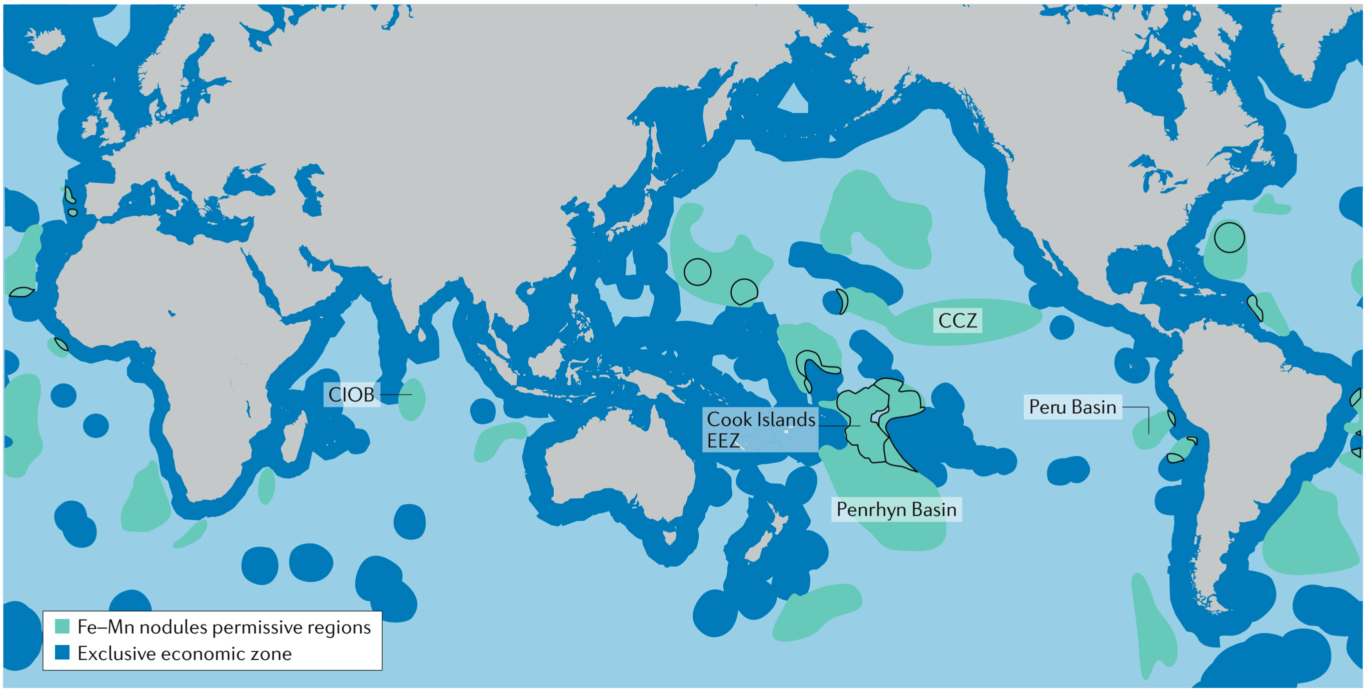

Fig. 1 | **Global permissive areas for deep-ocean polymetallic nodule deposits.** Global map showing the location of the polymetallic nodules permissive regions and the exclusive economic zones (EEZs). The four best known polymetallic nodule fields are the Clarion–Clipperton Zone (CCZ), Peru Basin, Penrhyn Basin (including the Cook Islands EEZ) and Central Indian Ocean Basin (CIOB). Nodule fields also occur between seamounts and ridges in much of the equatorial west Pacific and parts of other island and coastal nations' EEZs that occur within permissive nodule areas are outlined in black. Figure adapted with permission from REF.[8], Elsevier.

polymetallic nodules are made up of topotactic 7-Å and 10-Å manganates (which should strictly be termed vernadites)[51]. Topotactic means that the MnO_6 octahedral layers, which are stacked in the crystallographic *c* direction, are slightly offset to each other in the crystallographic *ab* plane. The minerals buserite and birnessite do not show this characteristic, as discussed elsewhere[1].

How polymetallic nodules remain on the sediment surface when their growth rates are so low compared to the surrounding sediments (3–5 mm kyr^{-1}) is still an unsolved paradox[52–54]. Benthic biological activity and/or seismic shaking may represent key processes[52–54]. Nevertheless, erosion and hiatuses in sedimentation are recognized as critical processes in the onset of nodule growth[55–57], whereas increased sedimentation rates and/or deposition of ash layers[57] may, ultimately, lead to the burial of a nodule generation.

It is important to note that ocean-floor nodules only represent the youngest generation of polymetallic nodules; hydroacoustic data reveal the presence of older nodule generations below the sediment surface[58,59]. Older nodule generations might be a common phenomenon beneath nodule fields worldwide but require relatively oxygenated conditions (free oxygen in the range of a few tens of μmol l^{-1}) in the sedimentary column to prevent dissolution[1,40].

Nodules found on and below the ocean floor represent an important but unexploited resource of a wide range of critical metals. Before considering the processes by which these nodules can be collected, and the metals of interest extracted, it is important to consider how the formation processes described above influence their chemistry and, therefore, metal grade.

Formation controls on nodule chemistry. The Mn oxides and Fe oxyhydroxides that form the framework of the deep-ocean polymetallic nodules are able to efficiently scavenge a large number of dissolved elements from ocean water, which are only present in ultra-trace concentrations. As a result, polymetallic nodules typically possess high concentrations of minor and trace elements (for example, Li, Co, REY).

