

# Potential of deep-sea mineral resources for the blue economy

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**The interest in deep-sea mineral resources has surged recently, driven by the increasing need for metals and the global push for sustainable, low-carbon energy sources under the ‘blue economy’ framework. The deep-sea minerals include polymetallic nodules, cobalt-rich Fe–Mn crusts, and polymetallic sulphides, which contain high amounts of copper, nickel, cobalt and other valuable metals. These mineral deposits are often associated with unique and fragile ecosystems, which necessitates the development of mining technologies with minimal environmental impact. Here, we review the key deep-sea minerals, their resource potential, exploration aspects and the need for sustainable extraction, with a particular focus on India’s exploration activities.**

**Keywords:** Blue economy, deep-sea minerals, manganese nodules, mining, sulphides.

## Introduction

DEEP-sea minerals were discovered over a century ago during the *Challenger* expedition in 1873. However, in-depth studies on their origin, distribution and resource potential have commenced only recently. As our global population continues to grow and technological advancements drive the ever-increasing demand for minerals and metals, the exploration and responsible harvesting of these hidden resources have emerged as vital components of the blue economy narrative. Blue economy advocates for sustainable use of ocean resources to foster economic growth, improve livelihoods and promote environmental health. While traditional marine sectors such as fisheries and shipping have long been associated with the blue economy, the spotlight is now turning to the largely unexplored realm of deep-sea mineral resources.

The ocean hosts diverse non-living resources owing to a complex interplay of geological and biological processes. In addition to well-known occurrences of petroleum, natural gas and gas hydrates, the deep sea harbours substantial mineral resources which can be categorized into five types: polymetallic nodules, cobalt-rich Fe–Mn crusts, polymetallic sulphides, marine mud rich in rare earth elements (REEs), and marine phosphorites (Figure 1 a). These minerals, with

their elevated concentration of valuable metals like Cu, Ni, Co, Pt, Ag, Zn and REEs, are essential for manufacturing batteries, renewable energy systems and electric vehicles, thereby playing a crucial role in the development of sustainable technologies and contributing to global transition towards a low-carbon economy<sup>1</sup>. As the world grapples with challenges of climate change and seeks cleaner, greener alternatives, the significance of these minerals becomes even more pronounced.

Exploration and extraction of deep-sea minerals can drive innovation and technological advancements, stimulating economic growth and job creation in the nations actively engaged in these endeavours. Further, access to deep-sea mineral resources and their sustainable extraction ensures a consistent supply of valuable metals necessary for driving the economic growth of developing countries such as India. Beyond immediate financial gains, harnessing deep-sea minerals can reshape our understanding of mineral formation processes and sustainable resource management, and lay the foundations for a thriving blue economy.

However, mineral exploration in the deep ocean presents substantial technological hurdles. Further, a regulatory framework, such as a mining code, is yet to be established for extracting these deposits<sup>2</sup>. Moreover, the lack of understanding of potential environmental and ecological impacts of deep-sea mining has raised concerns regarding the sustainable extraction of deep-sea mineral resources as envisioned under blue economy<sup>3–5</sup>.

