9

Seabed-Mining Technology and the Precautionary Approach

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9.1 INTRODUCTION

The issue of deep-seabed mining has lately evoked polarized positions, which is no surprise given that the history of seabed mining was also rife with contrasting positions during negotiations for the United Nations Convention on the Law of the Sea (UNCLOS).[1] At the Law of the Sea Conferences, the lack of information on technological developments and pressures for the reallocation of resources were foremost among the factors influencing the negotiations. Today, the specter of seabed mining evokes a different sense of polarization along the lines of environmental protection. Before we delve further into the details of the negotiation and technologies, it is essential to orient understanding about the minerals and their locations to better contextualize the issue.

From a geological perspective, the seabed can be classified into three areas: (1) the continental shelf where the depths are less than 200 m; (2) the continental slope indicating the transition from shallow waters to the deep sea; and (3) abyssal plains, which are generally vast areas at depths of 4,000 m. From a zonal perspective, deep-seabed mining takes place in areas beyond national jurisdiction and includes the seabed and ocean floor and subsoil thereof, often categorized as the "Area" (UNCLOS, Article 1(1)(1)). Within the Area, what captured the imagination of the negotiators and holds the most interest are resources, which include all solid, liquid, or gaseous mineral resources in situ or beneath the seabed, including polymetallic nodules (UNCLOS, Article 133(a)).

Subsequently, as deep-sea exploration evolved, polymetallic sulfides and cobalt-rich ferromanganese crusts were discovered within the diverse geography of the Area. To summarize their locations, polymetallic nodules – which by current estimates are in abundance – are found in the abyssal plains; polymetallic sulfides are found near hydrothermal vents; and the cobalt-rich ferromanganese crusts are

[1] UNCLOS, December 10, 1982, 1833 UNTS 397.

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found on seamounts. All are formed due to highly specialized and prolonged geological processes. Each of these complex polymetallic ores contains a rich chemistry of minerals – such as copper, manganese, cobalt, zinc, nickel, platinum, and rare earth elements – and is often found in grades higher compared to land-based sources (ISA 2021).[2] As to the scale of resources, mining across 4.5 million square kilometers of the Clarion-Clipperton Zone – an area encompassing 1.5 percent of the world's abyssal plains – could yield approximately 34 billion wet metric tons of nodules containing 6 billion tons of manganese, 270 million tons of nickel, 234 million tons of copper, and 46 million tons of cobalt (ISA 2021).

However, today the discourses on seabed mining are polarized, given its potential impact on the marine environment. For instance, seabed mining in the Clarion-Clipperton Zone would create sediment plumes and noise pollution across an area three times larger, affecting the entire 4,500-m water column and impacting around 6,000,000 cubic kilometers of the ocean (Amon et al. 2022). Paradoxically, the minerals outlined above are also serendipitously essential for the green transition, and the rising demand for green technologies is expected to drive demands for these minerals further, with projections suggesting that the demand for cobalt could increase by 460 percent, nickel by 99 percent, and rare earth elements by 37 percent by 2050 (Herrington 2021).

This highlights the paradox of mitigating climate change through the adoption of green technologies and the reduction of environmental damage that could result from seabed mining. It underscores the critical need for a balanced approach, one that weighs the need for resource extraction against the imperative to protect deep-sea ecosystems. The questions this chapter asks are these: What is the technology necessary, and being developed, to undertake seabed mining with an application of the precautionary approach? What are the legal and regulatory dimensions governing the development and use of technology? The chapter explores the state of seabed-mining technology at the time of the UNCLOS negotiations and its evolution to the present. However, the chapter does not delve into discussions of thresholds and acceptable-harm parameters, as these are currently ongoing at the International Seabed Authority (ISA).

In the following sections, the chapter will explore how such a balance might be achieved, at least within the technology and regulatory framework that could reconcile these competing demands. Since technology is the pivotal factor in achieving a balance between resource extraction and environmental protection, the chapter will investigate the scope of seabed-mining technology within the framework of international law. Section 9.2 will deconstruct the negotiating history of the seabed-mining regime through the lens of technology. Section 9.3 will develop the precautionary approach, which was in the early stages of development

[2] For polymetallic sulfides, polymetallic nodules, and cobalt-rich ferromanganese crusts respectively, see ISA (2021, 34, 42, 50).

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at the time of negotiations, and its influence on seabed-mining technology, including measures concerning technology. Section 9.4 will outline the different seabed-mining systems and subsystems currently in development and their impacts on the proximate environments. In conclusion, Section 9.5 will assess the challenges associated with the interface of technology with the precautionary approach.

9.2 SEABED-MINING TECHNOLOGY THROUGH THE NEGOTIATIONS OF UNCLOS

Concerns surrounding seabed-mining technology consistently remained a thematic discussion within the ambit of negotiations for UNCLOS. Interest in its economic potential considerably grew in the 1960s, when John L. Mero described the potential wealth of the ocean in the form of polymetallic nodules. However, the early stages of the negotiations had a pervading sense of uncertainty, owing to the lack of foreseeability or the lack of information about technological developments (Buderi and Caron 1985, 88–95). The deep-seabed-mining technology had received a disproportionate amount of attention among all marine technologies and was strongly politicized in the "North–South" conflict as the symbol of technology gap between the developed and developing States (Boczek 1982, 5). Further, several factors, such as the common heritage principle or the New International Economic Order, interceded the development of the negotiations and influenced the regulatory approaches to seabed technology.

9.2.1 *The Proposal by Arvid Pardo on the Common Heritage of Mankind and the Ad Hoc Seabed Committee*

In 1967, Arvid Pardo, the Maltese Ambassador to the United Nations, made an impassioned plea to the twenty-second General Assembly to address the risk of inequity emerging from the advanced technological capabilities of developed States to explore and exploit the seabed and prevent its national appropriation (UNGA 1967b, paras. 46–55, 1967c). While many assumptions embedded within his speech lacked proportion in the perceptions surrounding the mining of seabed minerals, his plea succeeded in achieving two critical objectives: the nonmilitarization of the seabed (UNGA 1967b, paras. 46–55; Schmidt 1989, 22–25), and the elucidation of the common heritage of mankind (UNGA 1967c, paras. 8–10; Li 1994) approach, capturing the imagination of the developing world as a principled means of accessing this mineral wealth. To this end, it was proposed that an international body be created that would balance the security and economic needs of States and ensure that the activities in the Area would conform to the proposed treaty (UNGA 1967c, paras. 8–10; Akaha 1985, 60).

Pardo's plea succeeded in drawing the focus of the delegates on the risks and opportunities the seabed offered, and led to the creation of the Ad Hoc Seabed

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Committee in 1967 (UNGA 1967a). The deliberations of the Ad Hoc Seabed Committee culminated in four resolutions (UNGA 1968). These resolutions created the Committee on the Peaceful Uses of the Sea-Bed and the Ocean Floor beyond the Limits of National Jurisdiction (Seabed Committee) to study, inter alia, the ways and means to promote the exploitation and use of resources through international cooperation on the foreseeable development of technology through international machinery while also studying the harmful effects of such exploitation activities on the seabed, water column, and adjacent coasts (UNGA 1968, A, para. 2(b)).

9.2.2 *The Seabed Committee, Moratorium Resolution, and 1970 Declaration of Principles*

At the Ad Hoc Seabed Committee, the divergences in approach to the modalities of participation in the future seabed-mining industry had become clearer. On the one hand, the developing countries articulated their proposal with international cooperation and share in the benefits accruing from the progress of modern science and technology as the centerpiece of their demands (UNGA 1969a). The developed countries forwarded a dispassionate proposition whereby "no nation, regardless ... of their technological capability should be denied the opportunity to participate in the exploitation of the seabed" (UNGA 1969a, Annex, 3). Overall, the proposals for the Declaration of Principles articulated the need for making the technology to access the resources of the seabed available to developing States (UNGA 1969a, Annex, 1, 7, 12). Against this backdrop, the Seabed Committee was created with the mandate to elaborate the legal principles; the ways and means of promoting the exploitation of resources, including technological aspects; and the economic implications of such activities (UNGA 1968, B).

