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Aspects of Estimation and Reporting of Mineral Resources of Seabed Polymetallic Nodules: A Contemporaneous Case Study

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Abstract: Exploration of seabed polymetallic nodules identifies the Clarion Clipperton Zone and the Indian Ocean Nodule Field to be of economic interest. Mineral resource estimation is important to the owner of the resource (all of mankind; and managed by the International Seabed Authority; ISA) and to developers (commercial and government groups holding contracts with the ISA). The Committee for Mineral Reserves International Reporting Standards was developed for the land-based minerals industry and adapted in 2015 for ISA-managed nodules. Nodules can be sampled in a meaningful manner using mechanical devices, albeit with minor issues of bias. Grade and moisture content are measured using the established methodology for land-based minerals. Tonnage of resource is determined via the abundance of nodules in kilograms per square metre of seabed. This can be estimated from physical samples and, in some cases, from photographs. Contemporary resource reporting for nodules classify the level of confidence in the estimate, by considering deposit geology, sample geostatistics, etc. The reporting of estimates also addresses reasonable prospects for eventual economic extraction, including factors such as mining technology, the marine environment, metallurgical processing, and metals markets. Other requirements are qualified persons responsible for estimation and reporting, site inspection, and sample chain of custody.

Keywords: polymetallic nodules; mineral resource estimation; mineral resource reporting; CRIRSCO; seabed geology; geostatistics

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1. Introduction

The estimation and reporting of mineral resources and their exploitable subsets, e.g., mineral/ore reserves, provide important information for the owners of the minerals, the owners of groups with development rights, and other stakeholders. We report here on aspects that we found important in producing some of the first contemporary mineral resource estimates for polymetallic nodules.

There are extensive deposits of high-grade polymetallic nodules resting on the seabed within the Clarion Clipperton Zone (CCZ) in the Pacific Ocean and the Indian Ocean Nodule Field (IONF) (Figure 1; International Seabed Authority [1], Mukhopadhyay et al. [2]). Recent interest in developing these resources has resulted in efforts to advance questions of mineral rights (e.g., Watzel et al. [3], Toro et al. [4], Hein et al. [5]).