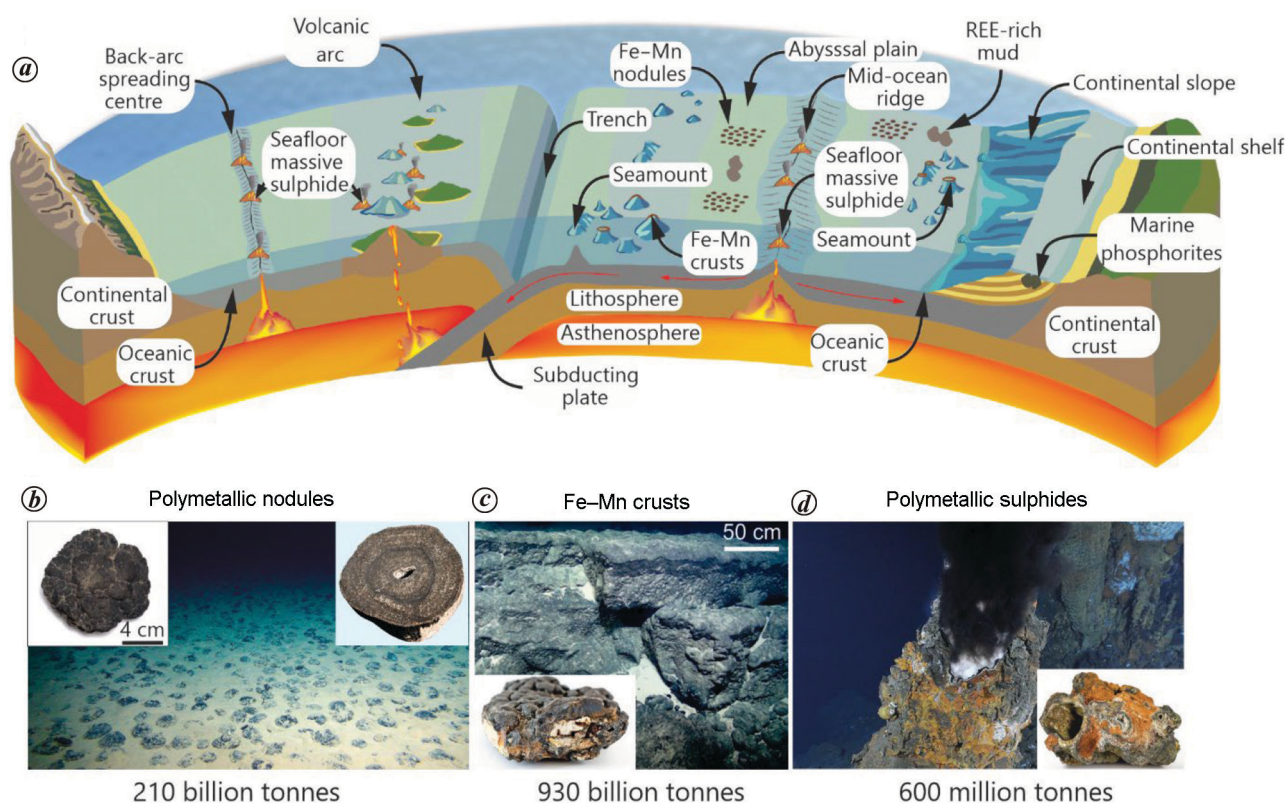
Here, we provide an overview of deep-sea minerals, particularly polymetallic nodules, cobalt-rich crusts and polymetallic sulphides, and their resource potential. These mineral deposits are the primary focus of exploration and future exploitation, and are unique in their global occurrence, formation processes, composition and geological setting. We also discuss the Indian endeavours in exploring deep-sea minerals and the need to exploit these resources with minimal impact on the deep-sea ecosystem.

## Deep-sea mineral resources

### *Polymetallic nodules*

Polymetallic nodules, often called manganese (Mn) nodules, occur on extensive abyssal plains deep below the ocean