Some of the key achievements of the Seabed Committee include the 1969 Moratorium Resolution (UNGA 1969b) and the 1970 Declaration of Principles (UNGA 1970a). The Moratorium Resolution was passed on the initiative of the developing States, which feared a "grab" of the seabed resources before much agreement could be achieved, and simply declared that "States and persons, physical or juridical, are bound to refrain from all activities of exploitation of the resources of the area" (UNGA 1969b). Several developed States objected to the Moratorium Resolution and voted against it, as they feared that it would stifle the technological development necessary for the extraction of resources from the international area (Li 1994, 25).

The Declaration of Principles emerging from the compromises in the Seabed Committee reflected a delicate balance between the developing and developed States (Li 1994, 27). It became the cornerstone for the development of a new international seabed regime (UNGA 1970d, 12). The Declaration also recognized that the seabed resources required the articulation of rules different from the customary rules applicable to the living resources of the high seas (UNGA 1970a,

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para. 4, preamble para. 3). On seabed-mining technology, divergences remained, with the developing States stressing that States without advanced technology should be involved in, and benefit from, seabed mining (UNGA 1970c), and the developed States favoring nondiscriminatory access to the seabed. Given these divergences, the Seabed Committee could only articulate cooperation on the technical and technological aspects, limited to participation in international cooperation programs for scientific research; the publication and dissemination of research; and strengthening research programs through participation as tenets for the transfer of seabed-mining technology (UNGA 1970a, para. 10(a)–(c)).

It was already realized that the monetary benefits drawn from the mineral resources of the seabed were overstated, and most developing States had a limited interest in gaining access to Western technology and to having their experts trained under an international regime (Anand 1975, 249–250). This Declaration of Principles later proved to be critical, as it found greater resonance after the negotiation culminated at the Third Law of the Sea Conference, and it became clear that provisions related to access to technology could not be implemented in spirit without the cooperation of the developed States. These principles later served as guidance for the conclusion of an international agreement that would regulate activities and implement select obligations with respect to the deep-seabed areas.

9.2.3 *Transfer of Technology in UNCLOS Annex III and the 1994 Implementation Agreement*

The Third Law of the Sea Conference bifurcated the discussion on marine technology across general provisions concerning other marine technology, which was deliberated within Sub-Committee III of the Seabed Committee, becoming Part XIV of UNCLOS. Specific provisions concerning seabed-mining technology fall under the broader theme of the legal regime for the seabed and the ocean floor beyond national jurisdiction and were incorporated into part of Annex III under the basic conditions of prospecting, exploration, and exploitation. These provisions had become a symbol of the North–South controversy and had warranted separate treatment within the negotiations, primarily due to the inextricable link to the questions related to access to the Area (Boczek 1982, 34).

Part XIV of UNCLOS reflects the aspirations of the States to facilitate access to and acquisition of marine technology, including seabed-mining technology for developing States. These provisions broadly appear in three parts: (1) Article 144, outlining the general obligations of the ISA; (2) Articles 273 and 274, outlining the role of the ISA; and (3) Article 5 of Annex III, consisting of detailed obligations for the transfer of technology (TOT) to the Enterprise (discussed below) and developing States. However, the overreaching postulates on TOT proved untenable, leading to some provisions, particularly Article 5 of Annex III, being subsequently abridged

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through the 1994 Agreement relating to the Implementation of Part XI of UNCLOS (1994 Agreement).[3]

The Seabed Committee had three subcommittees, with Sub-Committee I entrusted with the responsibility for preparing the draft provisions concerning the legal regime of deep-seabed mining. Sub-Committee I discussed TOT with the awareness that such provisions would reflect the progressive development of the law of the sea to be facilitated through international machinery (UNGA 1970b). It was also understood that the scope of such TOT was limited to the contours of "activities in the Area" – that is, the exploration and exploitation of seabed minerals in the Area. The underlying consciousness of TOT was inspired by the call for a New International Economic Order (NIEO; UNGA 1974). The NIEO recognized the entrenched sense of inequity among developing States and called for the development of an international order with embedded principles advancing the balanced development of the international community. A key component of such imbalance was articulated in the form of inequitable access to technological progress, with the NIEO promoting TOT to address this issue (UNGA 1974, para. 4(p)). The emergence of the NIEO and the principles embedded within it led to the development of certain progressive policy objectives within UNCLOS that mirrored those principles and called for increased equity in the development of the seabed-mining regime (UNCLOS, Article 150).

Overall, the developing States were driven by a threefold objective on TOT: (1) guaranteed access to seabed-mining technology; (2) just and reasonable terms and conditions; and (3) improved domestic capabilities, including the training of personnel (Li 1994, 146–149). These principles were later integrated into what became Article 144 of UNCLOS. The key point of difference that existed between the developing and the industrialized States on TOT was perhaps ideological, particularly as technology owned by contractors (private corporations or companies), in view of the developed States, was private property and government interference was not warranted (Boczek 1982, 11).

These divergences manifested more sharply through the negotiations, resulting in the developing States, led by the Group of 77, making ambitious proposals concerning TOT. These proposals centered around strong international machinery (by now, there was agreement that the machinery would be the ISA) acting as a repository from which TOT would be facilitated (Platzöder 1990, vol. XI, 230). The developing States also called for the creation of a dedicated fund to effectuate TOT (UNCLOS III 1975, 198–199) and for the establishment of international centers to provide information on technological markets and to help developing countries reduce the total cost of transferring technology (UNGA 1973, 82). These attempts received limited success in that they succeeded in allocating to the ISA the responsibility for

[3] Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of December 10, 1982, July 28, 1994, 1836 UNTS 3.

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facilitating such transfers, and by the mid-1970s, the negotiations had led to the inclusion of Articles 273 and 274 in the Convention.

As negotiations progressed, the 1976 session became a major turning point in the deliberations of the First Committee (Platzöder 1990, vol. VI, 83). As the concerns of the developed States found more accommodation, the TOT obligations of the contractors were weakened, and with the ISA at the center, the seabed-mining regime was redesigned toward a parallel system (UNCLOS III 1976). This led to the conceptualization of the Enterprise, a commercial arm of the ISA that would conduct mining alongside national enterprises or contractors, with industrialized States transferring technology to the Enterprise. It was expected that the Enterprise would obtain technology through the establishment of joint ventures or other forms of contractual agreements with contractors (Li 1994, 170).

With the parallel system in place, the issue of TOT to the Enterprise took center-stage in the First Committee at the Third Law of the Sea Conference. This concession on the part of the developing States led to the framing of the TOT provisions in mandatory terms, with multiple proposals emerging. Most notably, the "Brazil Clause" espoused the TOT from seabed-mining contractors to the Enterprise and to those developing States that secured licenses to mine in the reserved areas with a condition of nontransfer to other developed States (Juda 1979, 236). Another formulation mandated that contractors share the general description of the technology and equipment with the ISA, including subsequent changes and innovations (Juda 1979, 237). Overall both sides succeeded in including provisions favoring their interests, but both were also left dissatisfied with the text. The developed States expressed objections to the inclusion of TOT as a precondition for obtaining a mining contract by the contractors, while the developing States maintained that mandatory TOT was not sufficiently reflected in texts (Boczek 1982, 37–38).

When the Reagan administration took office in the United States in 1981, the new government immediately embarked on a major policy review of the draft Convention. As far as the TOT provisions were concerned, three features were considered unacceptable: (1) the compulsory sale of proprietary information and technology that American companies largely control; (2) guaranteed access for the Enterprise to the privately owned seabed-mining technology and also to the technology used by operators but owned by third parties; and (3) the guarantee that any developing country could have the same access to technology as the Enterprise (Reagan 1982a, 1982b; Schmidt 1989, 22–25). This change of policy led to several amendments to the TOT obligations being proposed by the developed States; however, the Group of 77 was not willing to reopen the negotiations at that stage. Therefore, Article 5 of Annex III was completed without further change.