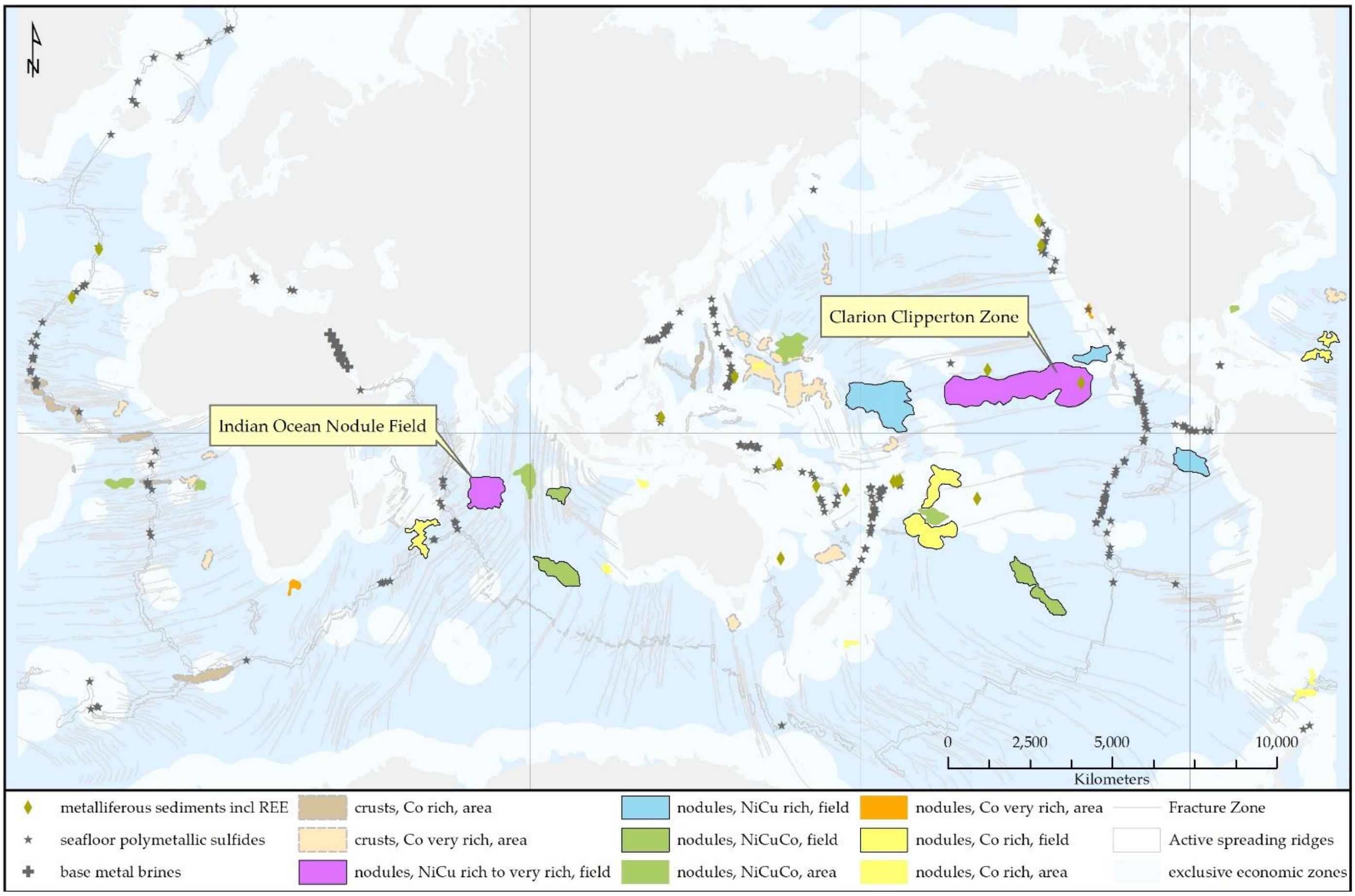


Figure 1. Locations of the Clarion Clipperton Zone and Indian Ocean Nodule Field. Adapted from Andreev et al. [6] and Matthews et al. [7]. Rich Co is generally >0.4%, very rich Co is >0.8%, NiCuCo is 0.7–1.7% Ni + Cu, rich Ni-Cu is >1.7% Ni + Cu, and very rich Ni-Cu is >2.5% Ni + Cu; the fields are better constrained from sampling than the areas.

1.1. Mineral Owners

These deposits are located on the seabed within international waters, and ownership of the minerals cannot be directly attributed to any particular nation (as is typically the case on land). At the United Nations in 1972, ownership of these minerals was declared as "The Common Heritage of Mankind", and a protracted process of defining international law to manage such minerals commenced [8]. The third United Nations Conference on the Law of the Sea (1973–1982) led to the United Nations Convention on the Law of the Sea (UNCLOS) of 1982 and the agreement adopted by the General Assembly of the United Nations in 1994 relating to the implementation of Part XI of UNCLOS. UNCLOS assigns the responsibility to organise and control activities in "the area" beyond national jurisdiction to the International Seabed Authority (ISA), especially regarding exploration and mining of the minerals; equitable distribution of the proceeds; adequate protection of the marine environment; protection of land-based industry (anti-dumping and anti-competition); and promoting development opportunities for citizens of developing states and marine scientific research [9]. State-owned or state-sponsored commercial enterprises can complete preliminary research on unclaimed seabed, and then apply for an exploration contract, with one condition being that they supply data for an area of equal quality that is then reserved for "Contractors" sponsored by developing states.

The ISA envisages that qualifying entities will convert part or all of their exploration contracts to exploitation contracts and will mine, process, and sell nodules and/or their derived metal products. These entities will pay fees, royalties, and taxes to the ISA and the nations in which they are located and who sponsor them. Remittances to the ISA will then need to be suitably dispensed to the mineral owners. The reporting of mineral resources and, in due course, mineral/ore reserves to modern international standards has thus become topical and of increasing importance (Madureira et al. [10]).

It is worth noting that countries that have not signed and ratified UNCLOS do not recognise UNCLOS's provisions. Most notably, the United States has issued its own seabed licenses for polymetallic nodules within the CCZ, albeit so far without any overlap with the ISA contracts or reserved areas (National Oceanic and Atmospheric Administration [11], Lipton et al. [12]).

1.2. Mineral Developers

At the time of writing, the ISA has issued 30 exploration contracts for deep-sea minerals (polymetallic nodules, polymetallic sulphides, and cobalt-rich ferromanganese crusts (ISA [13]), including 18 for polymetallic nodules, 16 in the CCZ, one in the IONF, and, most recently, one in the Prime Crust Zone (Figure 1). The contract holders are mostly national ministries or nationally owned entities, but in the case of CCZ polymetallic nodules, seven commercial entities are also included.

A recent revival of commercial interest in polymetallic nodules in the CCZ (Figure 2) has been driven by the improvement of metal prices in the 2000s, the expected increased demands for battery metals, the proposed release of exploitation regulations, and improvements in subsea technology (e.g., Sparenberg [14]). Any entity seeking or providing project financing will very likely need estimates of the mineral resources and mineral/ore reserves to be compiled and reported to modern international standards.

