Vysetti. *Miner Miner Mater* 2023;2:5
DOI: 10.20517/mmm.2022.12

Minerals and
Mineral Materials

Mini Review

Open Access

Deep-sea mineral deposits as a future source of critical metals, and environmental issues - a brief review

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How to cite this article: Vysetti B. Deep-sea mineral deposits as a future source of critical metals, and environmental issues - a brief review. *Miner Miner Mater* 2023;2:5. https://dx.doi.org/10.20517/mmm.2022.12

Received: 22 Dec 2022 **First Decision:** 23 Feb 2023 **Revised:** 31 Mar 2023 **Accepted:** 15 Apr 2023 **Published:** 30 Apr 2023

Academic Editor: Feifei Jia **Copy Editor:** Ke-Cui Yang **Production Editor:** Ke-Cui Yang

Abstract

For the whole world to deliver net zero by 2050, large-scale mining is more critical for metals such as lithium, cobalt, platinum, palladium, REE, gallium, tungsten, tellurium, and indium as these metals are essential for green technology applications such as making wind turbines, solar panels, fuel-cells, electric vehicles, and data storage systems required to transition to a low-carbon economy. Since land-based mineral deposits are depleting fast, seabed resources are seen as a new resource frontier for mineral exploration and extraction. They include mainly deep-ocean mineral deposits, such as massive sulfides, manganese nodules, ferromanganese crusts, phosphorites, and REE-rich marine muds. Manganese nodules contain mainly manganese and iron, but also valuable metals like nickel, cobalt, and copper, as well as REE and platinum, which are used in making several high-technology and green technology products. For example, deep-sea mud enriched in REE (> 2000 µg/g) was found in the western North Pacific Ocean. High concentrations of REE range from 1,727 to 2,511 µg/g in the crust samples collected from the Afanasy Nikitin Seamount (ANS) in the Indian Ocean. However, these deposits usually have lower REE grades than land-based REE deposits such as carbonatite-hosted deposits but form greater potential volumes. Though the mining companies and their sponsoring countries are in the process of developing the required technologies to mine the three deep-sea environments: abyssal plains, seamounts, and hydrothermal vents, due to severe concerns about the possible environmental damages, the International Seabed Authority (ISA) has not granted any mining permissions so far, although deep-sea mining becomes inevitable in the future green energy revolution.

Keywords: Rare-earth elements, deep-sea mineral resource, REE-rich mud, marine environment, ferromanganese nodules, Fe-Mn crust, phosphorites, seafloor massive sulfides

INTRODUCTION

To tackle the current climate emergency and achieve net-zero emissions, in the coming 30 years, a coordinated effort of all nations is required to switch over from fossil fuels to renewable energy systems such as solar, wind, and nuclear for electricity generation. In addition, all our vehicles have to be powered by electricity instead of fossil fuels, and the necessary technologies have to be developed to remove excess CO_2 from the atmosphere. All these require hi-tech metals such as Co, Ni, Li, Ge, Te, Pt, Pd, and rare earth elements (REE) as raw materials in huge quantities for manufacturing power generation systems, power storage systems, and several other hi-tech devices. For centuries, man used land-based metal resources to develop technologies for his comfortable living. Unfortunately, land-based mineral deposits are currently producing lower grades at higher production costs, and it is also becoming harder to locate economically viable high-grade deposits. Land mining involves various stages such as prospecting, explorative drilling, construction of infrastructure for mining, operation, extraction of metals, maintenance, expansion if required, mine closing, and environmental remediation activities. All these activities affect social and environmental systems directly or indirectly, many times more negatively[1]. In several cases, the extraction process of metals from the ores requires more harsh treatments by using large quantities of corrosive acids and other hazardous chemical reagents like cyanides[2]. In addition, due to the decrease in high-grade minerals in the earth's crust, production must be increased in extractive metallurgical processes, which in turn increases the amount of waste generated. For example, for the production of one ton of copper, 150 tons of copper ore is typically required to be excavated, crushed, concentrated by froth flotation, and then extracted using different methods depending on the sulfide or non-sulfide nature of the ore which produces large amounts of tailings containing very high levels of toxic metals such as Cd, Pb, and Zn[3].

The enrichment and formation of various metal deposits in the earth's crust are greatly influenced by local geology. This leads to a very uneven distribution of mineral deposits around the world. As a result, for example, even bigger countries like the US are dependent on China for the supply, as each element or metal is having a specific geologic association and there is a continuous technological-commercial war between the US and China. This kind of situation generates tensions even between the European Union and other countries such as Japan[4]. The Democratic Republic of Congo produces 60% of cobalt in the world, where there is child labor involving children between 3 and 7 years of age being exploited in hazardous mining works. Unfortunately, Congo is one of the poorest nations in the world, although more than half of the world's supply of cobalt comes from this country[5]. Given these developments, it is necessary to explore new alternative sources for the exploitation of critical metals, for example, deep-sea mining[6]. In addition, mining, extraction, metallurgical treatment, and recovery of REE and several other metals from marine sediments is relatively easy compared to the extraction of metals from land deposits, as most metals in marine deposits are not part of the crystal lattice of the minerals that host them in contrast to the land-based deposits. Very low radioactive Th and U concentrations in these deep-sea deposits do not pose many environmental risks, unlike in many well-known land-based REE deposits. As a result, mining and metallurgical treatment have become economically favorable[7,8].

Several studies revealed that the world's ocean bed is filled with large quantities of different mineral deposits that contain significant amounts of critical metals like Cu, Co, Li, and REE[6,9-11]. The possibility of mining the ocean floor for these valuable metals has generated huge interest and gained significant momentum in recent times to meet the growing demand for these metals. In fact, technological developments steered humans towards deep sea exploration in search of valuable minerals after the pioneering HMS *Challenger expedition*, between 1872 and 1876. Since then, the ocean floor has become one of the frontier areas for the search for mineral resources[12]. However, there are huge areas that are completely unexplored and unsampled, particularly after the environmental concerns of deep-sea mining. In general, these marine minerals precipitate slowly from seawater over millions of years and are unique, although hydrothermal minerals precipitation is usually very fast (e.g., Mid Atlantic Ridge, Solwara). On the other hand, diagenetic precipitation of Fe-Mn oxyhydroxides can be in the order of fast growth rates with an average value of 2,500 mm/My (e.g., Gulf of Cadiz, Baltic Sea). Several studies are underway for a complete understanding of these processes[13-17]. In view of the current interest in deep-sea exploration for hi-tech metals, an attempt is made here to describe the latest developments in understanding the mineral potential of deep oceans, their nature and formation, geological settings, the technologies developed for their exploration and mining, and the environmental issues.