After the Third Law of the Sea Conference, the final text of the proposed UNCLOS received a lukewarm reception from developed States as aspects of

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seabed-mining provisions remained overreaching (UNGA 1994, paras. 1–28). Since the adoption of UNCLOS, there have been significant political and economic changes that have had a marked effect on the regime for deep-seabed mining. There was a discernible shift toward a more market-oriented economy. Thus began a series of informal consultations under the aegis of the UN Secretary General on outstanding issues relating to the deep-seabed-mining provisions of UNCLOS. These informal consultations took place in 1990–94, culminating in the 1994 Agreement. The provisions concerning TOT were thereafter abridged. Section 5 of the Annex to the 1994 Agreement straightforwardly indicates that Article 5 of Annex III of UNCLOS will not apply. It provides that TOT will be governed by Article 144 of UNCLOS. The reach of the principles in Section 5 of the Annex of the 1994 Agreement can be interpreted as an attempt to facilitate access for the Enterprise and developing countries to the required technology on fair and reasonable commercial terms and conditions. However, these principles were implemented not through strict obligations on contractors but through cooperation and by following the principles of the market economy.

There was a growing consciousness in the 1990s of the anthropogenic effect on the environment, which led to a discernible shift in the discourse concerning the duty of the ISA and State parties to promote the advancement and transfer of technology with a view to protecting the marine environment and to apply the best available technology or environmentally sound technologies (UN 1992, 34.1, 34.3), although the transfer of such technology for deep-seabed mining did not attract sufficient attention during the Third Law of the Sea Conference.[4] It was understood that there would be rising concern regarding the environmental impact of seabed mining and with assurance that technology does minimal harm to the environment, through both greater scientific knowledge and the transfer of modern technology (Li 1994, 44). This line of argumentation further added to the call for the duty of States and the ISA to help the Enterprise and developing States to access and acquire relevant technology. In this connection, it is worth mentioning the emerging legal principles based on the need for pursuing sustainable development through the operationalization of due-diligence obligations and the precautionary approach.

[4] In the Third Committee, some delegates from developing countries linked the issue of TOT to the protection of the marine environment. For instance, the Iraqi representative stated that "making the best use of the seas meant preserving the marine environment, controlling pollution from all sources and controlling the exploitation of marine biological and non-biological resources. That called for efforts by every country, separately or through international organizations, to develop marine technology and facilitate its transfer to countries that needed it, especially the developing countries" (UNCLOS III 1975, 101). The Kenyan representative pointed out that developed countries had the duty to transfer technology "in order to ensure the proper utilization of resources and the protection of the marine environment" (103).

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9.3 THE PRECAUTIONARY APPROACH AND THE CURRENT DEBATE

Contemporaneous to the negotiations for UNCLOS, the environmental regime had been evolving simultaneously with some pivotal occasions, such as the 1972 Stockholm Declaration (UN 1972) and the enunciation of the 1992 Rio Principles (UNGA 1992). Those instruments served as the early foundations for the development of an environmental lens for existing and future human activities. They aim to strike a balance between the human yearning for development and economic growth, the imperatives of environmental protection, and the rational management of resources. In this regard, rational planning has been identified as an essential tool for reconciling conflict between the needs of development and the need to protect and improve the environment (UNGA 1992, Principle 14). And, to this end, States must adopt integrated and coordinated approaches to the development of resources so as to ensure compatibility with the protection of the environment (UNGA 1992, Principle 13). The tribunal in the *Ijzeren Rijn Railway* arbitration on the issue of the integration of the protection of the environment to development activities articulated the evolving jurisprudence as reconciliatory when it opined:

> Environmental law and the law on development stand not as alternatives but as mutually reinforcing, integral concepts, which require that where development may cause significant harm to the environment there is a duty to prevent, or at least mitigate, such harm.[5]

The International Court of Justice has reconciled these two elements as follows:

> New norms have to be taken into consideration, and . . . new standards given proper weight, not only when States contemplate new activities but also when continuing with activities begun in the past.[6]

This understanding is embedded within the seabed-mining regime as a key policy imperative for "the orderly, safe and rational management of the resources of the Area, including the efficient conduct of activities in the Area and, in accordance with sound principles of conservation" (UNCLOS, Article 150(b)).

Evolving from this discourse on environmental management, the Rio Principles espouse the precautionary approach, which "shall be widely applied by States according to their capabilities," so that where there are "threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UNGA 1992, Principle 15). The precautionary approach raises critical questions related to

[5] *Iron Rhine ("Ijzeren Rijn") Railway between the Kingdom of Belgium and the Kingdom of the Netherlands*, Award (Perm. Ct. Arb. 2005), 27 RIAA 35, para. 59.

[6] *Gabčíkovo-Nagymaros (Hungary/Slovakia)*, Judgment, 1997 ICJ Rep. 7, para. 140 (September 25).

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the viability and feasibility of seabed mining. The uncertainties surrounding the effects of seabed mining on the marine environment have led to calls for a precautionary pause or moratorium. However, a precautionary approach applies in the context of scientific uncertainty and in accordance with the capacities of States. Subsection 9.3.1 will explore best available techniques as a precautionary measure within international law to balance these interests. So, the critical question that emerges is this: How can the objectives sought to be achieved through seabed mining be reconciled with the precautionary approach?

9.3.1 *The Precautionary Approach in Seabed Mining*

The UNCLOS does not refer to the application of the precautionary approach to seabed mining, but the need for marine environmental protection and management is embedded within the Convention, particularly in Part XII and Article 145 of Part XI. Further, the Seabed Disputes Chamber of the International Tribunal for the Law of the Sea (ITLOS), in the Area Advisory Opinion[7] perusing the Nodules and Sulphides Regulations, opined that the sponsoring States "shall apply a precautionary approach, as reflected in Principle 15 of the Rio Declaration" in order "to ensure effective protection for the marine environment from harmful effects which may arise from activities in the Area" (para. 125). In view of the Chamber, "the provisions of the aforementioned Regulations transform this non-binding statement of the precautionary approach in the Rio Declaration into a binding obligation" (para. 127). It is critical to note that while there is a theoretical debate surrounding the legal status of precaution as an "approach" or as a "principle," it has largely appeared as an approach within the literature concerning seabed mining. In addition to the advisory opinion rendered by the Chamber, the Draft Regulations on Exploitation of Mineral Resources in the Area (Draft Mining Code; ISA 2019) refer to the application of the precautionary *approach* both as a "fundamental policy and principle" (Regulation 2) and as a "general obligation" applying to the activities in the Area (Regulation 44).

In the environmental law literature, the term "approach" appears to be less in normative content, leaving scope for the discretion of the States in deciding the scope of precautionary actions (Cançado Trindade 2015). The precautionary approach espouses a normative value as an ethical aspiration (Ali 2022, 157), and operationalizing it in the context of maintaining balance in a complex environment of competing goals requires a policy-oriented approach.[8] Precaution operates as a matrix for conscious and informed decision-making and does not advocate for

[7] *Responsibilities and Obligations of States with Respect to Activities in the Area*, Advisory Opinion of February 1, 2011, ITLOS Rep. 2011 (Area Advisory Opinion).

[8] *Indus Waters Kishenganga Arbitration (Pakistan v. India)*, Final Award (Perm. Ct. Arb. 2013), 31 RIAA 3, para. 112.

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indefinite inertia in a world with competing challenges. While it is important to exercise caution, indeterminate precaution must not lead to a paralysis in decision-making (Ali 2022, 157). Currently, the discourse on seabed mining is paralyzed by "what-ifs" and "fear of the unknown." Accordingly, the precautionary approach requires a balance between the use of best available techniques with a view to refining practices through a process of learning while enhancing the ability to detect actual risks of serious environmental harm (Ali 2022). In essence, the precautionary approach calls for a trade-off between the methods through which risk for serious environmental harm can be managed through the use of technology by keeping a balance between anticipating harm and trusting resilience, thereby promoting a certain degree of flexibility (Peel 2004, 491). This distinction in the debate over precaution discloses different attitudes to risk rather than fundamentally different appreciations of the importance of taking scientific uncertainty into account in decision-making (Peel 2004, 500).

In this regard, the relationship of the precautionary approach with the principle of prevention is critical to note. The distinction between prevention and precaution is based on the seriousness of the risk; that is, prevention is a general concept that dictates the general actions of States in terms of environmental protection, and precaution amounts to a reinforcement of the obligation in light of a potentially serious danger that cannot yet be predicted.[9] This approach frames the relationship between prevention and precaution as one of a continuum wherein, as the risk evolves from uncertainty to certainty, the sliding scale of action moves from precaution to prevention. Therefore, it appears that there is scope to identify a risk–reward ratio in seabed-mining activity, and technologies must evolve with the anticipation of harm existing systems will cause. Such an evolutionary understanding is also implicit in the development of the jurisprudence of the precautionary approach and its operationalization.