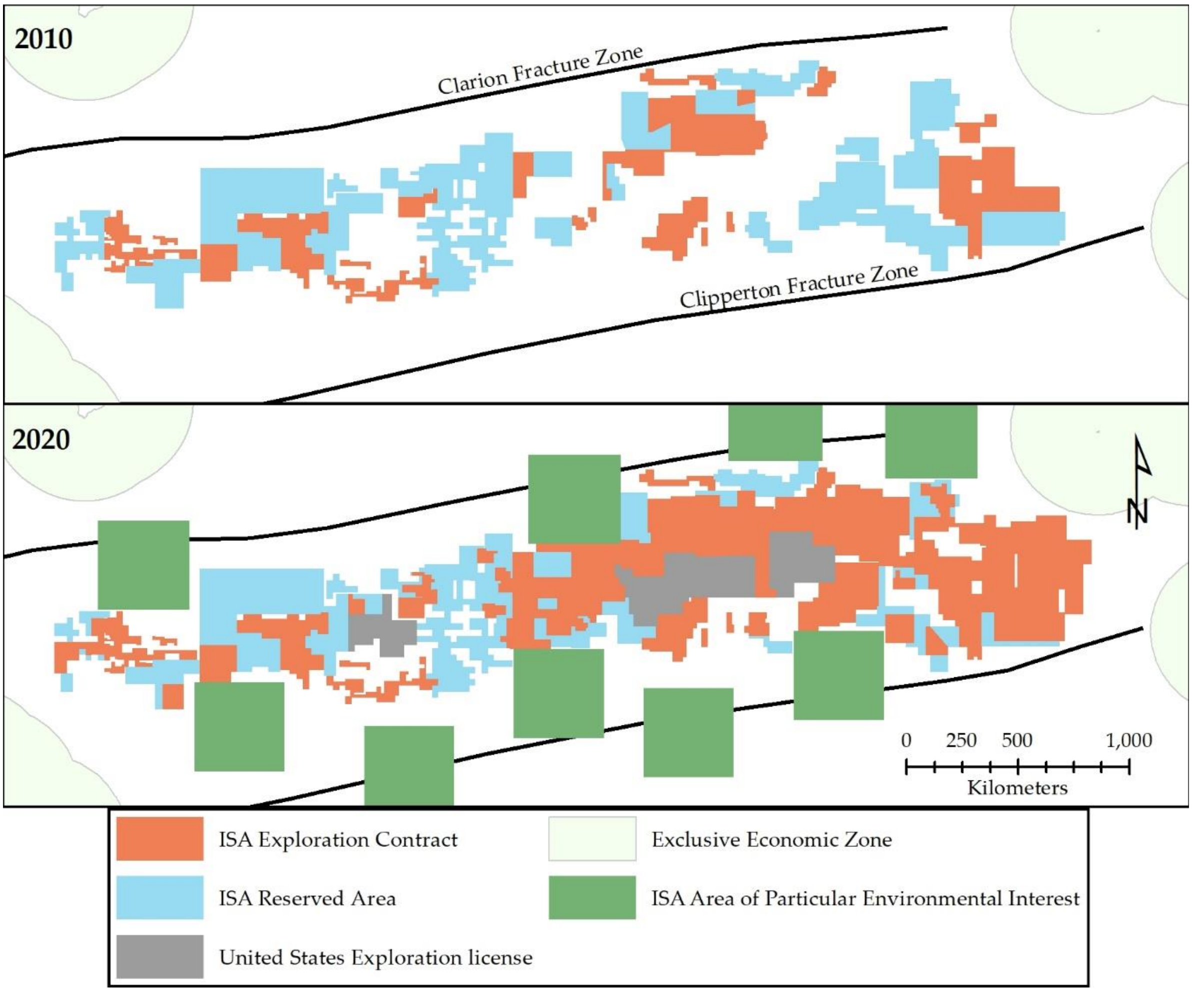


Figure 2. Growth in seabed claims in the CCZ. Sources: International Seabed Authority (ISA) [13], National Oceanic and Atmospheric Administration [11], and Marine Regions [15].

1.3. Reporting Rules

In many countries, the public reporting of mineral resources is regulated by formal codes or legislated instruments. The first formal code of this type among free-market economies was the Australasian Code for Reporting of Exploration Results, Mineral Resources, and Ore Reserves (the JORC Code), published in 1989 by the Joint Ore Reserves Committee of the Australasian Institute of Mining and Metallurgy and the Minerals Council of Australia (JORC). This code established several key criteria that should be addressed in public reports by companies listed on the Australian Securities Exchange (ASX). The code is explicitly guided by the principles of:

- Materiality;
- Transparency;
- Competence and responsibility.

The Committee for Mineral Reserves International Reporting Standards (CRIRSCO; [16]) was formed in 1994. CRIRSCO initially comprised an informal alliance of national reporting organisations such as JORC and has since evolved into a formally constituted committee with governing terms of reference. It has become the principal organisation coordinating the international mining industry on issues relating to the classification and reporting of mineral assets and is recognised by a range of global organisations, including the United Nations Economic Commission for Europe (UNECE) and the International Council on Mining and Metals (ICMM). There are currently 14 member regions and countries with mineral resource reporting codes within the CRIRSCO family (Figure 3).

Since 1989, the JORC Code has evolved, as have the other similar codes around the world (JORC [17]). In Canada, the Canadian Institute of Mining (CIM) publishes a guide to reporting on mineral resources and mineral reserves, which is updated periodically (CIM [18–20]). The other codes in the CRIRSCO family are very similar, and CRIRSCO draws on the various reporting standards to define an international reporting template (CRIRSCO [21]).