DEEP-SEA MINERAL DEPOSITS

The ocean contains a complex combination of processes leading to the formation of a wide variety of mineral categories. In addition to the well-known oil, natural gas, and gas hydrates, the deep oceans are also bestowed with massive metal deposits. These deep-sea mineral deposits can be divided into five types: manganese nodules, seafloor massive sulfides, ferromanganese crusts (also known as cobalt crusts because of the significant concentration of cobalt), REE-rich marine mud, and marine phosphorites. Deep-ocean mineral deposits also provide valuable information on the evolution of the earth, seawater, and insights into the past global climate history[12]. Figure 1 presents an overview of different types of major deep-sea minerals, which are described in a more detailed way in the following:

Ferromanganese (Fe-Mn) nodules

Ferromanganese (Fe-Mn) nodules or manganese nodules accumulate on the sea floor only in areas of low sedimentation rate and form extremely slowly, with a growth rate of 2-15 mm/million year, which is one of the slowest known geological processes[18]. These marine sedimentary rocks form in the oxidizing environment of the sediment-covered abyssal plains of the Indian, Pacific, and Atlantic Oceans at depths of 3,000-6,000 m [Figure 2]. They contain huge quantities of iron and manganese [Table 1] and also contain significant quantities of several other metals such as copper, cobalt, nickel, REE, and platinum[10].

They are mainly composed of tectomanganeate such as vernadite, birnessite, buserite, and todorokite minerals[49]. Ferromanganese nodules take up metals from seawater and pore water, and the precipitated colloids of hydrated Mn and Fe oxides acquire trace metals by surface sorption processes[50]. These manganese nodules support life in the deep-sea ecosystem by providing critical habitat for a large number of unique and largely unknown and understudied species. Clarion-Clipperton Zone (CCZ) in the Pacific Ocean, a 4.5 million square kilometers stretch of the seafloor between Hawaii and Mexico that extends 4,000-5,500 meters deep, has been one of the most intensely studied regions of the deep ocean from the point of view of exploitation of these valuable minerals[51]. According to Mizell *et al.*[52], the current global total tonnage estimates are 93 × 10^{10} dry tons for manganese nodules, which is 4.5 times higher than the 20 × 10^{10} dry tons reported earlier by Hein *et al.*[53]. Recently Li-rich ferromanganese oxide deposits are also reported from the South Andaman Sea, Northeastern Indian Ocean, with Li concentrations up to 781 μg/g[54]. High concentrations of Li up to 311 μg/g in manganese nodules from the Peru Basin were reported by Hein *et al.*[6]. Li-rich ferromanganese deposits (up to 738 μg/g) have also been reported in the Cocos-Nazca spreading center, Pacific Ocean[55].

Table 1. Average concentrations of some strategic metals in different types of marine sediments from different oceans, modified after[19]

Ocean	Type of sediment	REE range (μg/g)	Fe %	Mn%	Ni%	Co%	Cu%	Reference
East Siberian Arctic Shelf	Bottom sediments	104 to 220	-	-	-	-	-	[20]
Central North Pacific Ocean	Siliceous sediments	810.4	-	-	-	-	-	[21]
Afanasy Niktin Seamount (ANS) in the Eastern Equatorial Indian Ocean	Cobalt crust	1,727-2,511	15.75	19.61	0.40	0.53	0.10	[22,23]
Mid-Pacific seamount	Cobalt-rich crusts	2,085	16,76	24.38	-	0.71	-	[24]
Indian Ocean	Ferromanganese crusts/nodules	928-1,570	13.94	15.70	-	-	-	[25,26]
Scotia Sea	Ferromanganese crust	3,400	20,36	22.85	0.28	0.42	< 0.03	[27]
Seafloor massive sulfide deposits off Papua New Guinea, Pacific Ocean	-	-	-	-	-	-	6.8	[28]
Seafloor massive sulfide deposit SW Pacific	Pedestal slab	7.6	8.02	0.02	<0.01	<0.01	19.84	[29]
	Peripheral chimney	0.72	2.01	0.04	<0.01	<0.01	1.25	
	Precipitate	1.77	7.92	16.15	<0.01	<0.01	0.01	
Eastern South Pacific	Deep sea mud	1,000-2,230	-	-	-	-	-	[30]
North Pacific (east & west of Hawaiian Islands)	Deep sea mud	400-1,000	-	-	-	-	-	
Minamitorishima Island in the Western North Pacific	REE-Rich Mud	500-1,500 (REE + Y)	-	-	-	-	-	[31]
	Ferromanganese nodules		-	20.0	0.4	0.5	0.2	
South China Sea	Ferromanganese nodule deposits	1,460 (avg)	-	-	-	-	-	[32]
Indian Ocean	REY-rich mud	> 400	-	-	-	-	-	[33]
	Marine sediments	585-920	-	-	-	-	-	
Andaman Sea, Indian Ocean	Ferromanganese crust, the summit of southern seamount	1,139	0.60	31.3	0.10	< 0.01	< 0.01	[34]
	Ferromanganese crust within the two peaks of the same seamount	2,285	13.83	14.2	0.07	0.05	< 0.01	
Lakshadweep Sea, Indian Ocean	Ferromanganese crust	La (200) & Y (150)	-	-	-	-	-	[35]
West Sewell Ridge, Andaman Sea, Indian Ocean	Ferromanganese crust	1,600	-	-	-	-	-	[36]
	Manganese nodules	1,186	-	-	-	-	-	
Clarion-Clipperton Fracture Zone, Northeastern Pacific Ocean	Deep-sea sediments	> 700	-	-	-	-	-	[37]
Peru basin	Fe-Mn nodules	403	6.12	34.2	1.3	0.05	0.60	[38]
CCZ, Pacific Ocean	Fe-Mn nodules	813	6.16	28.4	1.3	0.21	1.07	
		-	5.9	28.1	-	-	-	[39]
Cook Island	Fe-Mn nodules	-	15.9	17.6	0.45	0.41	0.23	
Cook Islands	Fe-Mn nodules	1,707	16.1	15.9	0.38	0.41	0.23	[38]
West Clarion-Clipperton Zone, Pacific Ocean	Marine sediments	454.7 (REE + Y)	-	< 1	-	-	-	[40]
North Pacific Ocean near Minamitorishima Island, Japan	Deep-sea mud	> 5,000 (REE + Y)	-	-	-	-	-	[41]
Mid Pacific Ocean	Fe-Mn nodules	1,178-1,434	15.94	24.38	0.38	0.56	0.12	[42]
Canary Island, Atlantic Ocean	Fe-Mn crusts	335-3,485	28.4	13.79	0.25	0.44	0.06	[43]
Central Pacific	Fe-Mn crusts	678-2,649	6.0-18	13-27	0.17-0.73	0.25-1.18	0.02-0.22	[44]
Pacific Ocean	Fe-Mn crusts	1,060	-	22.5	0.49	0.71	0.04	[45]