9.3.1.1 Obligations of Sponsoring States

The Seabed Disputes Chamber in the Area Advisory Opinion approaches the question of the precautionary approach from two prongs. First, it considers applying the precautionary approach to the activities in the Area as a direct obligation of sponsoring States; and second, it links these direct obligations to the due-diligence obligations of States:

> The obligations of sponsoring States are not limited to the due diligence "obligation to ensure." Under the Convention and related instruments, sponsoring States also

[9] *Pulp Mills on the River Uruguay (Argentina v. Uruguay)*, 2010 ICJ Rep. 14, Separate Opinion of Judge Cançado Trindade, para. 112 (April 20); *Whaling in the Antarctic (Australia v. Japan: New Zealand intervening)*, 2014 ICJ Rep. 226, Separate Opinion of Judge Cançado Trindade, para. 64 (March 31).

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> have obligations with which they have to comply independently of their obligation to ensure a certain behavior by the sponsored contractor. (para. 121)

In effect, this means that States ought to integrate the precautionary approach in their decision-making on sponsoring activities in the Area and translate such intent through various rules, regulations, procedures, and administrative processes to exercise control and regulate the conduct of sponsored entities (paras. 107, 123). This is particularly critical because the application of the precautionary approach, being a treaty obligation, is binding only on States, and it is through this mechanism that the States must obligate the contractors under their control to apply the precautionary approach.

The Chamber further articulated the circumstances in which a State fails to meet its due-diligence obligation:

> A sponsoring State would not meet its obligation of due diligence if it disregarded risks [arising from scientific uncertainty]. Such disregard would amount to a failure to comply with the precautionary approach. (para. 131)[10]

Therefore, a sponsoring State must continuously manage its compliance with this due-diligence obligation and account for emerging risks to fulfill its obligations. The continuous and evolutionary nature of the due-diligence obligation vis-à-vis the precautionary approach has also been a subject of discussion elsewhere. The International Law Commission has understood the duty of due diligence as not intending to guarantee that significant harm be totally prevented (ILC 2001, 154, paras. 7–8, 1994, Article 7, para. 4). The standard of due diligence against which the conduct of the State of origin should be examined is that which is generally considered to be appropriate and proportional to the degree of risk (ILC 1994, Article 7, para. 4). Therefore, "the State may be responsible … for not enacting necessary legislation, for not enforcing its laws …, or for not preventing or terminating an illegal activity, or for not punishing the person responsible for it" (ILC 1994, Article 7, para. 4). This could be understood to be a learning-by-doing approach, whereby the assessment of the risk and the harm done must be made on a continuous basis, with appropriate mechanisms for the implementation of relevant measures to minimize such harm.

In this respect, due diligence requires States to "ensure" that such activities within their jurisdiction or control do not cause significant adverse effects. This does not mean, however, that due diligence applies solely to private activities, since a State's own activities are also subject to the due-diligence rule.[11] It is an obligation that

[10] See also *Southern Bluefin Tuna (New Zealand v. Japan; Australia v. Japan)*, Provisional Measures, Order of August 27, 1999, ITLOS Rep. 1999, 280 at para. 77.

[11] *Pulp Mills on the River Uruguay (Argentina v. Uruguay)*, 2010 ICJ Rep. 14, paras. 101, 197 (April 20); *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v. Nicaragua)*; *Construction of a Road in Costa Rica along the San Juan River (Nicaragua v. Costa Rica)*, 2015 ICJ Rep. 665, paras. 104, 153, 168, 228 (December 16); *Responsibilities and Obligations of*

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entails not only the adoption of appropriate rules and measures but also a certain level of vigilance in their enforcement and the exercise of administrative control applicable to public and private operators – such as the monitoring of activities undertaken by such operators – to safeguard the environment. It also requires considering the context and evolving standards of both regulation and technology (ILC 2021, Guideline 3, 26). This leads to this question: How are States expected to operationalize the precautionary approach in the context of seabed mining?

9.3.1.2 Operationalizing the Precautionary Approach

While it is now established that the precautionary approach is applicable to activities in the Area, this section will delve into understanding how the precautionary approach can be operationalized vis-à-vis these activities. The Seabed Disputes Chamber has provided guidance in this regard:

> The due diligence obligation of the sponsoring States requires them to take *all appropriate measures* to prevent damage that *might result* from the activities of contractors that they sponsor. The [precautionary approach] applies in situations where scientific evidence concerning the scope and potential negative impact of the activity in question is insufficient but where there are *plausible indications of potential risks*. (Area Advisory Opinion, para. 131)

The constitutive elements of the precautionary approach envisaged by ITLOS include the threat of environmental harm, uncertainty, and action. The threat of environmental harm is articulated in the form of damage that "might result" based on "plausible indications of potential risks"; in other words, this broadens the characterization of harm. However, unlike the Rio formulation, which characterizes harm to be serious or irreversible, the Chamber applies the precautionary approach to all "potential negative impacts." Should a State disregard these obligations, it would be in violation of its due-diligence obligations. Further, the obligation of States is qualified by the requirement that they take "appropriate measures" to prevent damage; that is, the standard of "appropriate" has an economic, as well as a social, pragmatic, and ideological character (Johnstone 2015, 117–118).

Finally, the most critical constitutive element of the precautionary approach is the remedial action concerning the prevention of environmental degradation. This addresses the element of the methods through which such precaution can be operationalized. Any remedial action must be effective; that is, it should be capable of achieving the desired level of protection. The aim is to create measures that are specific enough to be clear and meaningful, yet flexible enough to allow for changes

States with Respect to Activities in the Area, Advisory Opinion of February 1, 2011, ITLOS Rep. 2011, 10 at para. 131. See also ILC (2001, para. 97); ILA Study Group (2014, 2016).

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when new information becomes available (Cooney and Dickson 2005, 301). Additionally, the precautionary measures must be proportionate to the desired level of protection and are to be evaluated on a case-to-case basis. In this regard, ITLOS has provided meaningful guidance on the proportionality of environmental measures:

> Due diligence is a variable concept. It may change over time as measures considered sufficiently diligent at a certain moment may become not diligent enough in light, for instance, of new scientific or technological knowledge. It may also change in relation to the risks involved in the activity. As regards activities in the Area, it seems reasonable to state that prospecting is, generally speaking, less risky than exploration activities which, in turn, entail less risk than exploitation. Moreover, activities in the Area concerning different kinds of minerals, for example, polymetallic nodules on the one hand and polymetallic sulphides or cobalt rich ferromanganese crusts on the other, may require different standards of diligence. The standard of due diligence has to be more severe for the riskier activities. (Area Advisory Opinion, para. 117)

Consequently, precaution must be translated into concrete policy and management measures that are readily understood, that address the protection problem, and that identify actions to be taken in specific contexts (Jaeckel 2017, 47). On a sliding scale of enhanced protection measures, one of the critical tools for the implementation of the precautionary approach when it comes to exploitation activities is Best Available Techniques (BAT; Trouwborst 2006b, 172–174).

To wrap up this discussion on the precautionary approach, we note that seabed mining carries the potential risk of negative impacts on the marine environment. However, this risk can be mitigated or managed through the implementation of the precautionary approach, inter alia, by taking necessary measures to limit the harm caused by mining. The implementation of such measures calls for innovative technological approaches to limit the harm, including the application of BAT.

9.3.1.3 Scope of Best Available Techniques

BAT are measures closely affiliated with the precautionary approach, both in State practice and in academic writings. In addition, BAT has been set out as a requirement of the precautionary approach in Swedish legislation,[12] German case law (Trouwborst 2006a), and the jurisprudence of the Dutch Council of State.[13] Some regional frameworks also apply the BAT standard to activities such as the 1992 Convention on the Protection of the Marine Environment of the Baltic Sea

[12] Environmental Code of 1998, Article 3(2).

[13] Afdeling Bestuursrechtspraak van de Raad van State, Judgment of April 19, 1996, No. G05.93.2238.