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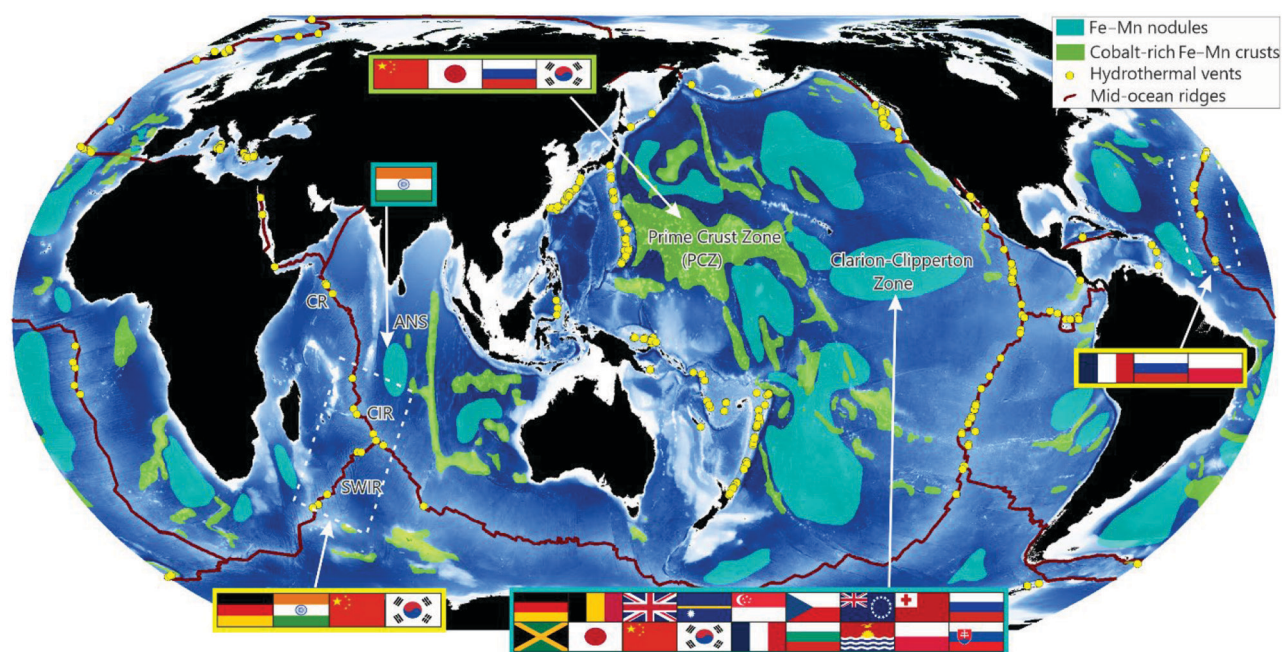
**Figure 1.** (a) Geological setting of various deep-sea minerals (modified from Lusty and Murton<sup>57</sup>). (b) Image of manganese nodules in the Clarion Clipperton Zone, Pacific Ocean (images from ROV KIEL 6000 during cruise M78/2, GEOMAR, Kiel, and Lusty and Murton<sup>57</sup>). (c) Image of cobalt-rich crust on the Tropic Seamount in the northeast Atlantic Ocean (images from Lusty and Murton<sup>57</sup> and GEOMAR, Kiel). (d) A black smoker hydrothermal vent with sulphide mineralization from the Pacific Ocean (source: GEOMAR, Kiel). The global resource estimates of various mineral deposits are also listed.

surface, typically at water depths of 3000–6000 m (Figure 1 a and b). They are mineral concretions, measuring 1–12 cm in diameter, and are composed of Mn and Fe oxides along with trace elements, such as Ni, Cu, Co, Mo, Pt, Te and REEs<sup>1,6</sup>.

Manganese nodules form in areas with very low rates of sedimentation ( $<20 \text{ mm kyr}^{-1}$ ) through a combination of processes like hydrogenetic growth, where precipitation of minerals occurs from water column and diagenetic growth, and minerals precipitate from porewater trapped in the sediments. Based on the dominating mechanism of formation, they can be found either on the seabed or partially (or completely) buried in the sediments. Typically, the precipitation of minerals occurs over time as concentric layers of Mn and Fe oxides along with other trace metals over a nucleus composed of rock fragments, shark teeth, older nodule fragments or plankton shells<sup>6</sup> (Figure 1 b). Polymetallic nodules exhibit an exceptionally slow growth rate, typically ranging from just a few millimetres to several centimetres over a million years<sup>7</sup>, influenced by various factors such as supply of materials to the sediment, sediment deposition and reworking, bottom-water currents and composition, and bioturbation<sup>8</sup>.

Nodules offer a hard substrate in abyssal plain regions for marine fauna, and higher densities of both sessile (non-moving) and mobile fauna are found living on or near manganese nodules compared to the other regions<sup>9</sup>. Nodule fields are a favoured location for certain species of sponges, molluscs and nematodes<sup>10</sup>.

Economically significant nodule accumulations have been identified in the Clarion–Clipperton Fracture Zone (CCZ) located in north-central Pacific Ocean, Peru Basin in the southeastern Pacific Ocean, Penrhyn Basin situated in the south-central Pacific, and the central area of the north Indian Ocean (Figure 2). Other notable areas of manganese nodule abundance include Phoenix, Line and Gilbert islands of Kiribati, and within the Exclusive Economic Zone (EEZ) of Tuvalu and Niue<sup>11</sup>. The CCZ region alone is estimated to contain ~21,100 million metric tonnes of nodules, yielding ~6000 million tonnes of Mn, surpassing the total known land-based reserves<sup>1,12</sup>. Likewise, Ni (270 million tonnes) and Co (44 million tonnes) contained in these nodules would far exceed the combined land-based reserves for nickel and cobalt (three and five times respectively)<sup>12</sup>. Additionally, copper content amounts to ~230 million tonnes, equating to 30% of the global land-based reserves<sup>6</sup>.