Atlantic Ocean	Fe-Mn Crust	2,221	-	14.5	0.26	o.36	0.09	[46]
Indian Ocean	Fe-Mn Crust	2,363	-	17.0	0.26	0.33	0.11	
Indian Ocean	Fe-Mn nodules	1,039	7.14	24.4	1.10	0.11	1.04	[47]
Pacific Ocean	Deep nodules	1,326	-	-	-	-	-	[48]
	Shallow nodules	1,398	-	-	-	-	-	

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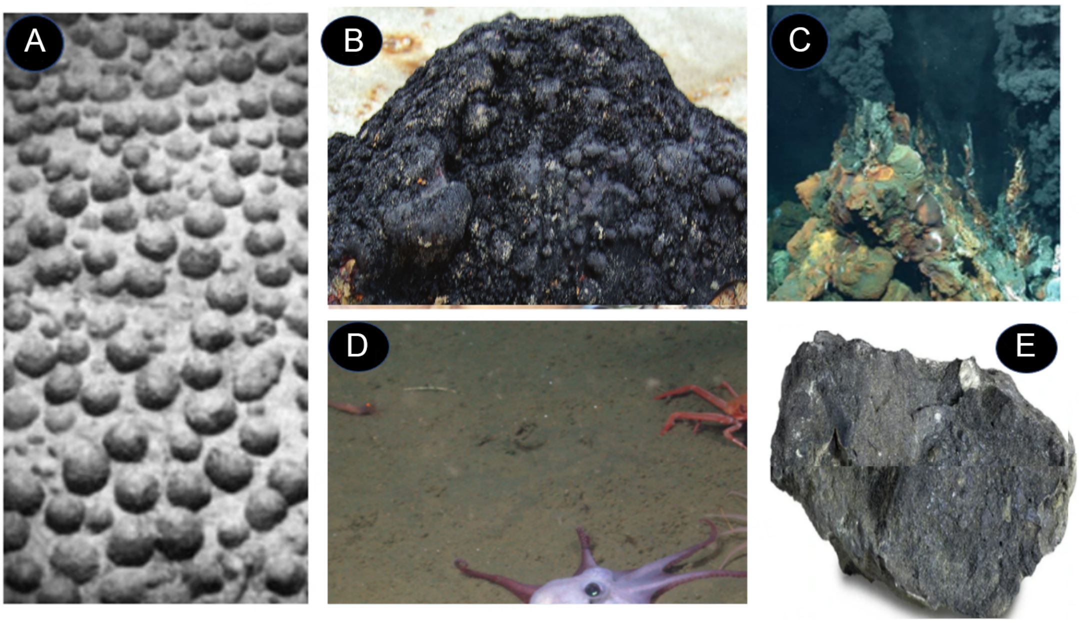


Figure 1. Deep-sea minerals: (A) manganese nodules; (B) ferromanganese crust; (C) a massive sulfide formation at hydrothermal vent site; (D) REE-rich marine mud; and (E) phosphorite is a sedimentary rock, defined as a chemical sediment of marine origin.

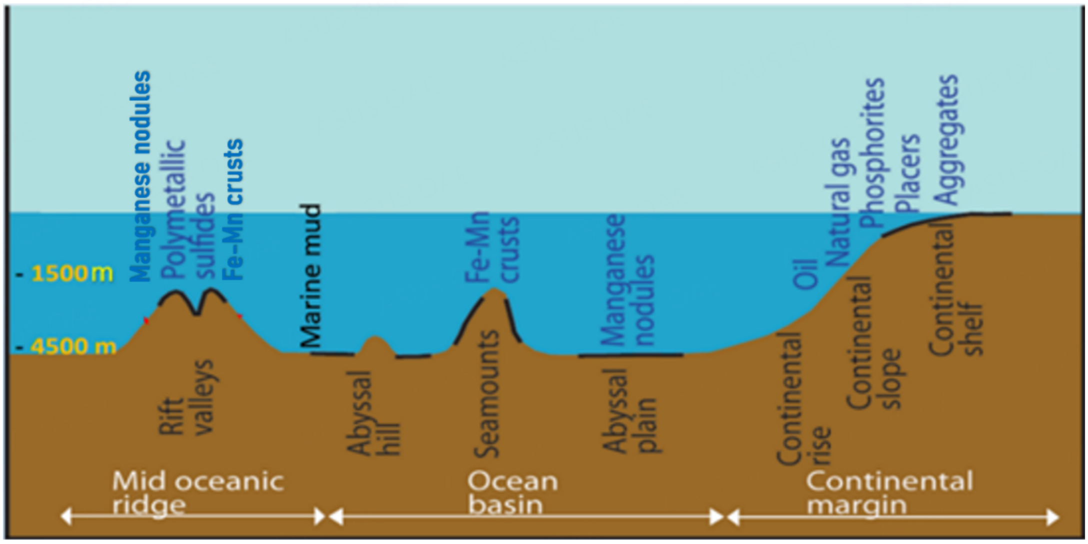


Figure 2. Occurrence of manganese nodules, ferromanganese crusts, massive sulfide deposits, REE-rich marine mud, and phosphorites at the ocean basins, mid-oceanic ridges, seamounts, and continental margins in the oceans.