Recent synchrotron-based methods, such as X-ray absorption near-edge structure and extended X-ray absorption fine structure spectroscopy, built on prior statistical analysis, experimental work and thermodynamic models to demonstrate that metal enrichment and the structural incorporation of minor and trace metals in deep-ocean polymetallic nodules is controlled by the mineralogy of the nodule[60–65]. As a result, nodule-formation processes — hydrogenetic versus diagenetic precipitation — that control the mineralogy of the polymetallic nodules also govern their chemical composition[1,2,39,41]. As outlined above, very different geological and oceanographic conditions are required for these two processes. Therefore, variations in sedimentation rates and the extent of metal cycling through suboxic sediment resulting from factors such as increased microbiological activity represent the base-level controls on nodule chemistry (FIG. 3).

The Fe oxyhydroxide and Mn oxide colloids formed by hydrogenetic precipitation possess slightly positive

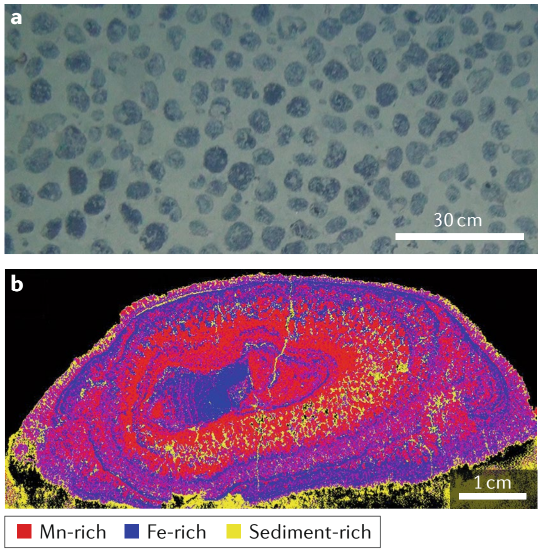

Fig. 2 | **Small-scale distribution and structure of polymetallic nodules. a** | Plan view of the seafloor in the central Clarion–Clipperton Zone at 4,900 m water depth with even coverage of about 20 kg m^{-2} (dry weight) of medium-sized nodules. **b** | X-ray scan of a nodule cross section from the Clarion–Clipperton Zone with typical alternation of Mn-rich and Fe-rich layers. Sediment within the nodules is an indication of their high porosity. Image in part **a** courtesy of T. Kuhn, Federal Institute for Geosciences and Natural Resources (BGR), Germany.

and negative surface charges, respectively. The surface charge of these colloids, under ocean-water conditions, results in attraction, surface adsorption and enrichment of dissolved critical metals on the nodule surfaces[32,41,42,66]. Cations (such as Cu^{2+}, Ni^{2+} and Co^{2+}) are attracted by the negatively charged δ-MnO_2 and anions (such as $UO_2(CO_3)_2^{2-}$) by the slightly positively charged FeOOH (FIG. 3a). In addition, the low charge density of the FeOOH surface enables the formation of covalent bonds with other slightly charged or neutral dissolved species, including $Ti(OH)_4^0$ (REFS[32,42,43]). Typically, hydrogenetic precipitates contain similar amounts of Fe and Mn (Fe/Mn ratio ~1 in bulk analyses), low Y/Ho and high Th/U ratios, and very high concentrations of Co, Te, Ce and Pt (REFS[8,20,41]). The high concentrations of Co, Te, Ce and Pt result from oxidation of these elements on the surface of δ-MnO_2 particles, which represents a very efficient process for enriching trace metals that can overcome the electrostatic repulsion of negatively charged species in solution (for example, for Te and Pt) by the negatively charged Mn-oxide surface[32,42,66–68].

On the other hand, the 7-Å and 10-Å disordered phyllomanganates that characterize diagenetic nodules typically incorporate metal ions such as Ni^{2+}, Cu^{2+} and Li^{+} to balance negative charge deficits in their crystal lattice[1,2,33,34,51,66,68,69]. Charge deficits form as a result of structural defects (gaps) or the incorporation of Mn^{2+} and Mn^{3+} instead of Mn^{4+} (REFS[1,34,46,63,68]). Diagenetic layers of polymetallic nodules are characterized by high Mn/Fe ratios (>10 in bulk analyses), high Ni, Cu and Li concentrations, low Co and Ce concentrations, high Y/Ho ratios and low Th/U ratios[1,33,34] (FIG. 3). Metals of economic interest (Co, Ni, Cu, Mo, Zn) either replace Mn or occupy vacant sites in the octahedral MnO_6 layers of the Mn oxides[1,33,34] (FIG. 3a). Interlayer sites of the 7-Å and 10-Å phyllomanganates are, by contrast, characterized by the presence of water molecules as well as alkali (such as Li, Na, K) and alkaline earth (such as Mg, Ca, Sr) elements[1,33,34,70].

In addition, X-ray absorption near-edge structure and extended X-ray absorption fine structure measurements further indicate that redox-sensitive elements, such as Co, Ce and Te, which are found bound in hydrogenetic nodules and crusts, are present in a higher oxidation state than in the overlying ocean water. This observation confirms that the exceptionally high concentration of such metals in polymetallic nodules results from redox processes involving Mn oxide[31,35,60,64,65,68]. By contrast, other elements (such as Pb) remain divalent during surface adsorption and incorporation[68]. Transition-metal cations and some anionic metal species form stable inner-sphere complexes on the surface of Mn and Fe oxides, which can lead to their isotopic fractionation. For example, Mo isotopes are fractionated during adsorption as molybdate, due to variations in the coordination environment of dissolved (tetrahedral coordination as $MnO^{2-}{}_4$) and adsorbed (distorted octahedral coordination) Mo (REF.[62]). Other species, for example, alkaline earth metals and anions such as chromate and selenate, form predominantly outer-sphere complexes on oxide surfaces, which are not associated with isotopic fractionation[61]. Hence, this molecular-scale information forms the basis for understanding the mechanisms by which critical metals are enriched in nodules to levels that foster economic interest.