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Area (Helsinki Convention),[14] as well as the 1992 Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention).[15] The Draft Mining Code also recognizes the application of BAT in carrying out precautionary measures (Regulations 44 and 58). Given that BAT appears only at a draft stage at the moment, the ordinary meaning can be derived by application of the rules of interpretation under Article 31 of the Vienna Convention on the Law of Treaties.[16]

BAT IN INTERNATIONAL LAW. At the outset, it is essential to acknowledge that the concept of "Best Available" is inherently relative and involves a comparative assessment. This was the question before the arbitral tribunal in the UK-Sandeel case, where the tribunal interpreted "'best' [to] be read in the context of 'available [technology]' and not in the absolute sense of the best possible" (UK-Sandeel 2025, 489). It is already established that the technology used must be sensitive to the deep-sea benthic environment and adhere to the precautionary approach. According to the arbitral tribunal it follows that "[available technology] is not limited to [one] that exists at the time …, but extends to [technology] which could reasonably have been [used] at that point in time" (UK-Sandeel 2025, 491). Therefore, seabed-mining contractors must make a reasonable degree of effort to obtain the BAT at the time the mining project is under consideration.

From the vantage point of a project opponent, it may be argued that the technology proposed for seabed mining is not the best available, either because superior technology exists or the current technology is fundamentally flawed. To interpret the view of the arbitral tribunal in the UK-Sandeel case, it does not require the opponent to identify a better technology. Instead, the opponent must demonstrate that the significant flaws in the technology prevent it from meeting the standard of best available technology (UK-Sandeel 2025, 494). Given this understanding of "best available," it is crucial to evaluate how BAT has been considered in international law.

In this regard, the Draft Mining Code borrows the definition of BAT from the OSPAR Convention and defines BAT through key elements such as the "latest stage of development" and "state-of-the-art processes" of "facilities and methods of operation" that are "practically suitable for limiting" environmental harm or pollution. Further, factors such as recent successful trials, technological advances, economic feasibility, time limits for installation, and the impact of technology on the environment are considered as constitutive elements of BAT

[14] Convention on the Protection of the Marine Environment of the Baltic Sea Area, March 22, 1974. 1507 UNTS 166 (Helsinki Convention).

[15] Convention for the Protection of the Marine Environment of the North-East Atlantic, September 22, 1992, 2354 UNTS 67 (OSPAR Convention).

[16] Vienna Convention on the Law of Treaties, May 23, 1969, 1155 UNTS 331.

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(OSPAR Convention, Appendix I; Helsinki Convention, Annex II Regulation 3). Additionally, the scope of the term "techniques" includes technologies, albeit with a qualification that they must be accessible to operators and industrially scalable under economically and technically viable conditions.[17] To augment the conditions of general availability of the technology, it also must be effective in achieving a high general level of protection of the environment as a whole.[18] These conventions have an embedded understanding that technology is an evolutionary concept and BAT for a given process or facility will change with time in the light of technological advances, economic and social factors, and changes in scientific knowledge and understanding (OSPAR Convention, Appendix I; Helsinki Convention, Annex II).

Further, BAT has been invoked in two cases: the *MOX Plant* case, in which Ireland alleged that the waste management regime concerning the hazardous activity implemented by the UK was falling short, which could be addressed through the use of currently available technology, and that BAT must be adopted.[19] The arbitral tribunal, however, did not opine on that assertion by Ireland. Further, in the *Pulp Mills* case,[20] Argentina had alleged that by not requiring the Orion Mill to employ BAT, Uruguay had failed to take all measures to prevent pollution.[21] This included the nonimplementation of tertiary treatments of discharges and the lack of an empty emergency basin for discharges, to which Uruguay had contended that its plant used state-of-the-art anti-pollution technology, ensuring that the effluent discharges are among the lowest in the world, including all measures to evolve the technology in response to the harm.[22]

The International Court of Justice, on an assessment of the technology employed in the Orion Mill, found:

> From the point of view of the technology employed and based on . . . the December 2001 Integrated Pollution Prevention and Control Reference Document on Best Available Techniques in the pulp and paper industry of the European Commission there is no evidence to support the claim that the Orion Mill is not BAT-compliant. (para. 225)

[17] Stockholm Convention on Persistent Organic Pollutants, May 22, 2001, 2256 UNTS 119 (POPs Convention), Article 5(f)(iii): "'Available' techniques means those techniques that are accessible to the operator and that are developed on a scale that allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages."

[18] POPs Convention, Article 5(f)(iv): "'Best' means most effective in achieving a high general level of protection of the environment as a whole."

[19] *MOX Plant Case (Ireland v. United Kingdom)*, Ireland Memorial (Segment 3), PCA Case No. 2002-01.

[20] *Pulp Mills on the River Uruguay (Argentina v. Uruguay)*, 2010 ICJ Rep. 14 (April 20) (*Pulp Mills*).

[21] *Pulp Mills*, Memorial of Argentina, paras. 5.74–5.76.

[22] *Pulp Mills*, Memorial of Uruguay, para. 4.34.

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In effect, the Court makes an assessment based on the availability of the technology and the industry standards prevalent at the time (paras. 224–225)[23] and does not indulge in a hypothetical assessment of what the technology should achieve to reduce or minimize harm. However, for States to be duly diligent, it would be important to inquire whether the technologies are best due to considerations of cost and convenience, or if there have been any improvements in the technology available.[24]

From a reading of the international instruments and the *MOX Plant* and *Pulp Mills* cases, it is conceivable that the use of BAT limits the margin of discretion of State parties concerning the implementation of the obligation to ensure effective protection for the marine environment from harmful effects that may arise from activities in the Area. Arguably, the obligation to use BAT may be a useful tool to specify a standard of due diligence (Tanaka 2006, 563–565). To this extent, the obligation could strengthen the regulation of harmful effects of the activities in the Area. In this regard, the seabed-mining regulations appear to push the boundaries of the limited conception of BAT in international law by devising an iterative process through Environmental Management and Monitoring Plans (EMMP) and Environmental Impact Statements (EIS), which ought to offer a continuous assessment procedure to the technology applied and its impacts. BAT is, therefore, a dynamic standard that evolves on technical, geographical, and economic considerations, and determining an objective BAT standard is difficult.

On an overall assessment of BAT in international law, while States have a due-diligence obligation to enact appropriate rules, regulations, and procedures to mitigate the effects of seabed mining on the environment, in effect, BAT also delegates action to contractors to innovate and develop technology that integrates these mitigating factors. Therefore, while States have a procedural obligation, the substantive obligation to implement the appropriate technology is incumbent upon contractors.

BAT IN THE DRAFT MINING CODE. The Seabed Disputes Chamber has also opined on the burden of implementing the precautionary approach and thereby BAT:

> Equality of treatment between developing and developed sponsoring States is consistent with the need to prevent commercial enterprises based in developed States from setting up companies in developing States, acquiring their nationality and obtaining their sponsorship in the hope of being subjected to less burdensome regulations and controls. (Area Advisory Opinion, para. 159)

[23] See also the Joint Dissenting Opinion of Judges Al-Khasawneh and Simma.
[24] Joint Dissenting Opinion of Judges Al-Khasawneh and Simma.

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This statement by the Chamber indicates that, rather than considering the capacity of the State, it prefers to consider the capacity of the contractor to adopt BAT and comply with the environmental standards (Papanicolopolou 2020, 154). In this regard, this chapter focuses only on BAT measures to be implemented on the part of contractors, and not the interface of such obligations vis-à-vis the ISA or sponsoring States.

For BAT to be fully implemented, it must fulfill the constitutive elements of the precautionary approach – that is, environmental harm, uncertainty, and action. The Draft Mining Code takes a progressive approach to BAT and has inculcated more dynamic standards within its Regulations. The draft regulation on exploitation expands upon Article 145 of UNCLOS. It articulates fundamental principles for the effective protection of the marine environment and integrates the precautionary approach, the ecosystem approach, the polluter pays principle, data sharing, accountability and transparency, and effective public participation (Draft Regulation 2(e)(i)–(vii)). The draft regulations outline that the activities in the Area must be conducted efficiently and in a manner that is orderly, safe, and rational in accordance with sound principles of conservation and the avoidance of unnecessary waste (Draft Regulation 2(b)(ii)). They integrate the dynamic nature of the due-diligence obligations and espouse the development of incentive structures to support and enhance the environmental performance of contractors beyond the legal requirements, including through technology development and innovation (Draft Regulation 3(f)(iii) and (vi)). Furthermore, it can be reasonably assumed that the final adopted regulations will reflect a more stringent standard compared to the initial draft language.