Seafloor massive sulfides

Seafloor massive sulfide ore deposits are formed at water depths ranging from about 3,700 to 1,500 m in diverse volcanic and tectonic settings such as mid-ocean ridges, back-arc, and island-arc rifts, by volcanic hydrothermal events when seawater penetrates the ocean's crust by chemically modified through, heat (up to 400 °C), high pressure (~350 bar), interaction with crustal rocks, and, sometimes by the input of magmatic fluids[56]. There are about 300 sites of hydrothermal activity in modern submarine hydrothermal systems, and mineral deposits have been recognized worldwide[57]. Seafloor massive sulfide deposits were first discovered during the exploration of the deep oceans and the mid-ocean ridge spreading centers in the early 1960s. Since 1979, several massive sulfide deposits were discovered, some of which were found in places like Loihi Seamount, Hawaii[58], East Pacific Rise[59], Mid Atlantic Ridge[60], Central Indian Ocean Basin (CIB) in the Indian Ocean[61], Bransfield Strait; Arctic[62] and the Bismarck Sea which lies in the southwestern Pacific Ocean within the nation of Papua New Guinea[63]. Several scientists believe that the earliest life on Earth may have originated from submarine-hydrothermal vents[64]. Hydrothermal vents form when two tectonic plates move away from each other and form a fissure at the bottom of the ocean [Figure 2]. A wide variety of minerals form through hydrothermal activity and reduced sulfur and may be enriched in several metals such as Cu, Zn, Fe, Au, and Ag. These deposits fall into four or five categories: *porphyry deposits* (*e.g., Cu, Mo, and Au deposits*), *skarn deposits* (*e.g., calcite and dolomite*), *volcanogenic massive sulfide deposits* (*e.g., iron and precious metal deposits*), *sedimentary exhalative deposits* (*e.g., Zn, Pb, Ag, and Cu deposits*), and *epigenetic deposits* (*e.g., limestone*). These deposits are considered modern analogs of land-based volcanogenic massive sulfide (VMS) deposits which were formed over the entire history of the planet's evolution from the Archean to the Cenozoic[65,66]. The size of these hydrothermal deposits can go up to 100 million tons which is similar to the size of many volcanic-associated massive sulfide deposits found on land[67]. Black smoker chimneys are formed from the deposits of iron sulfide (bathyal zone - between 200 and 2,000 m below the surface), while white smoker with non-sulfide minerals (e.g., barium sulfates and calcium carbonate, and silicon) is characterized by lower temperature (< 200 °C). Significant amounts of Pd and Rh concentrations in the massive sulfides from the hydrothermal fields, both active and inactive black smoker sites at the hydrothermal fields (up to 356 ng/g Pd and up to 145 ng/g Rh), in the eastern Manus basin, Papua New Guinea were identified[68]. Papua New Guinea, with its vast hydrothermal deposit's potential, has become one of the most important targets for seabed mining in recent years. Out of a 70,000 km long global system of mid-oceanic ridges, the extent of the Indian Ocean Ridge System (IORS) consists of four major ridge systems, namely Carlsberg Ridge (CR), Central Indian Ridge (CIR), South West Indian Ridge (SWIR), and South East Indian Ridge (SEIR) is quite significant. According to Kalangutkar *et al.*[69], the future blue economy of seafloor massive sulfides along the IORS sustainably ensures resource wealth.

Ferromanganese crusts

Ferromanganese crusts or Fe-Mn crusts are formed on seamounts [Figure 2] by the precipitation of colloidal components such as iron-manganese oxides from seawater and also, in some cases, from hydrothermal inputs, on volcanic and biogenic substrate rocks. Mineralogical and geochemical studies on the ferromanganese crusts collected from two seamounts in the Andaman Sea revealed two types of origin, namely hydrothermal and hydrogenous[34,70]. These crusts contain high concentrations of elements such as cobalt, REE, Nb, Pt, W, Bi, Ni, Mn, Te, and Ti. It was also observed that the majority of REE, including Y, were found to be associated with Mn-oxide and Fe-oxyhydroxide phases[71,72]. Balaram *et al.*[23] reported very high concentrations of ∑REE ranging from 1,737 up to 2,520 μg/g in the ferromanganese crust samples collected from the Afanasy Nikitin Seamount (ANS) in the Eastern Equatorial Indian Ocean in 2012. There is also considerable enrichment of platinum in these marine sediments as the bulk concentration varies between 0.14 and 1.02 μg/g and averages at 0.51 ± 0.24 μg/g[73,74]. Several studies[75-77] indicated that the elemental enrichment in ferromanganese crusts is the result of comprehensive factors, including low sedimentation rate, the high metal content of the bottom seawater, a non-carbonate depositional environment, oxidizing conditions, microbial activity, certain bottom current conditions, and cosmic spherules. Table 1 presents concentrations of ∑REE and also some critical metals in different marine sediments including ferromanganese crust samples.