The mean chemical compositions of polymetallic nodules in the best-known nodule fields can be used to define three types of potential ores[8,56,66,71] (TABLE 1). The CCZ and Central Indian Ocean Basin nodules, which represent mixed hydrogenetic–diagenetic nodules, have similar compositions, with high Mn, very high Ni and Cu, and moderate Co, Mo and Li contents[8,56,66]; nodules from the Peru Basin, which primarily form through diagenetic processes, are characterized by high Mn and very high Ni and Li contents[8,66]; and the Penrhyn Basin nodules, which primarily form through hydrogenetic precipitation, have the highest Ti, Co, Y and total rare earth elements content of the three nodule types[71] (TABLE 1). Therefore, these different nodule fields represent potential ores for a range of different critical metals, with the exact composition of the nodules (and, as a result, the metals that are of economic importance) controlled by the formation processes of each nodule field. Other elements with a high concentration relative to the Earth's crust are listed in TABLE 1 and may be available for extraction in the future.

Nodule distribution and exploration contract areas. The most well-studied nodule fields include the CCZ, Penrhyn-Samoa Basin, Peru Basin, Central Indian Ocean Basin and abyssal plains surrounding seamounts and ridges in the west Pacific[1,2,7,8,66] (FIG. 1). Although most nodule fields are in the ABNJ, important nodule deposits that represent large metal resources can also be found within the national jurisdictions of several Pacific Island countries and coastal nations, including Japan, Cook Islands, Kiribati, Niue and the United States[57,71–73] (FIG. 1). Permissive areas for nodule formation are defined as those with sedimentation rates <10 mm per 1,000 years, a source of material for nucleation of nodules (such as particles of rock debris, indurated sediment, nodule fragments and shark teeth), surface waters that have moderate to low productivity and small-scale ocean-floor topography[1,8,39,47,66] (FIG. 1). Permissive areas do not necessarily contain economically minable nodule deposits but simply represent regions where their formation is feasible.

Most contracts for exploration of marine mineral resources in the ABNJ are focused on the extraction of polymetallic nodules. At present, 18 contracts exist for nodule exploration, each covering 75,000 km^2, of which 16 are focused on nodule exploration in the northeast Pacific CCZ. Owing to the remarkable ability of polymetallic nodules to scavenge critical metals from ocean water, they represent a key resource of in-demand metals. As such, economic interest in deep-sea polymetallic nodules has boomed, necessitating deeper investigation into their exploration, mining and environmental impacts.