**Figure 2.** Global distribution of deep-sea minerals in the global oceans (compiled from Hein *et al.*<sup>1</sup> and InterRidge Vents Database v3.4). Also shown are the countries which hold mineral exploration licenses with International Seabed Authority (source: <https://www.isa.org.jm/exploration-contracts/>). ANS, Afanasy–Nikitin Seamount; CR, Carlsberg Ridge; CIR, Central Indian Ridge; SWIR, South West Indian Ridge.

In the central Indian Ocean basin, an estimated ~380 million tonnes of dry nodules is present with substantial amounts of nickel, copper and cobalt metal content (altogether ~9.5 million tonnes; Ministry of Earth Sciences (MoES), Government of India (GoI), press release, 21 August 2017). Most recent estimates of overall global reserves stand at 210 billion tonnes of nodules<sup>13</sup>.

### Cobalt-rich Fe–Mn crusts

Cobalt-rich ferromanganese (Fe–Mn) crusts or cobalt-rich crusts containing Mn, Fe and various trace metals, including Co, Cu, Ni and Pt, form through the precipitation of minerals from the surrounding seawater onto hardened substrate materials in the deep ocean<sup>1</sup>. They occur in areas devoid of sediments, such as the flanks of seamounts, ridges, guyots and plateaus, as layers of Mn and Fe oxides in water depths ranging from 800 to 3000 m (refs 1, 6) (Figure 1 *a* and *c*).

Cobalt-rich Fe–Mn crusts grow exceptionally slow at approximately 1–7 mm per million years and are typically 1–260 mm thick<sup>14,15</sup>. Due to their extremely slow growth rate and extensive surface area, they are capable of adsorbing a wide range of rare metals, resulting in very high concentration unparalleled in other environments<sup>15</sup>. For example, the mean cobalt concentration in Fe–Mn crusts is three to ten times higher than that found in land-based deposits<sup>15</sup>, making them highly attractive.

Seamounts that rise into the oxygen minimum zone (typically 200–1500 m below sea level) are ideal candidates

for the occurrence of cobalt-rich crusts as they furnish the essential conditions for the formation of Fe–Mn crusts, such as the presence of sediment-free hard substrates and sufficient supply of oxidizable manganese. Globally, seamounts occupy ~5% of the Earth's ocean floor and influence oceanographic currents, resulting in the upwelling phenomenon that bring nutrients to surface waters, promoting the growth of various marine organisms<sup>16</sup>.

The most promising potential for cobalt-rich crusts is found on the seamounts of central and western Pacific, called the Prime Crust Zone (PCZ)<sup>6</sup>. Additionally, Afanasy–Nikitin Seamount (ANS) in the equatorial Indian Ocean<sup>17</sup>, EEZs of Federated States of Micronesia, Republic of Kiribati, and French Polynesia are also being considered as potential sites<sup>11</sup> (Figure 2). Fe–Mn crust samples generally show very high concentration of Co and other rare metals, compared to that of nodules<sup>8</sup>. However, available data are limited on the abundance of Fe–Mn crusts. Latest global estimates indicate ~930 billion metric tonnes of Fe–Mn crusts in world oceans<sup>13</sup>. The central Pacific itself is estimated to contain a Fe–Mn crust tonnage of ~7500 million. This quantity may hold about four times more cobalt, three and a half times more yttrium and nine times more tellurium than the total reserves of these metals found on land<sup>1</sup>.

### Polymetallic sulphides

Polymetallic sulphides, or more commonly seafloor massive sulphides (SMS), form on or below the seabed by the interaction of high-temperature hydrothermal fluids with seawater



near mid-ocean ridges and rifted back-arc basins behind subduction zones (Figure 1 *a*). They are characterized by high sulphide content and are rich in valuable metals such as Cu, Au, Zn, Pb, Ba and Ag (ref. 1). Hydrothermal activity at the mid-oceanic ridges has sparked great interest since its discovery in 1977 at the Galapagos Rift due to the unique ecosystem associated with it and adjacent deposits of polymetallic sulphides<sup>18</sup>.