Besides the fundamental principles and general obligations, the Draft Mining Code references technology and BAT in three areas: (1) applications for approval of Plans of Work in the form of contracts; (2) reducing the risk of incidents; and (3) the protection and preservation of the marine environment.

Applications for Approval of Plans of Work First, applications for approval of Plans of Work submitted by contractors (Draft Regulation 5(1)) are accompanied by a certificate of sponsorship, which establishes the nationality – that is, the jurisdiction and control of the sponsoring State (Draft Regulation 6). Such applications made with the Secretary General of the ISA include, inter alia, the EIS and EMMPs (Draft Regulation 7(1) and (3)). The EIS entails sharing information concerning the technologies and mining process to be employed, including the likely effects of the technology at the time of recovery of the resources from the seabed (Draft Regulation 7, Annex IV, 3.3.2). The EIS also includes a description and assessment of the likely effect of the mining process on the physiochemical, biological, and socioeconomic environment in the mining area (Draft Regulation 7, Annex IV, 3.3.2). It is also accompanied by the environmental management, monitoring, and reporting requirements, reflecting the environmental policy of the contractor (Draft

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Regulation 7, Annex IV, 3.3.2). The EMMP includes an assessment of the potential environmental effects and the significance of the proposed activities on the marine environment, along with a description of mitigation measures, management control procedures and responses, and the necessary risk assessment and management techniques to minimize harm (Draft Regulation 7, Annex VII). The EMMP also includes a description of the technology to be deployed in accordance with good industry practice and BAT (Draft Regulation 7, Annex VII).

Once the application has been made, along with the requisite EIS and EMMP, the Legal and Technical Commission assesses the technical capabilities of the contractors on the basis of the necessary technical and operational capability to carry out the proposed plan of work and the technology and procedures necessary to comply with the terms of the EMMP, including the capability to utilize and apply BAT (Draft Regulation 13(3)(a)–(e)). Such assessment is made against the benchmark of the rules, regulations, and procedures set out by the ISA, in particular the fundamental policies and procedures (Draft Regulation 13(4)(e)).

Reducing the Risk of Incidents A contractor must minimize the risk of incidents as far as reasonably practicable, ensuring that the cost of further risk reduction is not grossly disproportionate to the benefits. This obligation aligns with the principle of due diligence by requiring contractors to continually evaluate and adopt risk reduction measures in accordance with new knowledge, technological advancements, established good industry practice, BAT, and best environmental practices.

Contractors are expected to regularly review their risk management strategies to ensure that they reflect current best practices and evolving standards. In determining whether additional risk reduction measures are feasible, contractors must assess whether the time, cost, and effort involved are justifiable in comparison to the potential benefits, considering best practice risk levels for the specific operations being undertaken. This approach closely replicates the assessment criteria of BAT relied on by the International Court of Justice in the *Pulp Mills* case. It not only fulfills the requirements of due diligence but also provides clear guidance on the scope and extent of contractors' due-diligence obligations (Draft Regulation 32). In order to deal with such contingencies and incidents, the contractors must submit an Emergency Response and Contingency Plan and ensure its implementation in the event of incidents (Draft Regulation 33).

Protection and Preservation of the Marine Environment Finally, Part IV of the draft regulations, on the protection and preservation of the marine environment, creates a binding obligation on the ISA, sponsoring States, and contractors to apply the precautionary approach and BAT in carrying out such measures (Draft Regulation 44). To this end, the ISA is developing environmental standards that provide for the environmental quality objectives, monitoring procedures, and mitigation measures (Draft Regulation 45). The mitigation measures identified in the

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EIS as such must limit the harm of seabed mining to acceptable levels (Draft Regulation 47(3)(d)). The procedure to implement such mitigation measures and limit such harm must also be articulated within the EMMPs to manage and confirm that the effects meet the environmental quality objectives and standards for the mining operation. The obligations are not limited and cover the entire gamut of activities, including monitoring the effectiveness of mitigation measures through a defined reporting system and maintaining the currency of that system (Draft Regulations 48(3)(c) and 51(c)).

The due-diligence obligation concerning environmental management is a continuous one, according to the mining code, wherein the contractor is expected to assess the validity and compliance of the mining operation with the EMMP (Draft Regulation 52(1)(a)). The reporting of such performance assessments is submitted to the ISA, along with a periodic review of the performance of the contractor by the Legal and Technical Commission of the ISA with adequate safeguards through independent reviews (Draft Regulation 52(3) and (4)). Should the contactor be assessed to have failed to comply with the terms and conditions of its EMMP, a compliance notice to that effect is issued requiring the contractor to take remedial action (Draft Regulation 103(2)(b)).

The incremental evolution in BAT is also recognized within the Regulations, with research on it funded through the Environmental Compensation Fund (Draft Regulation 55(d)). Based on dynamic feedback through the EMMP (Draft Regulation 52), the plans of work initially approved by the ISA are reviewed at intervals, including assessing the evolution in BAT (Draft Regulation 58(1)(f)). Finally, BAT is also a critical element at the end of the life cycle of a mine and is consistently under review and development for the closure plan of a mining site (Draft Regulation 59(2)(a)).

This leads to the final question: What are the technologies currently under testing and development by contractors to fulfill the obligations associated with BAT, and what is their interface with the surrounding environment? Subsection 9.4 will attempt to give a bird's eye view of the technological landscape and its likely effects. In no way is it an attempt to address this effect comprehensively, as a deeper assessment remains outside the scope of the legal obligations of due diligence. However, the section is aimed at orienting the reader to the effects of such mining.

9.4 KEY SUBSYSTEMS OF SEABED-MINING TECHNOLOGY AND THEIR IMPACTS ON THE MARINE ENVIRONMENT

The seabed-mining operation has three key subsystems to its operation from the surface to the deep seabed. First, the production support vessel (mining ship) hosts all the subsystems and serves as the platform from which the mining operation is conducted. This facility supports the collection, gathering, lifting, and storing of polymetallic ores that are mined and must also perform the initial dewatering or

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sorting of minerals from the seabed before sending them to a transport ship (Zhang et al. 2025, 14). This platform also hosts all the powering equipment driving the electric generators and dynamic position systems. There are two main types: platform-based, which are simple but need tugboats for relocation; and ship-based, which have self-propulsion, high-power systems and precise positioning. The mining ship generally has ample cargo space for dewatering treatment and mineral storage (Solheim et al. 2022).

Second, the seabed nodule collector (SNC) is an underwater vehicle that moves along the seabed collecting polymetallic nodules. The SNC is launched with the help of a launch-and-recovery system and is lowered to the depths of the oceans. It relates to the mining ship through a large umbilical cable, providing it with power, communication, and control of its movements on the seabed. The SNC is the most critical subsystem, as there are different iterations of this technology being developed by different proprietors to attain maximum efficiency with minimum footprint. An SNC generally includes complex hydraulics, mechanical equipment, and robotic collector arms, and based on its type, it may have varying levels of impact on the benthic environment. The third critical subsystem is the riser airlift system, which is used to inject air to reduce the buoyancy of water and to lift the slurry of crushed polymetallic ores from the mining vehicle on the seabed to the mining ship at the surface.

9.4.1 *Impact of Seabed Mining on the Seafloor*

The main objective of the SNC is to collect polymetallic nodules while adhering to certain environmental, economic, and operational parameters as set out by Part XI and the Mining Code. As a critical subsystem, the SNC consists of a nodule collection system, along with a propulsion system to maneuver on the seabed. The SNC must balance its impact on the benthic environment with its production rate to operate responsibly (De Bruyne et al. 2022). Currently, the SNC has the highest number of information and knowledge gaps, such as the environmental impacts and effects, its response to soil characteristics, trafficability, and nodule collection methodology (De Bruyne et al. 2022).