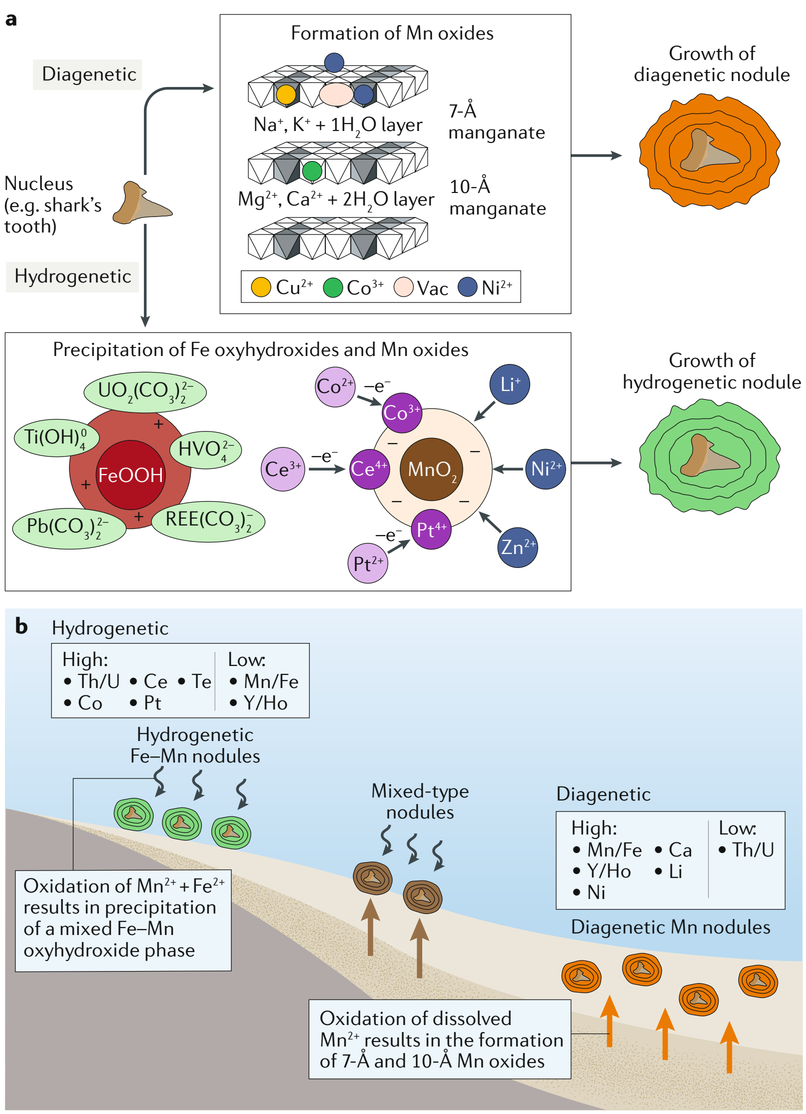

Fig. 3 | **Formation mechanisms and environments for polymetallic nodules.** **a** | Schematic showing the formation of δ-MnO_2 and ferrihydrite (bottom) and phyllomanganates (top), which precipitate around a nucleus to form hydrogenetic and diagenetic nodule layers, respectively. In addition to those shown here, many other anions and neutral complexes sorb onto the ferrihydrite and cations sorb onto the δ-MnO_2 and other phyllomanganates. **b** | Schematic showing the formation of hydrogenetic, mixed-type and diagenetic nodules, with variations in chemistry shown. Figure adapted with permission from REFS[36,128], Mineralogical Society of America.

Mining deep-ocean mineral deposits

The European Union recognized that raw materials are crucial to Europe's economy and sustainable development and, as of 2017, identified a list of 27 critical raw materials (CRM). In 2018, the United States Geological Survey produced an updated list of 35 CRM essential to the economic and national security of the United States. Identifying reliable and sustainable sources of these CRM represents one of the primary factors driving the development of the deep-ocean-mining industry, especially as many CRM are at high risk of supply disruption, owing to the lack of diversity of their worldwide production[74]. Typically, each CRM comes from just a few countries. For example, 60% of the current global production of raw Co, which is an indispensable component in lithium-ion batteries, comes from the Democratic Republic of the Congo and the dominant supplier of refined Co is China (with an 80% market share)[75]. Increased diversity of CRM production and refining operations will be essential to ensure a secure supply of CRM for low-carbon applications, such as green energy and green vehicles. Nevertheless, at the start of this new industry, it is important to consider the environmental and ecological impacts of deep-ocean mining, including how these can be minimized moving forward[8,36,73,76]. In this section, we focus on the practical side of polymetallic-nodule mining (in terms of its rationale, incentives, challenges, environmental implications and technologies).

Unique (or favourable) characteristics of deep-ocean mining. One of the first factors to be considered, with respect to potential deep-ocean mining, is whether the unique characteristics of marine-based mine sites provide favourable incentives for mine development. Marine-based mine sites do not require roads, ocean-floor ore-transport systems, water-transportation or electrical-transport systems, buildings, waste dumps or other infrastructure that characterize terrestrial mines. In addition, no overburden will need to be removed before mining can take place, as the deposits of interest are exposed at the ocean floor. Other crucial drivers of deep-sea mining include the fact that many of the deposits that are present at a single marine mine site contain three or more metals of economic interest[8,10,11]. Small deposits can be selectively mined simply by moving the production-mining vessel from one high-grade deposit to another, without the need to process intervening low-grade material. Therefore, compared to terrestrial mines, less ore is required to provide the same amount of metal[8,10,11]. Acid mine drainage and river or soil contamination will be avoided by deep-ocean mining, as will many other challenges faced by terrestrial mine sites, such as the

Table 1 | **Mean composition of polymetallic nodules in four nodule fields**

Element (units)	CCZ	CIOB	Peru Basin	Cook Islands–Penrhyn Basin
Iron/manganese ratio	0.22	0.21	0.25	0.96
Manganese (wt%)	28.4	24.4	34.2	16.9
Iron (wt%)	6.16	7.14	6.12	16.20
Nickel (wt%)	1.30	1.10	1.30	0.377
Copper (wt%)	1.070	1.040	0.599	0.231
Titanium (wt%)	0.320	0.420	0.160	1.280
Cobalt (wt%)	0.210	0.111	0.048	0.375
Molybdenum (ppm)	590	600	547	295
TREE (ppm)	717	931	334	1537
Vanadium (ppm)	445	497	431	504
Zirconium (ppm)	307	752	325	555
Thallium (ppm)	199	347	129	146
Lithium (ppm)	131	110	311	51
Yttrium (ppm)	96	108	69	141
Arsenic (ppm)	67	150	65	150
Tungsten (ppm)	62	92	75	59

Data obtained from: CCZ[8,56,66], CIOB[8,66], Peru Basin[8,66], Cook Islands–Penrhyn Basin[70]. CCZ, Clarion–Clipperton Zone; CIOB, Central Indian Ocean Basin; TREE, total rare earth elements.

relocation of towns and villages, deforestation and large-scale lowering of the groundwater table. Deep-ocean mining also offers the prospect of reduced risk to on-site workers and the absence of child labour. Many of these issues are pervasive challenges in land-based mining, particularly in developing countries[8,10,11].

Comparisons with land-based deposits. In addition to the advantages presented by the unique characteristics of deep-ocean-mine sites, it is important to consider how the tonnage of critical metals hosted within polymetallic nodules compares to that found within terrestrial ore deposits. The mean metal content of nodules (TABLE 1), and the estimated tonnage of nodules within the entire CCZ, can be used to calculate the tonnage of each metal hosted in deep-ocean polymetallic nodules compared to land-based resources (summarized in TABLE 2). CCZ nodules are shown to contain a greater tonnage of Mn, Ni, Co, Tl and Y (and a similar tonnage of As) than the entire global terrestrial reserve base. The nodule tonnage of Tl, for example, is approximately 6,000 times higher than the global terrestrial reserve base and 6.5 times higher than the global terrestrial resource (TABLE 2). TABLE 2 also highlights metals that represent terrestrial-dominant resources (especially Cu, Ti and total rare earth elements) and those that represent marine-dominant resources (especially Co, Ni, Tl and Te).