Hydrothermal activity is widespread at the global mid-oceanic ridges, occurring at depths of 1000–4000 m below sealevel. Generally, it entails interaction of ocean water with a heat source beneath the oceanic crust at the spreading centres. Seawater percolates through fractures and fissures in the seafloor, penetrating several kilometres below within the crust. During this process, cold seawater gets heated to temperatures exceeding 400°C and leaches minerals from the surrounding rocks. Due to its low density, this mineral-laden hot fluid ascends to the ocean floor and discharges into the water column through vents resembling chimneys. When hot fluid mingles with cold seawater, metals dissolved in the fluid precipitate, releasing from the vents as ‘smoke’, and forming a dispersing hydrothermal plume (Figure 1 *d*). Subsequently, upward-flowing plume fluids travel horizontally, depositing metals in the seafloor and producing sulphide deposits rich in metals, known as SMS deposits. The remaining metals in dissolved form are transported by ocean currents, covering distances of tens to hundreds of kilometres into the deep sea<sup>6,19</sup>.

The geological setting influences the location of hydrothermal vents and sulphide deposits, including the composition and mineralogy of hydrothermal fluids. For example, at the fast-spreading mid-ocean ridges, hydrothermal vents occur close to the axial zones of the spreading centres<sup>19</sup>, whereas at slower-spreading ridges, fluid flow can be diverted from the central axis of the ridge, resulting in the formation of sulphide deposits far away from the ridge axis<sup>20</sup>. Depending on the spreading rate, SMS deposits in the mid-ocean ridge setting are regularly spaced along the ridge. However, in back-arc settings, SMS deposits are associated with discrete volcanic centres with variable spacing due to deeper crustal controls on the magmatic activity along the plate boundaries<sup>6</sup>. The mineralogy of sulphide deposits is highly variable and is influenced by crustal host-rock composition<sup>6</sup>. For instance, some of the SMS deposits at the mid-Atlantic Ridge contain iron sulphides with no commercial value, while SMS in the southwest Pacific consists of high amounts of Cu and Zn. Sulphides sampled from the MESO field in the Indian Ocean show both Cu-rich sulphides and pyrites (Fe-rich sulphides)<sup>21</sup>.

Among over 200 known sulphide deposits, about 60% is hosted by global mid-ocean ridges, and over 50% occurs beyond national jurisdictions<sup>6</sup> (Figure 2). Most sulphide deposits are small compared to land deposits, with sizes varying between a few tonnes and <20 metric tonnes of sulphide material<sup>22,23</sup>. An extrapolation of the available SMS tonnage data from over 150 sites shows estimates of

600 million tonnes of sulphide deposits, containing around 30 million tonnes of Cu and Zn, comparable to the land deposits<sup>18</sup>.

Along with SMS, hydrothermal vent sites also support diverse and abundant communities of organisms, with a chemosynthetic bacterial ecosystem<sup>24</sup>. This ecosystem provides valuable insights into the origin of life on Earth and the possibility of extra-terrestrial life<sup>25</sup>. Around 85% of vent species is endemic to these environments<sup>24</sup>, with new vent species still being discovered<sup>26</sup>. The composition of hydrothermal vent communities is significantly shaped by geological settings, such as the type of host rock and composition of the deep crust and mantle, indicating mantle–microbe linkages.

### Exploration of deep-sea minerals

While manganese nodules on the deep seafloor were first discovered during the *HMS Challenger* expedition, it was not until the 1960s, when John L. Mero outlined the economic potential of these deposits<sup>27</sup>, that significant interest in their exploration emerged. He postulated limitless supply of manganese, copper, nickel and cobalt in ferromanganese nodules in the Pacific Ocean. This enthusiasm for polymetallic nodules subsequently increased exploration activities in the 1980s and 1990s, leading to the discovery of Fe–Mn crusts (or cobalt-rich Fe–Mn crusts) on the seafloor<sup>28</sup>.

The idea that volcanic activity might be a source of metallic deposits in the ocean was contemplated in the 19th century<sup>29</sup>. While the notion of seafloor hydrothermal activity was also hypothesized, tangible confirmation came in 1977 with the discovery of hydrothermal vents on the Galapagos Rift seafloor<sup>30</sup>. Subsequent observations of additional hydrothermal vents and actively forming sulphide deposits were made on the East Pacific Rise<sup>31</sup>. The recognition that these deposits represented modern counterparts to massive sulphide deposits on land sparked a surge in deep-sea exploration activities.