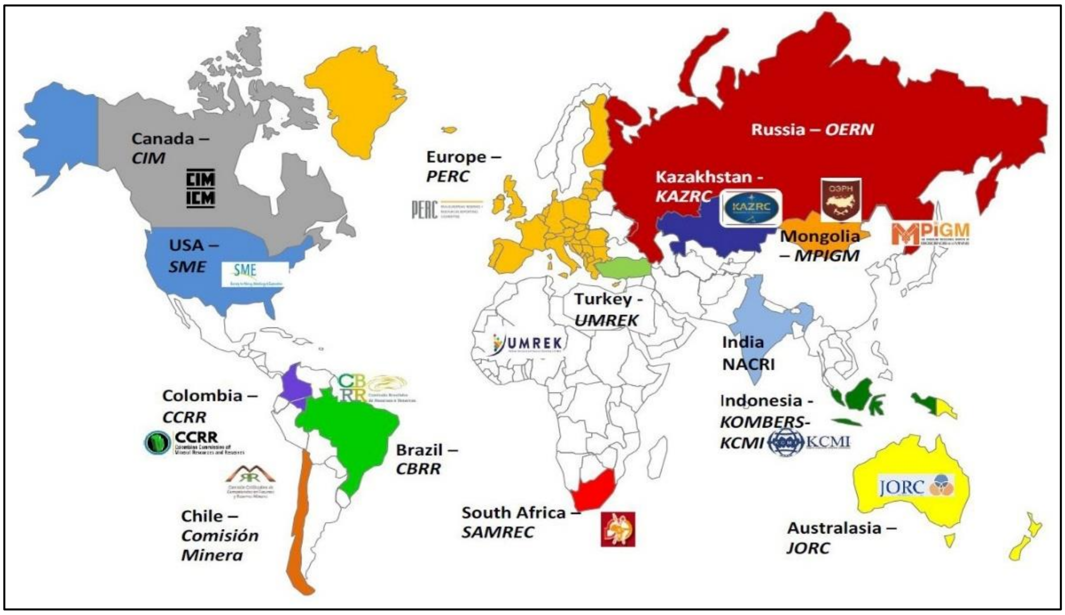


Figure 3. Map of member coders Committee for Mineral Reserves International Reporting Standards (as of August 2019). Source: Committee for Mineral Reserves International Reporting Standards [16].

The Canadian government, wishing to provide more clarity for investors, enacted National Instrument 43-101 (NI43-101), which sets strict rules for the reporting of mineral resources and mineral reserves and requires the CIM code to be followed for Canadian listed companies. Similar requirements exist in other countries or their stock exchanges.

A fundamental feature of the CRIRSCO family of codes is that they do not prescribe how a mineral resource should be sampled or estimated; instead, they set expectations as to what aspects of the data and estimation methods should be addressed in the mineral resource reports.

Estimating the sizes of seafloor polymetallic nodule deposits, especially at higher confidence levels (Figure 4), entails particular challenges because of their remote locations and inaccessibility for direct inspection due to the depth of seawater. There are also no terrestrial analogues to provide comparative data and precedents. Exploring and sampling deep-sea mineral resources is expensive, and the deposits are not amenable to the sampling methods typically used to define terrestrial deposits. To date, no commercial-scale mining operations have been attempted for the recovery of seafloor polymetallic nodules, although pilot-scale mining has been successfully completed. Consequently, satisfying the requirements of international mineral reporting codes, based on the relevant experience of the competent person or qualified person (QP) and the reasonable prospects of economic extraction, cannot rely on direct precedents.

This paper summarises some of the key issues related to determining mineral resource estimates of polymetallic nodules and reporting them to the CRIRSCO standard. This study necessarily focuses on the CCZ, as this is the first area for which Mineral Resource estimates have been compiled and reported publicly. It discusses the public reporting requirements under the Canadian National Instrument 43-101 (NI43-101) and how these requirements were addressed by the QPs. For a more detailed presentation of the sampling data and estimation methods, the reader is referred to the published mineral resource estimates, such as those by Nimmo et al. [22], Lipton et al. [12], DeWolfe and Ling [23], Lipton et al. [24,25].

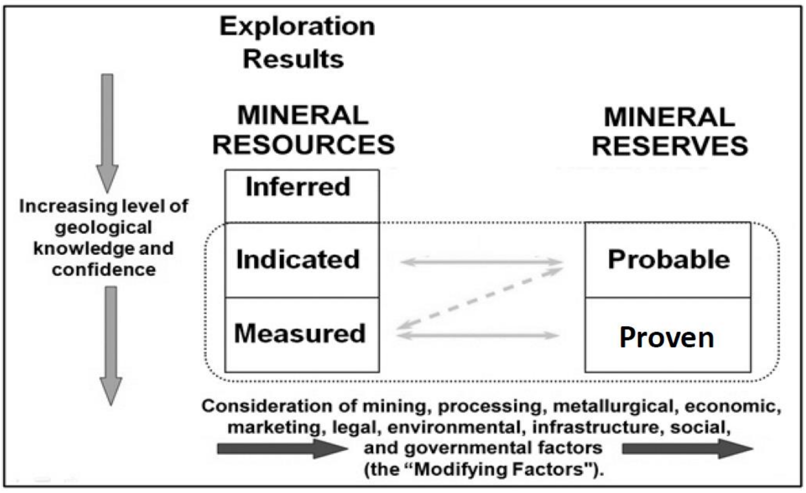


Figure 4. Levels of confidence and relationships for NI43-101 mineral resources and mineral reserves. Source: Canadian Institute of Mining Metallurgy and Petroleum [19].