Enormous quantities of metal evidently exist on the ocean floor in the CCZ, as well as other nodule fields. However, not all of that metal is economically extractable. Even for decades ahead, only a very small part of that enormous tonnage of nodules will be extracted. Nevertheless, TABLE 2 demonstrates that deep-ocean polymetallic nodules represent important resources for critical metals, which may be extracted in the future. However, before the mining and extraction of nodule-bound critical metals can occur, exploration is needed to identify economically viable, first-generation nodule-mine sites.

Exploration techniques. Exploration carried out by different groups since ~1980 showed that two main parameters can be used to distinguish between economic and uneconomic deposits: nodule abundance in kilograms per square metre (tonnage; cut-off ~10 dry kg m^{-2} in the CCZ) and metal content in weight percent (cut-off, which will vary depending on tonnage and global markets, is ~2 wt.% Ni + Cu + Co for the CCZ)[3,5,7,71].

Polymetallic nodule exploration therefore requires, as a first step, the detection and delineation of large nodule fields in water depths between 3,500 and 6,500 m. Detection of nodule fields is generally achieved using multibeam echo-sounding systems mounted on the hull of research vessels[3,77,78] (FIG. 4). In addition to bathymetric information, such systems provide acoustic imagery (backscatter) that can be used to interpret the geological conditions on the ocean floor, including the separation of flat, sediment-covered areas that contain nodules from areas devoid of them[45,79–84]. After areas of interest (which can cover several thousand square kilometres) have been identified, a detailed bathymetric survey is conducted using autonomous underwater vehicles or deep-towed acoustic systems, such as side-scan sonar. Underwater systems survey at tens of metres up to about 100 m above the ocean floor, thus providing higher resolution (less than a few metres) bathymetric surveys than achievable from vessel-mounted systems (50–100 m)[82,83]. High-resolution acoustic survey are typically accompanied by video mapping using either deep-towed video or photo sledges, remotely operated vehicles or autonomous underwater vehicles[3] (FIG. 4). Sample collection, which is essential, is achieved using box corers (FIG. 4). This tool consists of a ~0.13-m^3 metal box that samples a block of undisturbed sediment from the seafloor with polymetallic nodules still in place[1]. As box corers sample a defined seafloor area, the mass of nodules per unit area can be measured directly. Moreover, representative samples are used to determine the nodule grade and metal content using optical emission spectrometry, mass spectrometry and other analytical techniques[33,34].

Data gathered by sample collection and high-resolution acoustic surveys are then fed into multivariate (geo)statistical models to predict nodule abundance and metal resources over large areas[5,78,79,83,84]. Such predictive models are based on artificial neural networks or random forests, as well as on classical geostatistics, such as variography and kriging, in order to assess the quantity of the resource[5,83,85–87]. Once the economic potential of a nodule field has been determined, then, if favourable, the operations will move on to mining.

Mining techniques. Polymetallic-nodule-mining operations in the deep ocean consist of the following major components: collector robot on the ocean floor, vertical riser system, surface mining vessel, bulk carrier vessels at sea and processing plant on land[1,11] (FIG. 4).

Consortia from South Korea, India, China and Europe have been developing several of these components up to a semi-industrial level[88–92].

Since polymetallic nodules lie either on the ocean floor or within the upper 20 cm of deep-ocean sediments, they can be harvested in a manner similar to potatoes in the field. Thus, mining machines might collect nodules from the ocean floor by either a mechanical or hydraulic uptake mechanism[1,91,93,94]. The mechanical machinery uses fork-like tools mounted on drums, which rotate backwards. By contrast, hydraulic uptake uses a water jet to lift nodules, together with ambient sediments, which are subsequently sucked into the nodule collector. Within the collector, sediment is cleaned from the nodules, which are then crushed to a certain size and pumped to a buffer chamber at the lower end of the vertical riser system[90,91,95]. This buffer chamber ensures the continuous flow of nodules into the riser pipe. Vertical transport of nodules is achieved using either centrifugal pumps or air lift[93,95]. At present, there is a major focus on the development of these pumping systems to provide improved flow-rate control and prevention of plugging from density waves[95]. The full-scale vertical riser system must have a capacity of 300–500 tons of ore per hour and include critical links to the collector system on the ocean floor and the surface mining vessel[95]. Collector locomotion on the ocean floor is achieved using a caterpillar track system in most mining machines. The surface mining vessel provides power to, and control over, all subsea systems, as well as housing ore-receiving, storage and ship-to-ship transfer capacities. Bulk carrier vessels with at least 50,000 tons storage capacity are required for the shipment of nodules to shore[96].

Extractive metallurgy. Following the mining and collection of polymetallic nodules from the abyssal plain of the deep ocean, as well as transport to onshore facilities, the metals hosted in these nodules will need to be extracted. Development and upscaling of metallurgical routes for the processing of polymetallic nodules are essential prerequisites for the commercial viability of nodule mining. To ascertain the commercial viability and to increase public acceptance, the metallurgical processing of these nodules must lead to zero or minimal waste, a low carbon footprint, recycling of reagents and additives, and capital and operating costs that are similar to existing commercial operations. Because polymetallic nodules are a special type of oxide deposit that do not possess a terrestrial analogue, the development of new and green methods for metallurgical processing of polymetallic nodules is necessary and has been the subject of considerable research during the past few decades (discussed elsewhere[97]).