REE-rich marine mud

Recent studies suggested that pelagic sediments may contain large amounts of REE and have received global attention as an important reservoir of the global REE budget and a potential resource for future use. The first report by Kato *et al.*[30] indicated that pelagic sediments have the potential to become important REE resources. They reported very high concentrations of ∑REE (up to 2,230 µg/g) in marine mud on the deep-sea floor in the Pacific Ocean off Hawaii and Tahiti. Subsequently, deep-sea mud containing over 5,000 µg/g REE content was discovered in the western North Pacific Ocean near Minamitorishima Island, Japan by Takaya *et al.*[41]. In general, Ca-phosphate (e.g., bioapatite fossils) and Fe-Mn (oxyhydr)oxides have been considered important REE carriers in deep-sea sediments[78]. Deep-sea mud enriched in REE (∑REE > 2,000 µg/g) was found in the western North Pacific Ocean, and the sediment cores collected near topographic highs in the Central Pacific Ocean yielded ∑REE 4,489 µg/g[79]. According to the authors, the enrichment of REE was attributed to the enhanced deposition of fish debris which acts as a host for REE. REE resource amount in a 1-km^2 area around the study sites based on mining to the depth where the average grade is maximum when mined from the surface revealed that this REY-rich mud could provide 1.4% of the global annual mine production of REE, and this mud deposit in the Central Pacific Ocean can be considered a potential REE resource for the future. Of course, these calculations are based on a very limited area's potential within the vast ocean. Recently Fujinaga *et al.*[80] reported marine mud markedly enriched with REE (up to ∑REE 1,120 µg/g) from the Aki umber deposit in the Northern Shimanto Belt, central Shikoku, southwest Japan. The geochemical features suggested that the Aki umber represents a hydrothermal iron oxyhydroxide-type REY-rich mud deposited originally in a pelagic deep-sea setting during the Middle Cretaceous (113.2-100.5 Ma). Yasukawa *et al.*[81] studied the geochemistry and mineralogy of REY-rich mud in the eastern Indian Ocean. These sediments consist mainly of siliceous ooze, with subordinate zeolitic clay that contains relatively high REY concentrations. The maximum and average ∑REY contents of this material are 1,113 and 629 µg/g, respectively, which are comparable to those reported from the Pacific Ocean. Iijima *et al.*[82] discovered extremely REY-rich mud in the Japanese exclusive economic zone (EEZ) around Minamitorishima Island, in the western North Pacific Ocean. The maximum ∑REY concentration, especially rich in heavy rare-earth elements, reaches approximately 7,000 µg/g, which is much higher than that reported for conventional REY deposits on land and other known potential REY resources in the ocean.

Phosphorite deposits

Phosphorites are phosphorous-rich sedimentary rocks, usually composed of carbonate hydroxyl fluorapatite $Ca_5(PO_4, CO_3)_3F$. They occur in the global ocean in three general environments: (i) as nodules and crusts originally formed in oceanic environments: continental margins - shelf, slope, banks, and plateaus, (ii) seamounts, especially the old (Cretaceous) seamounts, for example, in the NW Pacific Ocean, and, (iii) lagoon/insular deposits[83]. Marine phosphorites primarily occur along continental margins where upwelling large volumes of phosphate-rich cold water rise from great depths to the surface. In the warmer surface waters, phosphate precipitates out of the solution and then sinks to the seafloor forming deposits of phosphorite[84,85]. Phosphorite deposits are widespread on the seafloor of continental shelves and slopes along the western continental margins of both the Pacific and Atlantic Oceans. Some of the areas where these deposits form includes the Peru-Chile margin, on plateaus such as Chatham Rise offshore New Zealand, the Blake-Bahamas Plateau off the southeast United States, offshore Baja California, and on the shelf off Namibia. Significant deposits of phosphorite are found in the Xisha Islands[86]. González *et al.*[87] reported extensive phosphorite deposits in upwelling areas in the Atlantic Iberian margins. They can also form on seamounts where ferromanganese crusts grow. Some of the phosphorite deposits contain ΣREE up to 2,000 µg/g[88], although the composition of these rocks and REE concentrations mostly depend on their type and origin, and they also contain up to 4% fluorine[89]. Seamount phosphorites contain higher concentrations of REE than continental margin phosphorites[83]. In fact, land-based phosphorite deposits also offer similar potential for metals such as REE and phosphorus which drive the exploration, mining, and extraction studies in the future. Figure 3 shows the occurrence of different marine minerals in different environments in the oceans.

EXPLORATION STUDIES, CONTROLLING AUTHORITIES, AND TECHNICAL CHALLENGES OF DEEP-SEA MINING

Over the past decade, interest in deep-sea minerals, and exploration studies have increased rapidly within both national and international waters. The International Seabed Authority (ISA), established in 1994 under the 1982 United Nations Convention on the Law of the Sea (UNCLOS), is authorized as a United Nations organization to regulate party nations to UNCLOS conducting mineral-related activities. Since 2010, the ISA which is responsible for writing the rules for mining in seabed areas beyond national jurisdictions, issued exploration study permits mostly to explore manganese nodules, seafloor massive sulfides, and ferromanganese crusts to many exploration companies across the global oceans[91]. As of December 2022, the ISA had issued 31 exploration contracts to both public and private mining enterprises for seabed mineral resources. More details are provided by Sakellariadou *et al.*[51]. The EEZ extends 200 miles from a country's shoreline and gives the country control over the exploration and exploitation of marine resources in that area. Beyond national jurisdictions, no state can claim sovereignty over the international seabed, and all resources within the areas are deemed to be the common heritage of mankind (Articles 136 and 137 of the United Nations Convention on the Law of the Sea, UNCLOS; 1982) which adequately represents the interests of developing nations in portioning out mining rights (Common Heritage of Mankind). A few private companies have collected nodules on exploratory missions in CCZ and found very encouraging results, and are pressuring the ISA to approve commercial operations. A typical area of 75,000 km^2 with an estimated nodule resource of > 200 million tons is expected to yield about 54 million tons of metals (Mn + Ni + Cu + Co)[92]. Several new exploration projects are being developed by European countries for the future exploitation of seabed mineral deposits in European Seas with very well-defined objectives such as: (i) to characterize deposit types; (ii) to identify the principal metallogenic provinces; (iii) to develop harmonized mineral maps and datasets of seabed deposits; (iv) to study present-day exploration and exploitation status in terms of regulation, legislation, environmental impacts, exploitation and future directions (https://geoera.eu/projects/mindesea2/). The concept of deep-sea mining and the process of retrieving mineral deposits from the deep seabed is explained in Figure 4.