2. History of Evaluation of Polymetallic Nodule Deposits

The occurrence of seabed nodules has been known since the mid-1800s (Murray and Renard [26]), and perhaps the first realisation that nodules in the region of the CCZ might be of economic interest was published in 1958 (Menard and Shipek, [27]). However, the first known published estimate of the size of the CCZ deposit was by Mero [28], who estimated 1656 Bt for the entire Pacific from a set of 29 photographs, 10 dredges, and 62 box cores (Mero did not specify the wet or dry weights; instead, wet tonnes were commonly quoted in early work, as wet sample mass is more easily measured at sea). Mero was clear on the sparsity of his dataset and provided ranges of nodule abundance.

Mero's work helped to spark a boom in the exploration of nodules through the late 1960s and 1970s [12]. There are no known published mineral resource estimates from this era. Explorers quickly focused on the Clarion Clipperton Zone (CCZ) and Indian Ocean Nodule Field (IONF) due to their higher abundances and higher metal grades, as indicated by initial sampling.

In 1982, the United Nations Ocean Economics and Technology Branch issued an assessment of manganese nodule resources [29] that included a systematic discussion on the available data types and estimation methodologies. This assessment included short summaries of global and CCZ-focused estimates of mineral resources, including those of Pasho and McIntosh, Bastien-Thiry et al., McKelvey et al., and Lenoble [30–33].

Pasho and McIntosh's [30] assessment of the recovery of polymetallic nodules involved Monte-Carlo simulations. These analyses were driven by a then-proposed mining methodology, whereby a towed collector is towed repeatedly at different headings in a given area with very limited seafloor steerage control (T. Brockett 2016 pers comm). The simulation aimed to predict when recovered nodule volumes would become uneconomic due to a high proportion of the collector re-covering his or her old tracks with few—if any—remaining nodules.

Lenoble ([33]) presented a careful consideration of modifying factors to convert a mineral resource into a mineral reserve (albeit not to any current code).

In 2002, Kotlinski and Zadornov [34] published the average grades and abundances for the contract area held by the Interoceanmetal Joint Organization (sponsored by Bulgaria, Cuba, Czech Republic, Poland, Russian Federation, and Slovakia) and described variation by latitude.

In 2003, the ISA convened a special workshop for Contractors and other experts (e.g., [35–37]) who pooled their data (>10,000 data points) and expertise, enabling the mineral resources for the entire CCZ to be estimated by the ISA. This estimate was updated in 2010 [38]. Using different approaches (based on sample statistics and considering a biochemical model), an Inferred Resource of between 21.1 and 30.7 Bt was estimated for the entire CCZ. None of the ISA estimates were reported using an internationally recognised code.

For the Federal Institute for Geosciences and Natural Resources of Germany (BGR), Ruhleman et al. [39] reported a table of "basic values… including averaged bulk nodule metal contents", including 795 Mt (dry) @ 1.3% Ni, 1.1% Cu, 0.17% Co, 7.0% Fe, and 29.2% Mn within 58,000 km^2 for their E1 area.

The first mineral resource estimate for deep-sea polymetallic nodules reported in compliance with a CRIRSCO code was published in 2013 for Nautilus Minerals by Nimmo et al. [22]. The authors issued an NI 43-101 Technical Report documenting an inferred mineral resource of 410 Mt (wet) @ 1.2% Ni, 1.1% Cu, 0.24% Co, and 26.9% Mn. This was within an area of 51,891 km^2 held under contract by Nautilus subsidiary, Tonga Offshore Mining Limited (TOML). This estimate was followed up in 2016 by Lipton et al. [12] under the same codes with mineral resource estimates to inferred, indicated, and measured levels of confidence. Much of this work forms the basis of the present paper.

In late 2014, the ISA convened a workshop with subject matter experts and existing mineral rights holders (called Contractors; see Table 1) to better understand the status of the polymetallic nodule mineral resources and establish a standard for reporting within the area [40,41]. The standard could then be used by Contractors in complying with their obligations to annually report their exploration activities. This workshop led to the ISA adopting the CRIRSCO guidelines as their reporting standard and specific guidelines being published for the estimation of mineral resources for polymetallic nodule deposits.

Table 1. Summary of CCZ mineral resource estimates from the ISA 2014 workshop.