Since nodules are built up of nanometre-scale manganese oxides and iron oxyhydroxides that are epitaxially intergrown (crystallographically aligned FeOOH and MnO_2 laminae), it is not possible to separate and enrich the metals of interest from the other nodule components by conventional beneficiation methods, such as flotation, density separation or magnetic separation[97,98]. The polymetallic-nodule matrix has to be completely destroyed to release the metals. This destruction can be

Table 2 | **Global tonnage of metals in CCZ polymetallic nodules versus terrestrial deposits**

Element	Total CCZ nodule resource[a] ($\times 10^6$ tons)	Global terrestrial reserve base[b] ($\times 10^6$ tons)	Global terrestrial resource[c] ($\times 10^6$ tons)	Example metal uses
Manganese	5,992	5,200	ND	Steel, batteries
Nickel	274	150	ND	Stainless steel, superalloys, wind turbines, batteries
Copper	226	1,000	5,600	Electrical, electronic, most high-tech products
Titanium	67	900	1,200	Aerospace, superalloys
Cobalt	44	13	ND	Batteries, superalloys, electromagnets
TREE	15.1	128	ND	Turbines, high-tech smartphones etc.
Molybdenum	12	19	25.4	Steel for strength and hardness
Vanadium	9.4	38	~63	Steel alloys, jet engines
Zirconium	6.5	77	ND	Nuclear industry
Thallium	4.2	0.0007	0.65	Photoresistors, infrared optics
Lithium	2.8	11	62	Batteries, aircraft
Yttrium	2.0	0.6	ND	Red phosphor for televisions
Arsenic	1.4	1.6	ND	Semiconductors
Tungsten	1.3	6.3	ND	High-strength steel, superalloys, electrodes
Tellurium	0.08	0.05	ND	Solar cells, superalloys

CCZ, Clarion–Clipperton Zone; ND, no data; TREE, total rare earth elements. [a]Calculated on the basis of an estimated 21.1 billion metric tons of CCZ nodules in place on the seafloor and the mean chemical composition detailed in TABLE 1. [b]Reserve base is the measured plus indicated resource that includes resources that are currently economic (reserves), marginally economic and some that are currently subeconomic[129]. [c]Terrestrial resource is a concentration of a naturally occurring material in or on the Earth's crust that is in such a form and amount that economic extraction is currently or potentially feasible[130].

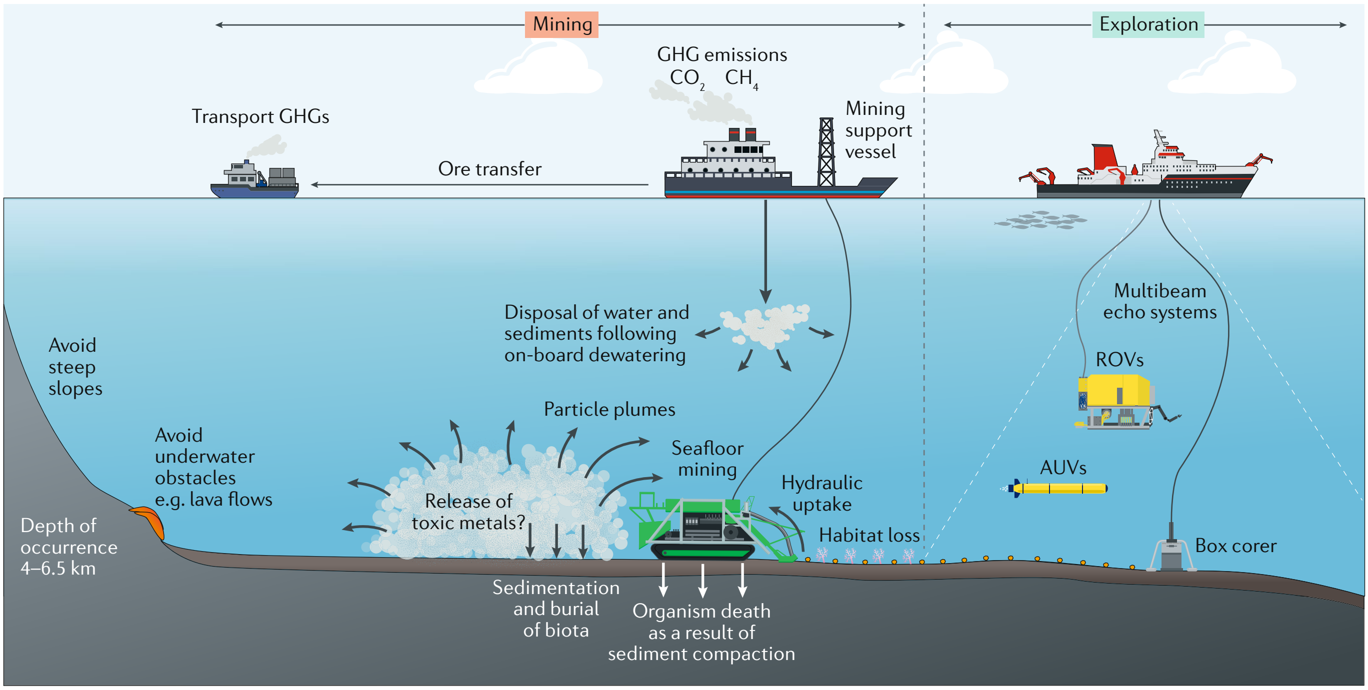

Fig. 4 | **The components of a polymetallic-nodule-mining project.** Major components include the collector on the seafloor, the vertical riser system, the surface mining vessel, bulk carriers and the processing plant on land. Multibeam, hydroacoustic mapping with a system mounted on the hull of a vessel provide information about the ocean-floor topography and water depth (bathymetry), and the characteristics of the ocean floor (hard rock, sediments, nodules). Deep-towed systems and autonomous underwater vehicles (AUVs) can get closer to the ocean floor and, thus, provide a higher resolution (smaller footprint). GHG, greenhouse gas; ROV, remotely operated underwater vehicle.