Increased exploration activities and potential for future exploitation led to tangible changes in the governance of the deep sea, since majority of the identified deep-sea mineral deposits fall outside national jurisdictions (Figure 2). Under the United Nations Convention on Law of the Sea (UNCLOS), the International Seabed Authority (ISA) was established in 1994 to organize and control all activities in the oceans beyond national jurisdictions, commonly referred to as the ‘Area’. Its primary mission is to administer resources in the Area on behalf of States Parties. A key responsibility of ISA is to establish guidelines for assessing and monitoring environmental risks associated with prospecting, exploration and exploitation of mineral resources in the Area to prevent or mitigate environmental harm.

ISA awards exploration contracts for deep-sea minerals in the Area, which gives a contractor the right to investigate mineral resources within specified seabed areas for

15 years. In addition, the contractor is also obliged to conduct extensive environmental data collection and evaluate the potential impact of mining activities. So far, ISA has approved 31 exploration contracts, which include 19 for polymetallic nodules, 7 for polymetallic sulphides and 5 for cobalt-rich crusts (Figure 2) (<https://www.isa.org.jm/exploration-contracts/>).

### Indian endeavours in deep-sea mineral exploration

India, with an extensive coastline, has been actively promoting blue economy as a key driver for sustainable development. The Blue Economy Policy aims to boost the contribution of blue economy to India's GDP, which stands at ~4% in 2023. To that extent, GoI has launched the 'Deep Ocean Mission' programme in 2021, aiming to explore and harness the resources of the deep ocean. Exploration of deep-sea minerals and developing technologies for their extraction are key elements of the programme, as it presents a promising source of critical minerals essential for advanced technologies, including those integral to India's burgeoning renewable energy sector. Apart from ensuring a stable supply of critical metals for a low-carbon economy, the innovation and technological advancements associated with extracting deep-sea minerals will have spill-over effects in other fields, benefitting society. An overview of historical and current efforts by India in the exploration of deep-sea minerals is given below.

#### *Polymetallic nodules*

India achieved a significant milestone in oceanic research on 26 January 1981, when the first polymetallic nodule was retrieved from the depths of the sea floor by the research vessel *Gaveshani*. This discovery marked the inception of the ambitious polymetallic nodules (PMN) programme in the country, an initiative to unlock the mysteries of the Central Indian Ocean Basin (CIOB).

India's active involvement in the formulation of UNCLOS paved the way for its crucial role in investigating these underwater resources. In April 1982, the country was recognized as a pioneer investor in this venture by the United Nations and received an allocation of pioneer area spanning 150,000 km<sup>2</sup> in CIOB. The UN Preparatory Commission had registered seven pioneer investors: China, France, India, Japan, the Republic of Korea and Russia, as well as a consortium known as the Interoceanmetal Joint Organization (IOM encompassing Bulgaria, Cuba, the Czech Republic, Poland, Slovakia and Russia).

In 2002, India signed a contract with ISA for nodule exploration in CIOB, spanning 15 years. Under the aegis of MoES, GoI, extensive exploration efforts were conducted within CIOB and the CSIR-National Institute of Oceanography (CSIR-NIO), Goa, was tasked with identifying potential

regions for nodule occurrence in both pioneer and allocated areas. This involved collecting samples at approximately 11,000 locations in CIOB, encompassing around 72 expeditions<sup>32</sup>.

In compliance with the UNCLOS regulatory framework, a phased relinquishment was implemented, leading to a 50% reduction in the initially allocated area, which covered 150,000 km<sup>2</sup>, to finally have a retained area of 75,000 km<sup>2</sup> within CIOB<sup>33</sup>. A significant milestone during this period was the identification of a first generation mine site (FGM) within this retained area. This retained area is estimated to hold substantial metal resources of ~9.5 million metric tonnes (Cu (~4.5), Ni (~4.5) and Co (~0.5))<sup>32</sup> (MoES, GoI, press release, 21 August 2017), which equates to INR ~110 lakh crores in current market prices. Upon completion of the contract period, MoES, GoI, and ISA extended the agreement for an additional five years, until March 2022 and a further five years until 2027. The next goal is to pinpoint the most promising area within the retained area, which will serve as the core of FGM for nodules in CIOB.