Contractor	Tonnage	Abundance	Grades	Comments
State Scientific Center Yuzhmorgeologia [42]	448 Mt (dry)	Not provided	1.39% Ni 1.1% Cu 0.23% Co 29.3% Mn	Used classification of State Commission on Mineral Reserves of the Russian Federal Government Agency
Korea Institute of Ocean Science and Technology [43]	188.4 Mt (?dry)	10.4 kg/m2 (?dry)		Relates to a Priority Mining Area (PMA) with an area of 18,113 km^2 and an estimate that 60% is mineable
Deep Ocean Resources Development Co Ltd. [44]	643Mt (wet)	8.57 kg/m2	1.35% Ni, 1.06% Cu, 0.23% Co and 27.85% Mn, 29.02% total moisture	Global estimate for their entire 75,000-km^2 contract area, referenced the JORC code but did not mention the role of competent persons
Interoceanmetal Joint Organization [45]	48.1 Mt (wet)	Not provided	1.31% Ni, 1.29% Cu, 0.16% Co, 32.6% Mn	H11 sub-area
Tonga Offshore Mining Limited [46]	410 Mt (wet)	9.4 kg/m2	1.2% Ni 1.1% Cu 0.24% Co, 26.9% Mn	Abundance cut-off of 6 kg/m^2. To NI 43-101 standard, from Nimmo et al. [22]

DeepGreen Metals Inc. released a NI 43-101 Technical Report documenting mineral resource estimates for the entire contract area held by its subsidiary, Nauru Ocean Resources Inc. (NORI), in 2018 [23] and for the NORI Area D in 2019 [24].

In 2018, Global Sea Mineral Resources, a member of the DEME Group and an ISA contract holder, referred to a mineral resource estimation process related to a test area within their B4 sub-block [47]. This included the use of autonomous underwater vehicle images (nodule coverage) and the application of factors for nodule size and sediment cover. Some grade data were presented, but the report did not provide all of the information required by the CRIRSCO code.

3. Reporting Standards and the International Seabed Authority

The reporting of a mineral resource estimate is usually done to a standard or code required by the users of the estimate—for example, the regulatory body for the financial capital market being used for project funding or the nation in which the deposit resides. In some cases, a company is required to report under more than one code, even though this can lead to inconsistencies in the reporting and even in the estimates.

For the ISA, the existing structure of CRIRSCO works well to meet the requirements of regulators and Contractors alike, especially as the Contractors developing mineral resources in the area come from over a dozen different countries. To this end, the ISA updated its reporting requirement for Contractors to include reporting to a standard, as outlined in Annex V of the ISA ([48] replicated on the CRIRSCO site [48]). This standard is largely based on the JORC Code (one of the CRIRSCO member codes) but is notably different as it does not include the need for a qualified or competent person. The ISA standard does note that reporting under other regulatory requirements needs to be considered and that, in many cases, the more conservative of the two codes will need to be followed.

As the ISA is an associated body of the United Nations, CRIRSCO has also produced a bridging document ([49]) to try and relate the member codes to the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC; [50]).

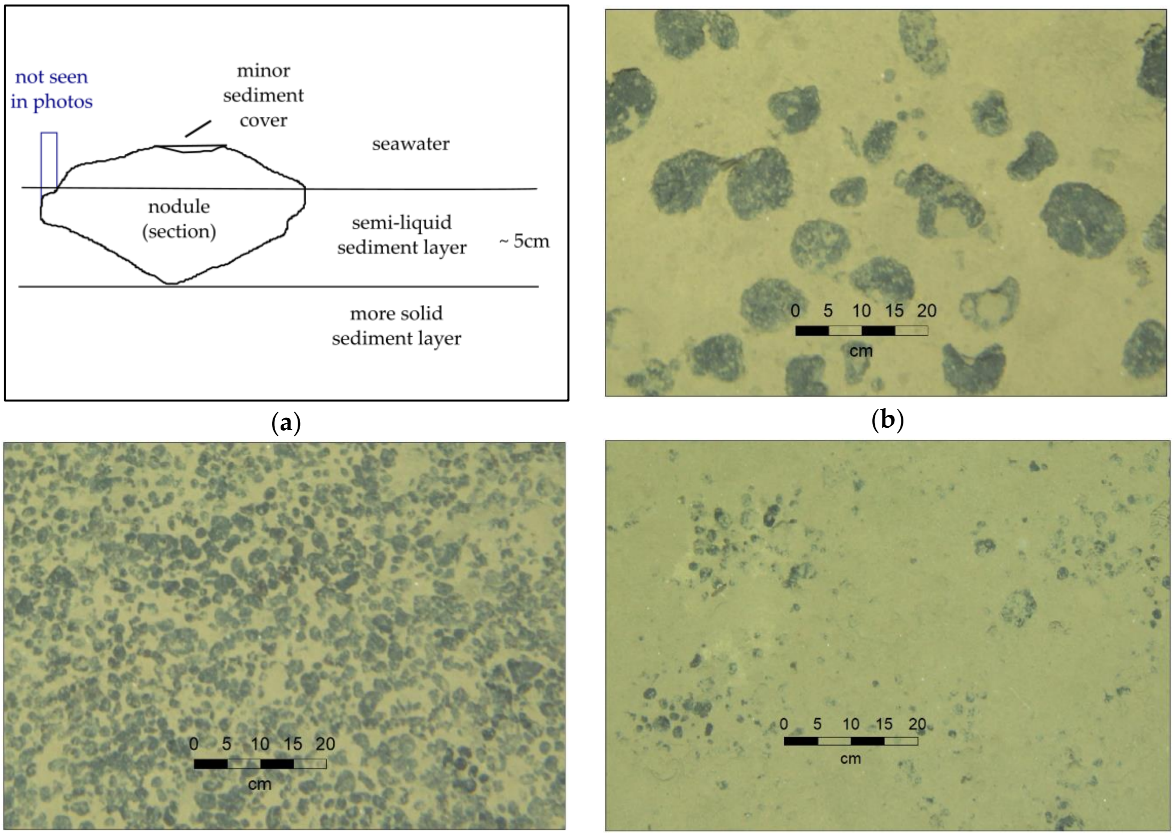
4. Methods for the Evaluation of Polymetallic Nodule Deposits