Ferromanganese nodule mining is easy as they sit on the sediment surface whereas crusts are weakly to strongly attached to substrate rock and it is essential to collect the crust without collecting the substrate rock. Hence, technical solutions for economic mining are not yet available[93]. From an engineering standpoint, highly sophisticated and expensive mining equipment and several important breakthroughs are required for crust mining to become viable. Recently Xie *et al.*[94] designed a compact underwater vehicle for cobalt-crust mining. In addition to being a mining vehicle, this also serves as a general-purpose support vessel for sample collection, exploration, and for resource evaluation studies.

Role of miniaturized analytical instruments in deep-sea geochemical exploration

Many countries such as the US, Canada, China, Spain, the UK, Germany, and Japan have begun extensive exploration studies in search of rich ocean floor deposits by geological, geophysical, geochemical, and mineralogical approaches. In this context, it is worth mentioning the application of portable analytical instruments such as the Raman spectrometer, laser-induced breakdown spectrometer (LIBS), near IR spectrometer, and a couple of nuclear techniques in geochemical exploration studies. When these miniature

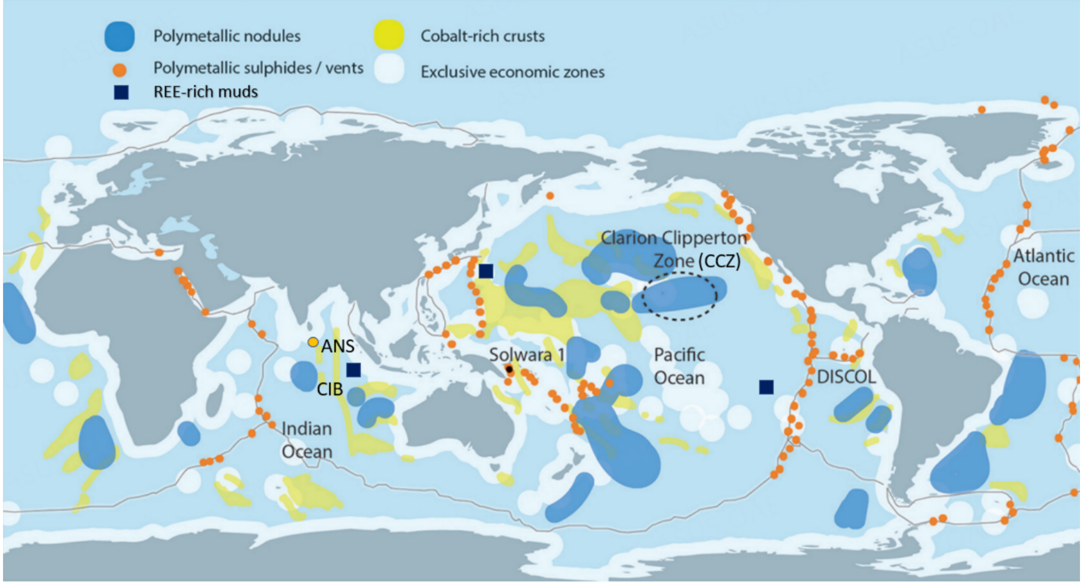
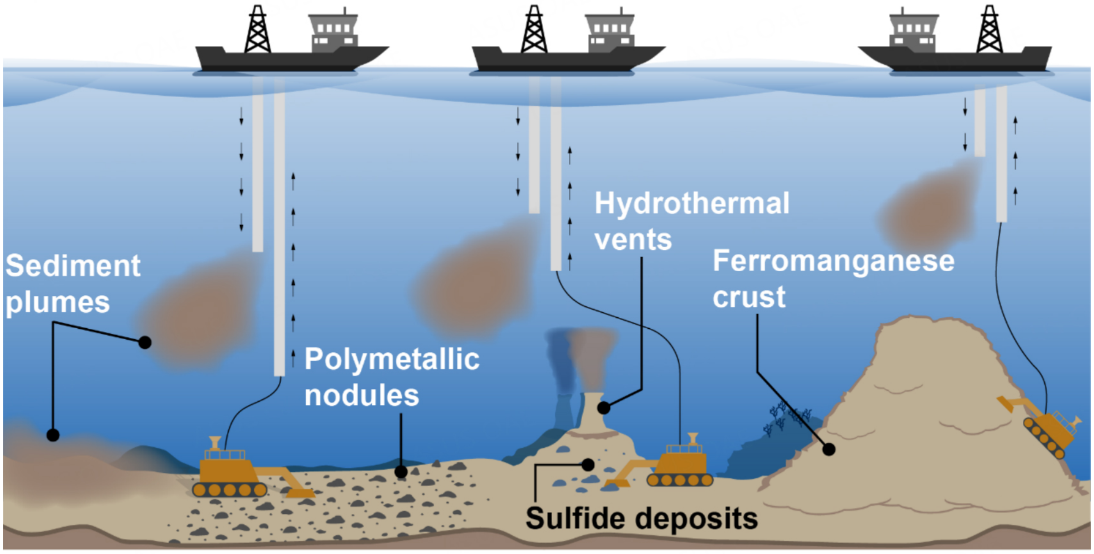


Figure 3. Global distribution of the four primary classes of metal-rich deep-ocean mineral deposits: polymetallic nodules (blue); polymetallic or seafloor massive sulfides (orange); cobalt-rich ferromanganese crusts (yellow); and REE-rich muds (dark blue). The EEZ, identified potential zones such as CCZ, Central Indian Ocean Basin (CIB), Afanasy Niktin Seamount (ANS), Papua New Guinea's first offshore mining project-Solwara 1, and the site of Seabed Disturbance and Recolonization Experiment (DISCOL) by a German project are also shown. Modified after Miller *et al.*[90].