To ensure environmental sustainability of nodule exploration and extraction, India prepared an environmental impact statement (EIS) in January 2020 to assess the ecological conditions and potential impacts at the Indian PMN site within CIOB. The environmental impact experiment, which included simulated PMN mining and subsequent monitoring of disturbed deep-sea benthic habitats after 44 months, showed that recovery of the disturbed benthic environment, especially the biological species, was slow and may take several decades to restore the physically disturbed benthic habitats and biodiversity<sup>34,35</sup>.

#### *Polymetallic sulphides*

India's exploration of seafloor hydrothermal activity along the Indian Ocean ridges traces back to 1983 when the GEMINO (geothermal metallogenesis Indian Ocean) programme, a collaborative Indo-German initiative, was launched on-board the research vessel *RV SONNE*. This programme aimed to locate hydrothermal activity and involved Indian scientists<sup>36</sup>. The investigations and findings revealed inactive and active hydrothermal systems within the Central Indian Ridge (CIR) and South West Indian Ridge (SWIR). Following these discoveries, India initiated an extensive research and exploration programme. While preliminary efforts commenced in 1985–86, significant advances occurred in 2002 when CSIR-NIO started high-resolution geophysical mapping of the Carlsberg Ridge and the northern segments of CIR. Bathymetric and water column data collected over Carlsberg Ridge and CIR led to the revelation of hydrothermal plume signatures within the region<sup>37,38</sup>. Autonomous underwater vehicle (AUV) investigations also played a pivotal role<sup>39</sup>.

In 2011, MoES, GoI, entrusted National Centre for Polar and Ocean Research (NCPOR) to lead the hydrothermal exploration programme. Preliminary bathymetric surveys

and exploratory endeavours conducted over southern CIR and SWIR segments, particularly in proximity to the Rodriguez Triple Junction, suggested potential areas of hydrothermal activity in the region. These results paved the way for India to seek approval from ISA for exploration activities within a designated 10,000 km<sup>2</sup> area May 2013. In July 2014, ISA approved India's proposed plan of work and subsequently, on 26 September 2016, the country signed an agreement with ISA for a 15-year exploration programme within the area. This agreement aims to identify potential hydrothermal mineralization zones and comprehensively addresses the intricate interplay of physical, chemical, biological and geological factors within hydrothermal systems, thereby enhancing our understanding of their genesis, environmental factors, and the distribution of hydrothermal plumes and mineralization in the region<sup>40</sup>. After signing the agreement, multi-disciplinary surveys conducted over CIR and SWIR have shown evidence for active hydrothermal venting in the southern CIR region<sup>41</sup>. Exploratory surveys are ongoing to verify and evaluate the resource potential of sulphide deposits in the region.

### *Cobalt-rich Fe–Mn crusts*

In 1994, CSIR-NIO conducted the first sampling of cobalt-enriched Fe–Mn crusts from ANS during an expedition aboard *R/V Sidorenko*<sup>42</sup>. The ANS, located at 3°S lat. and 83°E long. in the Indian Ocean, was discovered during the *R/V Vityaz* cruise of 1959 (ref. 43). This massive structural feature spans approximately 400 km in length and 150 km in width, located at the southern extremity of the 85°E Ridge, and may have evolved during the Late Cretaceous<sup>44–46</sup>. CSIR-NIO, under the aegis of MoES, GoI, initiated a project in 2003 to explore seamounts within the equatorial and northern regions of the Indian Ocean to investigate Co-enriched Fe–Mn crusts. CSIR-National Geophysical Research Institute (NGRI) and NCPOR were the other participants in this project. High-resolution multibeam bathymetric survey of the ANS region revealed the presence of five seamounts in the northern ANS at depths ranging from 1.7 to 3 km, each characterized by Fe–Mn crust cappings with areas measuring 272, 32, 46, 1297 and 184 km<sup>2</sup> respectively, cumulatively encompassing a surface area of 1831 km<sup>2</sup>. Bathymetric surveys conducted in the ANS region provided valuable insights and unveiled clusters of seamounts at depths ranging from 1.7 to 3 km featuring Fe–Mn crusts. Subsequent sampling and analysis of these crusts revealed high concentration of cobalt, reaching up to 0.9%. The ANS deposits exhibited notably high Ce concentrations, reaching up to 0.37%, with an average of around 0.22%, making them one of the most Ce-enriched oceanic ferromanganese deposits discovered to date<sup>47</sup>. Additionally, REEs in these crust samples ranged from 1482 to 2310 µg/g, comparatively higher than those found in the mid-Pacific seamount nodules (1180–1434 µg/g)<sup>17</sup>. Fur-

ther geological sampling and analysis are required to evaluate the resource potential of cobalt-rich Fe–Mn crusts in the ANS region.