Another subcomponent of the SNC that is critical in its impact is the nodule collection system, which has two major functions: (1) a pickup function, picking up the nodules at the entrance of the collector by means of an active jet system; and (2) a transport function, transporting the nodules for further handling. Within these two functional categories, parameters can further be categorized as either process control parameters, geometrical parameters, or environmental parameters. It is the trade-offs between these parameters that define the efficiency and effectiveness of the collection system. Currently, mechanical and hydraulic systems are being tested along these parameters. The hydraulic collection method is classified into three types: suction, wall-attached jet, and double-row jet. It impacts the sediment layer less than

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the mechanical method, which often damages the seabed and causes more sediment suspension (Zhang et al. 2025, 6). Within the mechanical model, multiple prototypes have been tested, including a rotary chain-toothed collecting head (Welling 1981) and a combined comb-like shovel to lift nodules (Handschuh et al. 2001).

The SNC, which has a direct interface with the seafloor, will cause two main types of impact: (1) impact on the seafloor; and (2) benthic plume on the seafloor.

9.4.1.1 Impact on the Seafloor

The SNC has a twofold impact on the seafloor: the disturbance it causes at the time of nodule pick-up, and through its traction movement or driving system. Sea trials found that the hydraulic collection method was more adaptable, efficient, and stable on varied terrain, while the mechanical method consumed less energy. Overall, the hydraulic collection method shows higher reliability and environmental sustainability than the mechanical collection method, though it consumes more energy (Muñoz-Royo et al. 2021).

The second type of impact results from the forward movement of the SNC picking up nodules along with sediments. Further, traction of the nodule collector with the seafloor causes benthic organism mortality. This will impact the area accessible to the flora and fauna on the seafloor, and different technological choices exist, such as the Archimedes screws or the caterpillar's tracks, or noncontact suspended vehicles. It is important to note that, owing to the increased sensitivity to environmental impacts, the concept of an SNC has evolved from passive to active collectors, as the former was deemed inefficient and not in sync with current environmental impact policies (Muñoz-Royo et al. 2021). On an assessment of the principles currently opted by contractors for traction of the SNC on the seafloor, it is largely based on caterpillar tracks (Global Sea Mineral Resources 2018) and noncontact suspended vehicles (BGR 2018; BPC 2024).

For tracked SNCs, the soil characteristics define the designs of tracks. The trade-off to be made is increasing the surface area interface of the tracks and the material used for it. A high-surface-area and lightweight material will minimize sinkage and excessive slip and guarantee maximum traction performances, but will run the risk of a larger area of impact. The SNC traction is designed with a low internal friction angle[25] to minimize harm to seafloor organisms. Instead of relying on friction as do ground vehicles, it primarily depends on the sediment's shear resistance (Liu et al. 2014). A good comparative example in this regard is the Archimedes-screw drivetrain

[25] A "low internal friction angle" means that a material, such as soil or rock, has a low resistance to shearing forces, indicating that its particles easily slide past each other, making it less stable and more prone to failure under stress, compared to a material with a higher internal friction angle; essentially, it signifies a lower capacity to withstand shear forces due to poor particle interlocking (Keaton 2017).

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used by the early prototype SNC (by Ocean Minerals Company – OMCO), which created deep furrows of a depth of 80 cm (Jones et al. 2025) in comparison to more recent tracked SNC of Nauru Ocean Resources Inc. (NORI) that have reduced depth of sediment disturbance to 3 cm (Metals Company 2023).

A 2023 study revisiting a 1979 collector test conducted by OMCO showed similar densities of nodule-dwelling macrofauna in disturbed and control areas. However, it concluded that near-complete nodule removal during mining would likely cause further significant reductions in nodule-dwelling macrofauna, as nodules serve as essential habitats for these organisms. The overall densities of megafauna were found to be very low on tracks and significantly different from control areas and pre-collection tests. However, mobile organisms, such as megafauna and macrofauna, had come to inhabit even the most disturbed regions, suggesting resilience. Sessile (immobile) megafauna displayed early stages of reestablishment, though communities differ significantly from those in unaffected areas. The study demonstrates that technological approaches may be effective in mitigating the broader ecological impacts of mining activities on seafloor biota (Jones et al. 2025).

A new generation of technology that is being tested by the German Federal Institute for Geosciences and Natural Resources (BGR) comprises the noncontact suspended SNCs that hover about 50 cm over the seafloor using positive buoyancy (BGR 2024). The key feature of this technology is its use of AI to detect benthic life on the nodules. Due to its precision collection process using robotic arms, it picks nodules with the least disturbance; that is, those with attached or proximal megafauna are avoided. Further, its robotic arms do not pick up or disturb the seafloor sediment, as it penetrates only to the extent of 2–5.5 cm in the seafloor. Importantly, the depth of penetration into the sediment does not mean that the entire sediment above that depth will be picked up; rather, the claws will penetrate into the sediment in order to grab the nodule (BGR 2024). The benefit of the noncontact suspended vehicle is that it has a high collection efficiency, low operational energy consumption, minimal sediment disturbance, and reliable operation (BGR 2024).

9.4.1.2 Impact of the Benthic Plume

Similarly, another component of the SNC that has a direct effect on the marine environment is the collection system, which is also seeing the testing of different methodologies. The collection system either sucks up the nodules from the seafloor or dislodges them from the seafloor using a moving comb or robotic arms. In each of these methodologies, the sediment is dislodged along with the nodules, albeit in different proportions (De Bruyne et al. 2022). These collection activities cumulatively create the benthic plume – that is, the movement of the SNC and the collector stirs up the sediment and the rejected particulate matter from the nodules is also released through a hopper (Berge et al. 1991). Within this benthic plume,

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larger particles will settle quickly, but finer particles hold the potential to spread over a large area of seabed assisted by currents. These sediments can disturb sensory functions and the assimilation of nutrients in living organisms. They can also bury flora and fauna on the seabed (Berge et al. 1991, 33–34).

While the impacts of suspended noncontact SNCs are rather minimal due to the negligible sediment disturbance (Liu et al. 2014),[26] it is the tracked SNCs that generate benthic sediment plumes and remain the subject of several studies. A 2025 study found that sediment from a nodule collector vehicle at 4 km depth forms a seafloor turbidity current, staying close to the seafloor and not rising into the water column to be carried by ocean currents (Gazis et al. 2025). This study further indicated that sediment particles flocculated rapidly and redeposited quickly (Gazis et al. 2025). One of the key recommendations of the study has been to consider the gradient of the mining site to reduce the impact of gravity-driven turbidity currents and prioritize mining in flat areas (Gazis et al. 2025, 6). Additionally, another study found that sediments from the plume created by the 1979 collector test are not immediately visible but can be detected using photogrammetric measurements of sediment infill (up to around 10 mm) between nodules. This study suggests higher densities of megafauna in these areas compared to undisturbed regions (Jones et al. 2025).

9.4.2 *Impact in the Water Column*

Once collected, the nodules move up the discharge duct and fall into a single trough, called the hopper. Much of the initial pickup water flow is also used to transport the nodules up the duct, flushes through the hopper, and is discharged through the diffusor exhaust. As such, this sediment-laden water is immediately released on the seabed before it enters the subsequent transport and processing systems – that is, the riser airlift system (De Bruyne et al. 2022). During this process, the mineral material will not interact with the water column and will not contribute to any change in the physical or chemical equilibrium in the water column except for accidental leaks. However, the pumps and motors will cause noise and vibrations in the ambient water (De Bruyne et al. 2022, 35).

The riser airlift system can be divided into two types: pneumatic lifting and hydraulic lifting. The pneumatic lifting method works by injecting high-pressure gas into the bottom of the deep-sea-mining pipeline from a surface vessel. This creates an upward flow that transports minerals vertically. The hydraulic lifting method uses a high-lift mixed transport pump in the pipeline center for vertical transportation (She et al. 2022). In this case, the choice of the system will be key to minimize the environmental impacts. The most prevalent method is the use of hydraulic-driven pumps – that is, the airlift system.

[26] The results of the impacts will be released after the tests of Eureka III by BGR.