4.1. Contrasting Estimation of Terrestrial Mineral Resources and Polymetallic Nodule Mineral Resources

Metalliferous mineral deposits occurring on land were commonly formed deep in ancient oceanic or continental crust or covered after deposition by younger rocks. The majority of these deposits are buried or only partially exposed on the modern land surface. Evaluation of these mineral resources is, therefore, a three-dimensional task, requiring estimation of the volume of the mineralised body, its density, and the grades and spatial distribution of the elements or minerals of interest. The CRIRSCO family of codes requires that the volume of waste removed to access the mineral resource be considered as part of an assessment of the reasonable prospects of eventual economic extraction.

Because the nodules of economic interest are all located on the surface of the seafloor, the third dimension (vertical depth) has no impact on their economic assessment. The process of mineral resource estimation is, therefore, essentially two-dimensional.

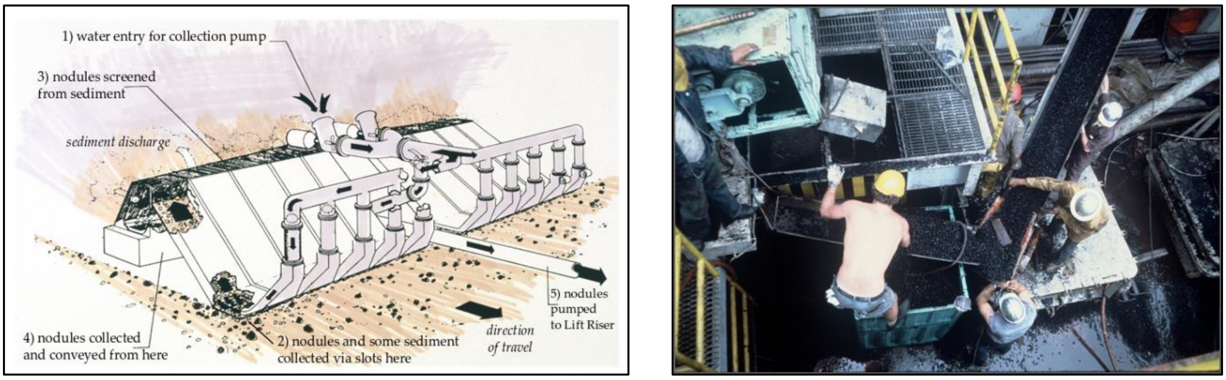
The seafloor polymetallic nodule deposits that are currently recognised have no overburden (Figure 5). Furthermore, the proposed nodule mining systems (including those piloted in the late 1970s (Figure 6)) all separate and reject, in the very first step of mining, almost all of the unconsolidated seabed sediment upon which the polymetallic nodules rest (e.g., Brockett et al. [51]). Thus, the volume, mass, and grade of the sediment are not material to the economic value of the mineral resource, even if they have considerable significance in terms of the marine environment and the geotechnical aspects of subsea mine engineering.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Polymetallic nodules on the seabed. (**a**) Schematic cross-section of nodules on the seabed; (**b**) example of large nodules (source: Tonga Offshore Mining Limited (TOML) image 2015_08_17_044250); (**c**) example of small nodules (source: TOML image 2015_08_17_105534); (**d**) example of covered nodules (source: TOML image 2015_09_16_183847).



(**a**) (**b**)

Figure 6. Polymetallic nodule pilot mining by Ocean Management Inc. of Seattle, United States in 1978. (**a**) Pilot nodule collector schematic; (**b**) reception of nodules at the surface vessel. Sourced and adapted from Brockett et al. [51].

By convention, polymetallic nodules are estimated and reported in terms of their abundance, in wet kg/m^2, on the seabed (e.g., [12,25,37,52]). What constitutes the seabed, however, is not consistently defined. The majority of nodules are found at the surface or within the top 5 cm of clay-ooze (e.g., Figures 5 and 7), but sampling in the CCZ has revealed that, locally, there can be up to 25% more nodules buried at depths of 5–40 cm ([12,45]). Buried nodules were not considered important for, or included in, the mineral resource estimates by Lipton et al. [12] because of the lack of data on the extent of their occurrence.

Nodule abundance is typically reported in wet kg/m^2 because the water content is relevant to the behaviour and cost of the nodules during collection from the seafloor and transportation to processing facilities. Water content also has a direct impact on the cost of processing the nodules to extract the metals of economic interest. This convention is akin to the reporting of coal resources on an "air-dried" basis.