Exploration efforts have extended to other regions within India's EEZ<sup>48</sup>, including the Lakshadweep Sea and the Andaman Sea, where the Geological Survey of India documented the recovery of Mn crusts<sup>49</sup>. Furthermore, several other seamounts have been uncovered within the Indian Ocean region in the Andaman Sea, including the cratered seamount and the southern seamount<sup>50–52</sup>. These discoveries hold particular significance for India, given the country's lack of known cobalt and tellurium resources. It underscores the importance of identifying potential deposits within the Indian EEZ and international waters.

### **Need for sustainable extraction of deep-sea minerals**

The exploration and potential extraction of deep-sea minerals have opened new frontiers in resource development, promising economic growth and technological progress. However, developing sustainable practices for deep-sea mineral extraction is imperative to mitigate adverse impacts on delicate and largely unexplored deep-sea ecosystems. Deep-sea mining involves the extraction and, in many cases, excavation of mineral deposits from the seabed at depths greater than 200 m. The deep seabed covers about two-thirds of the ocean floor, and is vital to marine biodiversity and ecosystems. The biota associated with specific mineral deposits is unique and often exclusive to particular ecosystems, such as active hydrothermal vents, cold seeps and seamounts.

Some critical environmental and ecological impacts of deep-sea mining include habitat destruction, biodiversity loss, sediment plumes, noise, light, chemical pollution and slow recovery rates. Polymetallic nodules, for example, provide critical hard substrate for marine species in the deep ocean, and their removal can result in significant habitat loss<sup>9,53,54</sup>. Simulated polymetallic nodule mining experiments conducted in the Pacific Ocean<sup>55</sup> (CCZ) and in the Indian Ocean<sup>34</sup> (CIOB) showed severe damage to biological communities present on the seabed<sup>56</sup>.

Given the unexplored nature of many deep-sea areas, accurately predicting the potential impacts of mining is challenging. Acquisition of comprehensive environmental data and understanding deep-sea ecosystems is equally challenging, yet indispensable for effective mitigation and regulation. Moreover, these efforts may play a crucial role in the development of sustainable technologies for mineral extraction.

While exploration and exploitation of deep-sea mineral resources offer economic and technological opportunities, it is essential to prioritize sustainability, responsible governance and environmental conservation. A balanced and inclusive approach involving international collaboration and

robust regulations is necessary to ensure that the blue economy benefits society without causing irreversible harm to the delicate ocean ecosystem.

### Summary and future outlook

The depletion of terrestrial resources is compelling humanity to turn its attention towards the vast reserves of the seabed to meet its unending demands for a wide range of natural resources, particularly deep-sea minerals. Polymetallic nodules, cobalt-rich Fe–Mn crusts and polymetallic sulphides represent such vast resources, and their potential extraction could significantly contribute to the blue economy.

However, exploration and extraction of deep-sea minerals can introduce significant environmental and ecological threats to the fragile and largely unexplored ecosystems of the deep ocean. Striking a balance between the economic advantages of mining and safeguarding the distinctive habitats and species gives rise to a multifaceted ethical and environmental quandary, necessitating thoughtful evaluation, comprehensive research and global collaboration. Despite the concerns, there is growing interest in deep-sea mining, driven primarily by the depletion of land deposits of some strategic and battery metals such as copper, nickel, aluminium, manganese, zinc, lithium and cobalt. In addition, the demand for these metals is increasing, mainly to support the production of low-carbon and renewable technologies such as wind turbines, solar panels and power-storing batteries. The technologies developed for the extraction of deep-sea minerals, therefore, have to be environmentally acceptable, causing minimal disturbance and protecting ecologically sensitive habitats.

Under UNCLOS, the deep sea is often considered a common heritage of humankind. Establishing sustainable mining practices and implementing rigorous environmental regulations are imperative to preserve that heritage and guarantee the well-being of our oceans.

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