Source: GAO analysis of peer reviewed journal articles. | GAO-22-105507

Figure 4. Concept image with examples of using remotely operated vessels (ROVs) from a vessel on the surface for the extraction of different mineral materials during deep-sea mining (with permission from GAO Science & Tech Spotlight on Deep Sea Mining, 2021).

instruments were mounted in ROV, they were successful in detecting metal-rich deposits in the deep oceans[95-97]. A new, more compact, and lighter underwater LIBS known as LIBSea II was developed for the investigation of the hydrothermal regions and polymetallic mineral areas. When the system was deployed on a ROV of Haima for deep-sea trial, atomic lines of K, Na, Ca, and strong molecular bands of CaOH from a carbonate rock sample were obtained for the first time at depths of 1,400 m[98]. Such miniature analytical systems will have great potential to be used in deep-sea exploration studies in the future.

Potential areas for deep-sea mining

Ferromanganese nodules in CCZ, Peru Basin, Penrhyn Basin-Cook Islands EEZ, and the Central Indian Ocean Basin; seafloor massive sulfide deposits in the EEZ of Papua New Guinea, Japan, and New Zealand as well as the Mid-Atlantic Ridge, and the IORS; ferromanganese crusts in the Pacific Prime Crust Zone, and the Canary Islands Seamounts and the Rio Grande Rise in the Atlantic Ocean, and the REE-rich deep-sea muds around Minamitorishima Island in the western North Pacific are the major targets of economic interest for seabed mining[51]. The development of technologies to collect manganese nodules first began in 1970. Later on, in 2021, a 25-ton robotic mining machine was developed by a Belgian company, to collect manganese nodules. In 2022, an international mining company known as The Metals Company (TMC) announced a successful deep-water test of a manganese nodule collector vehicle at depths of 2,470 meters in the Atlantic Ocean. In the same year, a study was undertaken to understand the dynamics of sediment plumes generated when a prototype seabed manganese nodule collector vehicle was used at a depth of 4,500-m in the CCZ in the Pacific Ocean. Such experiments through light on the subsequent ambient sediment plumes generated during nodule collection on the seabed, the turbidity current dynamics, and the possible environmental effects of seabed mining enable the regulatory authorities to make decisions on future seabed mining[99]. González *et al.*[100] summarized a compilation work on seabed mineral deposit types with 692 occurrences comprising 1,194 samples from different deposits such as ferromanganese crusts, manganese nodules, phosphorites, marine placer deposits, volcanogenic massive sulfides, and hydrothermal mineralization in pan-European seas based on extensive studies carried out utilizing geophysical surveys, sampling stations, underwater photography, and ROV surveys, and mineralogical, geochemical and isotopic studies. Such studies help in identifying the potential areas for responsible future resource exploration and mining, and the standards to be used.

A case study from Papua New Guinea, Pacific Ocean

Papua New Guinea's first offshore project at the international level "Deep Sea Mining of Submarine Hydrothermal Deposits - Solwara 1" was granted a 20-year license for mining the hydrothermal vents for Cu, Au, and Ag around a mile (1.6 km) below the ocean's surface (0.1 square km of the seafloor) and given to an underwater mineral exploration company known as Nautilus Minerals Inc, but failed before the extraction phase[101]. The maritime communities from the Bismarck and Solomon Seas have resisted the Nautilus Minerals Inc. experimental project since 2008 and appealed to their government to not only revoke the project but also to put a total ban on further seabed mining projects in their customary waters. The mining activity was experimental, there were no examples from anywhere in the world, and Papua New Guinea even has no regulatory framework for such activities. Moreover, environmental concerns have also been raised by these indigenous communities, suggesting that mining will cause irreversible damage, disrupt their cultural practices, and affect food sources. The company stopped its activities in 2018, and by 2019, Nautilus, the first company to ever receive a deep-sea mining license, had gone bankrupt before extracting any minerals, and the Papua New Guinea government, which had invested in the project, was left with millions of dollars in debt[102]. However, in 2022, some areas in the CCZ in the Central Pacific Ocean were licensed for mining by ISA, although several groups including Greenpeace have been very strongly opposed to deep-sea mining as it might cause irreversible damage to the marine environment.

ENVIRONMENTAL CONCERNS

Commercial mining activity in oceans can have widespread environmental consequences. For example, manganese nodules, which take millions of years to form, provide a critical habitat for an array of unique and largely understudied species, including deep-sea corals, sponges, sea urchins, starfish, jellyfish, octopus, squid, shrimp, and sea cucumbers. Deep-sea sediment plumes are created during mining activity, and the processed material that is discharged as wastewater by the surface support vessel can have devastating effects on marine biota[103]. Many anti-deep sea mining organizations like Greenpeace and several other communities are pushing for a moratorium on deep-sea mining until 2030. They argue that the available scientific knowledge is not enough to go forward. Deep-sea habitats and species are slow-growing, so a full recovery after mining could take thousands, if not millions, of years - if at all a recovery is possible. Mining of manganese nodules is predicted to lead to a significant loss of biodiversity in the marine environment[104]. Even in the earlier stages of understanding deep-sea ferromanganese nodules and their possible exploitation, several environmental studies including small-scale *in-situ* artificial disturbances were conducted[105-108]. For example, in order to monitor and understand the potential impacts on the recolonization of benthic biota by the disturbance that would be caused by commercial mining of manganese nodules, the first long-term disturbance and recolonization experiment (DISCOL) was established in the Peru Basin during a German environmental impact study associated with manganese-nodule mining in 1989 in the southeast Pacific Ocean in a circular area of the seabed measuring 10.8 km^2 at a depth of 4,140-4,160 m[109]. High-resolution optical and hydroacoustic sea floor data acquired recently indicated a remarkable difference between natural sedimentation in the deep sea, and sedimentation of a resettled sediment plume, revealing that disturbing nodules on the sea floor for commercial mining will cause long-term damage to the benthic ecosystem[110].

In order to have more insight into the deep ocean, underwater robots are being extensively used as they are capable of tracking and recording high-resolution images of slow-moving and fragile zooplankton, gelatinous animals, and particles[111,112]. Filho *et al.*[101] described the environmental risks involved in deep-sea mining, which include significant disturbance of the seabed, light, and noise pollution, the creation of plumes, and negative impacts on the surface, benthic, and meso- and bathypelagic zones. In fact, there are also mounting concerns that there will be more mining activities before environmental effects are adequately evaluated.