accomplished by one of several methods: pyrometallurgy, which involves smelting the nodules at 1,400–1,500 °C; hydrometallurgy, the chemical dissolution of nodules in sulfuric or hydrochloric acid or in ammonium sulfate and carbonate solutions; and microbiological treatment, such as dissolution by microorganisms[97].

During pyrometallurgical processing, nodules are smelted in an electric arc furnace under reducing conditions to separate the Mn–Fe–Si slag from a Cu–Ni–Co–Mo metal alloy. The slag can further be treated to produce ferromanganese and silicomanganese for the steel industry and the metal alloy will then undergo hydrometallurgical processing to separate the metals. Finally, the generation of a compact, environmentally stable and toxin-free final slag, applicable to the construction industry, ensures an almost zero-waste processing route for the nodules[99].

By contrast, many different nodule-processing schemes are solely based on hydrometallurgy. For example, the Cuprion process uses CO as the reducing agent in the presence of ammonium (NH_4) as a lixiviant. Other hydrometallurgical treatments include reduction roasting at 500–750 °C and subsequent leaching with $(NH_4)_2CO_3$ solution (Caron process), and high-pressure acid leaching or HCl-$MgCl_2$ leaching (both of which are widely used to process Ni laterites)[97].

New approaches include the application of microbiological methods based on the use of bacteria or fungi to dissolve and release metals from the oxide lattice[100,101], but such methods have, so far, been confined to laboratory-scale experiments. The recovery of trace metals, such as REY and Li, by microbial activity is another area of research, since their extraction could have a positive effect on the economics of nodule processing[102].

Environmental impacts. Before polymetallic-nodule mining enters large-scale operation, it is necessary to consider the possible environmental impacts and how they might be minimized or mitigated. Critically, it is imperative to obtain an adequate understanding of the ecosystems that characterize deep-ocean environments and their interconnectedness. The extraction of marine minerals and the environmental and ecological impacts are a concern in many countries, even in those that are not expected to be directly affected, which could lead to opposition to deep-ocean mining[103]. It is, therefore, important to provide evidence-based risk assessments of deep-ocean mining and to effectively communicate findings to all relevant authorities and countries, as well as the public.

The mining of polymetallic nodules will have biological and geochemical impacts on the ocean floor and overlying water column, the extent and magnitude of which remain uncertain[104]. Nodules serve as a hard substrate for a variety of sessile organisms (such as sponges and corals), and octopods have been observed to brood clutches of eggs laid on the stalks of dead sponges attached to nodules[105]. The nodule collector is a heavy vehicle that will crush any organisms that are unable to escape and compact the sediment, reducing its habitability for sediment infauna[106–108]. Additionally, nodule mining could alter the geochemical composition of the sediment–water interface and cause a short-term release of potentially toxic metals into the water column[109] (FIG. 4). However, a clear assessment of the potential toxicity of released metals remains a challenge because of the complex composition of polymetallic nodules and sediment particles, as well as the lack of toxicity studies for deep-ocean organisms[110]. Moreover, the suspension and redeposition of sediment will affect filter-feeding organisms that depend on the supply of nutrient-bearing particles in clean water. The extraction of nodules will, therefore, cause habitat degradation[111].

The collector systems also pose major problems due to the mobilization of large amounts of sediment. With a mining rate of 0.5 $m\,s^{-1}$ and a collector width of 15 m, 65,000 m^3 of sediment is mobilized per day for hydraulic uptake (which impacts the top 10 cm of sediment), resulting in the formation of sediment plumes along the track of the collector (see technical details from REF.[91]). The particle plumes might affect not only areas adjacent to the mine sites but also regions at much greater transport distances, depending on prevailing bottom currents and the behaviour of the particles in the dispersing plume. Numerical models published in 2001 indicate that these sediment plumes could have a far-reaching impact[112,113], although an experimental study published in 2019 demonstrated that aggregation and rapid sinking processes encompass more than 95% of the particles of a sediment plume, thus significantly limiting plume spreading[114]. However, the effect of the colloidal fraction, which could remain in the water column over much longer timescales and might also transport potentially toxic metals, is not known.

In addition, water and particles from the mining vessel (originating from the dewatering process of the ore on board) will be discharged back into the ocean. By general consensus, such disposal must not take place in surface or shallow waters to avoid interference with biological productivity in the photic zone or redissolution of material in the oxygen minimum zone, but should, instead, be confined to a water depth of at least 1,000 m, preferably close to the ocean floor[115]. However, no large-scale mining test including the disposal of mine water has taken place as yet. Moreover, the exact composition of the dewatering waste is unclear; predictions of the fate and effects of these discharge waters are also limited[116].