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The airlift system creates low fluid pressure at varying depths of the riser, causing low fluid pressure on the seabed through which the mineral material is transported. Given that the air injections take place in the upper portions, the capacity requirement of the pumps is limited, thereby reducing environmental impacts (Berge et al. 1991). Multiple approaches for lift systems exist; for instance, Japanese researchers conducted research on an eight-stage lifting pump (Yamada and Yamazaki 1998); China adopted a space guide vane centrifugal pump (Kang et al. 2019); and Germany and India have proposed and adopted a plugging-type positive displacement pump lifting system (Kang et al. 2024). Overall, commercial mining systems typically use multiple multistage centrifugal pumps connected in series.

Further, different technologies are being tested with a novel approach. In the Eureka III trials by BGR, the collected nodules are stored in the autonomous SNC based on the suspended noncontact nodule collector, which would be transported back up to the production support vessel once its storage is full, thereby minimizing any environmental impact of the collection process on the water column (DHI 2024).

However, the key impact on the water column takes place at the time of dewatering the mineral material – that is, when the seawater is separated from the nodules collected in the production support vessel. The discharge of the wastewater from this process implies adding a significant volume of water with different physical and chemical characteristics, such as seabed water, sediments, fragments of nodules, and benthic biota from the seabed to the water column (Berge et al. 1991). Also, the temperature of the seabed water is significantly lower than surface-layer water and can have an impact on the surrounding ecosystem where the water is released. However, testing has suggested that the impacts of such variant temperatures are limited, given the ratio of the volume of wastewater released to the seawater, thereby having only local and short-duration impacts (Berge et al. 1991, 37; Muñoz-Royo et al. 2021).

Sediments in the midwater plume would likely be released in the disphotic or aphotic zone to reduce the impact on photosynthesis and vertical migrations (Le et al. 2017). To assess the environmental impact of a midwater plume, two phases must be understood: the dynamic plume phase, occurring near the release before ocean currents take over, setting initial depth and dilution; and the ambient plume phase, involving advection, settling, and turbulent diffusion. The dynamic plume model is well established (Wang and Adams 2016), considering its effect on turbulent entrainment (Devenish et al. 2010). This model was recently used to predict midwater plume properties for nodule mining (Rzezni et al. 2019). A key uncertainty for midwater plumes is the role of flocculation, where particles aggregate into larger flocs. The studies conducted have assumed that flocculation was insignificant for a dynamic plume, treating sediment as a passive tracer (Rzezni et al. 2019). This study used plume-monitoring results to model a twenty-year seabed-mining operation,

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concluding that midwater plume properties near the discharge can be reliably predicted and sediment aggregation effects are minimal (Muñoz-Royo et al. 2021).

However, more sophisticated data and metrics will be required to assess the impacts of such midwater plumes on marine organisms that move with the ocean in the midwater column (van der Grient and Drazen 2021) and the effects on such mobile and stationary marine organisms due to extended exposure to the sediments near a mining operation (Amon et al. 2016). And, while progress is being made on the understanding of the midwater and benthic ecosystems in the Clarion and Clipperton Fracture Zone, there still exist significant knowledge gaps to inform the setting of environmentally acceptable threshold levels (Muñoz-Royo et al. 2021). The questions that are currently being reflected from an environmental point of view concern the depth at which such wastewater must be released to minimize the impacts concerning such particulate matter, as it runs the risk of reducing visibility for marine organisms and interfering with nutrient assimilation and, potentially, other physical functions, such as respiration, development, growth, and reproduction. Therefore, it has broadly been concluded that releasing the wastewater at a depth beyond the most productive zone of the water column would significantly reduce environmental impacts (Berge et al. 1991, 39).

9.4.3 *Impact on the Surface Water*

The impact of the seabed-mining activity on the surface water would be akin to other uses of the sea, such as shipping. The most significant emissions would be related to the exhaust released by the mining vessel in the atmosphere and the noise and vibrations on the surface water. In this regard, this is a critical area of intersection between the work of the ISA and that of the International Maritime Organization (IMO). The IMO in this regard has a range of regulatory and area-based management tools developed for international shipping that could be useful to enhance the safety of seabed mining. Further, the IMO has extensive regulatory experience that could be useful to the ISA as it continues to develop new regimes, regulations, and guidelines for seabed mining. These include guidelines for the assessment and disposal of wastes, as well as civil liability and compensation schemes for pollution damage to the marine environment developed under various maritime law conventions (ISA and IMO 2019).

On an overall assessment, the most significant environmental impacts from seabed mining will be those caused by the SNC on the seafloor. Different technologies are being tested to minimize that impact. Pioneer Beijing Hi-Tech Development Corporation and BGR are currently testing noncontact suspended nodule collectors. The collection system being tested by BGR involves the use of robotic arms, which, as per the performance parameters, should avoid harm to the living organisms on the seafloor and extensive seafloor damage through traction dynamics (BGR 2018; BPC 2024). However, other contractors are testing SNC

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technologies that have a greater impact on the seafloor. Insofar as the impacts on the water column are concerned, studies have suggested that the sediment plumes, especially at the seafloor, do not significantly harm the environment and have short-term effects (Metals Company 2023). Further, sediment plumes in the upper reaches of the water column, particularly emerging from wastewater discharges, are also considered to be less significant because wastewater quickly dilutes in the ambient surface water. Thus, any deviation from the normal values for temperature and metal concentrations should be local and short-term transient (De Bruyne et al. 2022). Several tests have shown that particulate matter in the wastewater settles much faster than expected, so that the resultant sediment plume is smaller and less disturbing (De Bruyne et al. 2022, 57).

9.5 CONCLUSION

The evolution of discourses on technology in seabed mining has been a journey marked by significant transformations. Initially, these discussions were deeply entangled in the North–South divide, reflecting the broader geopolitical and economic disparities between the developed and developing nations. Developing countries, often lacking the advanced technological capabilities of their developed counterparts, were concerned about equitable access to the resources and technology needed for seabed mining. This divide was exemplified in the negotiations leading to UNCLOS, where developing States advocated for robust technology transfer provisions to ensure their meaningful participation in seabed-mining activities.

During the early stages of the negotiations, the lack of information on technological advancements and the pressure for resource reallocation were critical factors influencing the discourse. Developed nations, since they possess superior technological capabilities, were perceived as having a distinct advantage in exploiting seabed resources, leading to calls for an international regime to manage and regulate these activities equitably. The adoption of the principle of the common heritage of mankind and the establishment of the ISA were significant milestones in addressing these concerns, aiming to balance the interests of all nations.

As technology has advanced, the focus of the discourse has shifted from geopolitical considerations to environmental sustainability. The realization that seabed mining carries significant risks to the marine environment has driven the development and implementation of stringent environmental standards. The application of the precautionary approach and BAT has become central to the regulatory framework governing seabed mining. These measures are designed to mitigate the environmental impact of mining activities, ensuring that they are conducted responsibly and sustainably.

The ISA, in conjunction with sponsoring States and contractors, has made substantial progress in integrating these environmental principles into the seabed-mining regime. The dynamic nature of BAT, which evolves with technological

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advancements, ensures that the best possible practices are employed to minimize harm to the marine environment. This adaptive approach is crucial in addressing the inherent uncertainties and potential risks associated with seabed mining.

Additionally, examination of the precautionary approach through the perspective of technology indicates that measures should aim to optimize trade-offs across interconnected risks. Its application should rely on thorough assessments to reduce uncertainty over time. The key question is not whether to adopt the precautionary approach but rather what the appropriate action should be. It is essential to evaluate whether the technology can support seabed mining while protecting the marine environment, rather than simply assessing risks to justify strict restrictions or a ban. It is possible that some technologies in seabed mining may require more caution due to higher uncertainty and potential harm. However, this decision should involve stepwise, scalable, and experimental methods rather than a simple yes-or-no answer.

In conclusion, the evolution of the discourse on technology in seabed mining reflects a significant shift from addressing the North–South divide to fulfilling environmental parameters for deep-sea governance. This transformation underscores the complexities associated with international cooperation on technology transfer, technological innovation, and a commitment to sustainability in harnessing the resources of the deep seabed. As seabed mining moves closer to reality, the continued development and application of advanced technologies, guided by robust regulatory frameworks, will therefore be essential in balancing resource extraction with environmental protection.

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