Efforts are underway by ISA to describe that many species are yet to be discovered and identified and to understand the structure and function of ecosystems in the deep ocean. The past decade saw a significant increase in the knowledge about biodiversity in the deep sea. In recent times at least 500 species have been collected/observed in many of the major faunal groupings, including metazoan meiofauna (~500 species), macrofauna (> 500 species), invertebrate megafauna (~630 species), and foraminifera (> 1,000 species) in the CCZ. Such knowledge underpins effective measures to protect the marine environment in the deep ocean (https://www.isa.org.jm/protection-of-the-marine-environment/).

Gollner *et al.*[103] carried out restoration experiments in manganese nodule areas in the CCZ in the Pacific Ocean to understand the biological responses to disturbance from simulated deep-sea manganese nodule mining. Earlier, the results obtained by Jones *et al.*[112], showed considerable negative biological effects of seafloor nodule mining, even at the small scale of test mining experiments. These experimental studies are expected to help in understanding the adverse long-term effects of nodule removal. EU, under an EU Horizon Europe Research Program, is developing a technology-based impact assessment tool for sustainable, transparent deep-sea mining exploration and exploitation. For example, TRIDENT Project (starting date: January 1, 2023) aims to contribute to the sustainable exploitation of seabed mineral resources, by developing a reliable, transparent, and cost-effective system for prediction and continuous environmental impact monitoring of exploration and exploitation activities in the deep sea by identifying all relevant physical, chemical, geological and biological parameters to be measured at the sea surface, mid-water, and seabed in specific areas like the Canary Island Seamounts. This project also aims to provide technological and systemic solutions for forecasting potential environmental impacts using the developed monitoring and mitigation methods (https://cordis.europa.eu/project/id/604500).

We still do not know much about the impacts of deep-sea mining. Currently, the available data on the recovery of deep-sea biota following physical disturbances from the potential mining is not enough to arrive at a firm decision. It also highlighted that there are many gaps in knowledge about deep-sea habitats and species, and how very little is known or understood about the risks of deep-sea mining. On the other hand, more than 80% of the seafloor remains unmapped at a resolution of 100 meters or better by 2019 which is expected to be completed only by 2030 if everything works favorably[113].

High seas agreement-2023

In early 2023, more than 190 countries agreed on a long-awaited pact to help safeguard the high seas, reverse biodiversity loss, and protect billions of marine species ranging from tiny plankton to giant whales from any threats such as pollution, overfishing, shipping, and deep-sea mining, at a UN conference agreeing, on a common framework for establishing new protected areas in international waters. The new treaty establishes an official mechanism for creating more marine protected areas in international waters (or "high seas") for the first time. The new agreement is the first of its kind to protect oceans since 1982 when the UNCLOS was adopted. However, it is expected to take some time for the treaty to be formally adopted by member states and come into force. Although several companies are preparing to mine the seafloor, any major disturbance to the ocean's ecosystems also reduces their ability to absorb carbon to keep climate change in check. In fact, ISA is fully committed to protecting the marine environment and regulating economic, exploratory, and scientific activity in the deep sea and is currently negotiating the approval of a mining code, laying out the rules under which companies will be allowed to extract minerals from the seabed. In view of this, deep-sea mining is likely to be exempted in certain designated relatively smaller areas such as CCZ in the near future.

CONCLUSIONS AND THE FUTURE

Currently, humanity is facing disastrous consequences and harmful effects due to climate change and global warming because of increased emissions of CO_2 into the atmosphere. During the past one hundred years, the planet has experienced a substantial increase in surface temperatures. We need to combat the increasing concentration of CO_2 by adopting green technology options which need huge supplies of several critical elements like Co, Ni, REE, Li, Pt, and Pd. However, there is a shortage of the deposits of these critical metals in the earth's crust, while selected countries like China, the US, and Australia currently have a monopoly in the mineral market. Under these circumstances, seabed mining is a viable option for several countries in the years to come. This would also decrease political tensions and controversies generated by the exploitation of critical metals[114].

However, the development of a blue economy strategy requires a better knowledge of the environmental impacts of deep-sea mining through thorough assessments and understanding. At present, the deep sea remains understudied and poorly understood, and there are many knowledge gaps in our understanding of its biodiversity and ecosystems. We need to firmly address the potential impacts on local ecosystems, biodiversity, fisheries, and social and economic dimensions before taking up deep sea mining. The deep-sea mining operations can potentially have long-lasting negative effects and even irreversible physical and environmental impacts on the deep-sea ecosystems, including biodiversity and ecosystem functioning. It is necessary to ensure that there is no significant loss of biodiversity as a result of mining operations well before any mining approvals are issued. We need to apply a precautionary approach that is considered the best path which benefits all of us.

The miniature instruments such as the Raman spectrometer and LIBS are continuously being upgraded by reducing their limitations to increase their capabilities in search of mineral deposits on the ocean beds, as well as for environmental assessment studies. It requires that new technologies have to be adopted to better understand the marine environment and protect the vulnerable areas for deep-sea mineral exploration, mining, and metal extraction. With the recent approval of the "High Seas Treaty" by more than 190 countries to protect the marine species and biodiversity in deep oceans, the mining of seabed may take a long road ahead.

DECLARATIONS

Acknowledgments

The author would like to acknowledge the support of Prakash Kumar, Director, CSIR-National Geophysical Research Institute (NGRI), Hyderabad, India. This review benefitted from a collaborative project entitled "Exploration for Cobalt-rich Seamount Ferromanganese Crusts in the Indian Ocean" with the colleagues of Geochemistry Group, NGRI; Dr. V. K. Banakar, and team, NIO, Goa, India; Dr. M. Sudhakar, NCPOR, Goa, India; and Dr. J. R. Hein. USGS, Menlo Park, California, USA, supported by the Ministry of Earth Sciences (MoES), New Delhi, a decade back.

Authors' contributions

The author contributed solely to the article.

Availability of data and materials

Not applicable.

Financial support and sponsorship

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflicts of interest

None.

Ethical approval and consent to participate

Not applicable.

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