As shown by the disturbance and recolonization experiment (DISCOL), and the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans mining impact project), nodule mining will have impacts that can be considered permanent on human timescales, if remediation after the removal of nodules (the hard substrate for sessile biota) does not take place[117,118]. Nodule mining requires large areas to make the enterprise economic[11]; however, only a certain fraction of each contract area (possibly in the range of 15–20%)[3,119] will be mined as a first-generation mine site because large parts of the region will have either insufficient nodule coverage or the morphology of the seafloor will preclude harvesting by the mining machine. Hence, organisms are likely to have refugium areas and large areas from which larvae can be dispersed. Nevertheless, even if the overall biomass in an affected area resembles that of the former undisturbed area, following some period of recovery, the changed habitat may host a different faunal community[106,108,117].

Although research on deep-ocean ecosystems[120,121] has highlighted the high biodiversity and the slow growth and reproduction of deep-ocean fauna, the exact genetic distribution of species (including possible endemic species in certain nodule-bearing areas), as well as the interconnectedness among these populations, are still largely unknown. Furthermore, most studies have primarily focused on benthic fauna, whereas the possible impacts of deep-ocean mining on pelagic and benthopelagic fauna are not often addressed[122]. As a result, it is very difficult to present reliable predictions for the long-term impact of mining on recovery rates and resilience of the deep-ocean ecosystems.

In addition to the marine impact of nodule mining, it is important to consider possible atmospheric and terrestrial environmental consequences to assess the full footprint of deep-ocean mining. For example, greenhouse gas emissions from the mining ship, transport ship and nodule processing on land are all important factors to consider. As long as heavy fuel oil is used for shipping, the release of greenhouse gases and air pollution will be an important issue[123]. Metallurgical processing of nodules at land-based facilities will also result in the release of greenhouse gases and, possibly, toxic waste[124]. However, the extent of these emissions will depend on the type of technology used and the environmental legislation of the responsible or sponsoring state.

Growth of the deep-ocean-mining industry offers the opportunity to develop green technologies and policies as the industry develops, and concomitantly initiates new strategies to mitigate the environmental effects. Green technologies can be developed for mineral exploration and extraction, as well as ore processing. Development of the deep-ocean-mining industry also provides key opportunities to collect new biological, geological, geochemical and oceanographic data to provide a much clearer understanding of the processes that control the geochemical properties of the ocean floor and water column in mineral-deposit areas.

Finally, deep-ocean mining might help to reduce the pressure on ecologically sensitive ecosystems on land (for example, the deforestation of rainforests to mine laterites for Co and Ni). The replacement of terrestrial mines that impact critical ecosystems with deep-ocean mines could contribute to fulfilling recent climate treaties and United Nations sustainability goals.

Future perspectives and conclusions

The United States and the European Union, respectively, listed a set of 35 and 27 CRM that are essential to their continued security and prosperity, but are vulnerable to disruption of supply. The sources of CRM required for high-tech, green and alternative energy applications are currently limited and it has become necessary to dig deeper and deeper in terrestrial mines. Deep-ocean mineral deposits, in the form of polymetallic nodules on the seafloor, are rich in many of these CRM. As a result, a complex new industry focused on the recovery of polymetallic nodules from the abyssal plains of the global ocean, and extraction of the metals they contain, is taking shape.

A holistic approach to this developing industry must encompass the concept of 'cradle-to-grave' analysis: assessment of the entire life cycle of product manufacture from exploration and extraction to restoration and/or remediation. This approach is essential and routinely considered as the most constructive way forward for the mining industry. A global strategy for the management of critical metal resources and energy production (such as that implemented by the United Nations) will be required to meet climate and sustainable-development goals[74,125]. Opportunities exist to develop new green technologies for exploration, mining and ore processing. Application of the precautionary approach, along with adaptive management supported by real-time monitoring, offers the opportunity to ensure the long-term sustainability of this new industry.

The greatest challenge associated with the development of deep-ocean mining is understanding and minimizing its environmental impact, which will determine whether deep-ocean mining should be undertaken and whether it will be of value to societies. In this regard, it is commonly asked whether deep-ocean mining will be more environmentally sustainable than terrestrial mining. However, it is difficult to compare the value of a terrestrial rainforest or grassland with that of a deep-sea ecosystem. What measures should be used? Ecosystem service, biodiversity of the system as a whole, operational CO_2 emissions or respective economic, social and environmental impacts? Certainly, for CO_2 emissions, mining one deep-ocean mineral deposit for three or four metals would have a lower CO_2 footprint than that of three or four terrestrial mines each producing one metal. CO_2 footprint perhaps represents a more easily understood metric than ecosystem-based metrics, but it cannot be considered alone. It is important to note that, although deep-ocean mines will eventually replace some terrestrial mines, especially for critical metals, terrestrial mines will continue to operate well into the future. Both will need to apply best environmental practices using the precautionary approach, which might be easier to achieve in a new industry than to retrofit these concepts to a mature industry that was underway long before the concept of the precautionary approach existed.

Modern societies cannot exist without the materials that are found in polymetallic nodules, and demand for these metals is projected to increase markedly in the future. The question is, however, where should these metals come from? Economic models show that recycling alone is not a viable solution, and that, even in 2050, a substantial part of our economy will depend on primary metal resources[126,127]. Recycling could become an important part of the answer by 2100, but a much greater focus on education and technology in this arena must take place. The enormous amount of marine mineral resources, and the development of technology to access them, makes deep-ocean contributions to the production of critical minerals seem inevitable. The size of that contribution will, however, depend on other factors, including increased efforts to expand efficient recycling and the success of materials science in finding efficient and high-capacity substitutes for critical materials.

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