Despite its scale, the CCZ is effectively a single mineral deposit [22]. The nodules in the CCZ all formed via broadly similar processes in a single (prolonged) event. Land-based and shallow marine deposits have similar distributions (albeit at a smaller scale), with a single deposit comprising several lenses, shoots, or gravel beds.

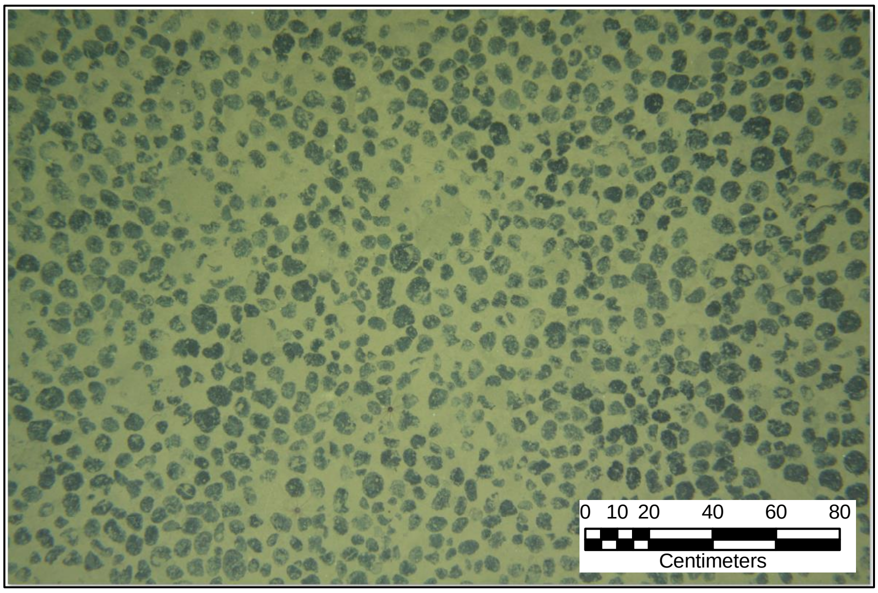


Figure 7. Example of an area with a high abundance of nodules. Source: TOML image 2015_08_10_155723.

4.2. Geology of Polymetallic Nodule Deposits

Consideration of the geology and the spatial distribution of mineralised material is essential for a reliable estimation of mineral resources. Although the areal extent of polymetallic nodules is enormous, nodules are not equally developed or preserved on all parts of the seafloor. At the scale of the estimation, discrete domains can be defined (geologically mapped) to more accurately constrain the mineral resource estimate.

The bulk of the seafloor is geomorphologically classified as abyssal hills (gently crenulated ridges; Figures 8–10). Cooling and structural reorganisation, following seafloor spreading, are believed to have given rise to this seafloor form, which is the most common geomorphological form on Earth (Kennish [53]). Within the CCZ, the ridges are typically oriented NNW–SSE, with an amplitude of 50 to 300 m and a wavelength of 2 to 10 km.

The basaltic basement of the abyssal hills is covered by sediments, and within the CCZ, these is a stratigraphic sequence of carbonate chalks and overlying siliceous clay-oozes (Figure 10). Seabed currents can move the clay-oozes into thicker drifts, which typically host few, if any, nodules (Figures 8 and 11).

Superimposed onto the abyssal hills are more recent volcanic units, including mappable seamounts and knolls (Figures 8 and 12), sheet flows, and fissure lavas/dykes. There are also numerous narrow, and often rocky, fault escarpments (Figures 10 and 13) that can expose the chalk layer or basement volcanic rocks. All of these units are less prospective for nodules (Fouquet et al. [54], COMRA, [55]).

Ship-based 12-kHz multibeam echosounder survey (MBES) can be used to measure (a) the distance to the seabed (bathymetric depth or seafloor topography) and (b) the reflectance (backscatter) of the seabed. Analysis of the two responses, especially backscatter, allows for some interpretations of seabed geology. Hard substrates, nodule fields, and nodule-free areas are often distinguishable qualitatively in the backscatter data, especially if supported by towed camera survey and/or higher resolution sidescan and sub-bottom profiler acoustic surveys (e.g., Figures 8 and 9). Use of the backscatter response is effective in helping explorers to find and delineate larger nodules, and larger nodules may also be associated with higher abundances (e.g., Ruhlemann et al. [39]).

The wide swath of MBES means that its potential use in geological interpretation and mineral resource estimation is attractive. COMRA ([38]) used acoustic response in their Multi-Frequency Exploration System (MFES), which was refined by Tao et al. [56]. Knobloch et al. [57] included MBES response in their combined artificial neural network and geostatistical mineral resource estimation, and Wong et al. [58] observed >85% average accuracy for their study area, using a combination of bathymetry and backscatter processed through an artificial neural network. Gaziz et al. [59] applied machine learning to AUV (autonomous underwater vehicle) MBES and photographic data for predictive modelling at a smaller scale (i.e., pre-mining scale). However, Lipton et al. [12] illustrated that the sediment type also affects the response, with near-surface chalk absorbing more sound than siliceous clay-ooze, so care may be needed in new areas.

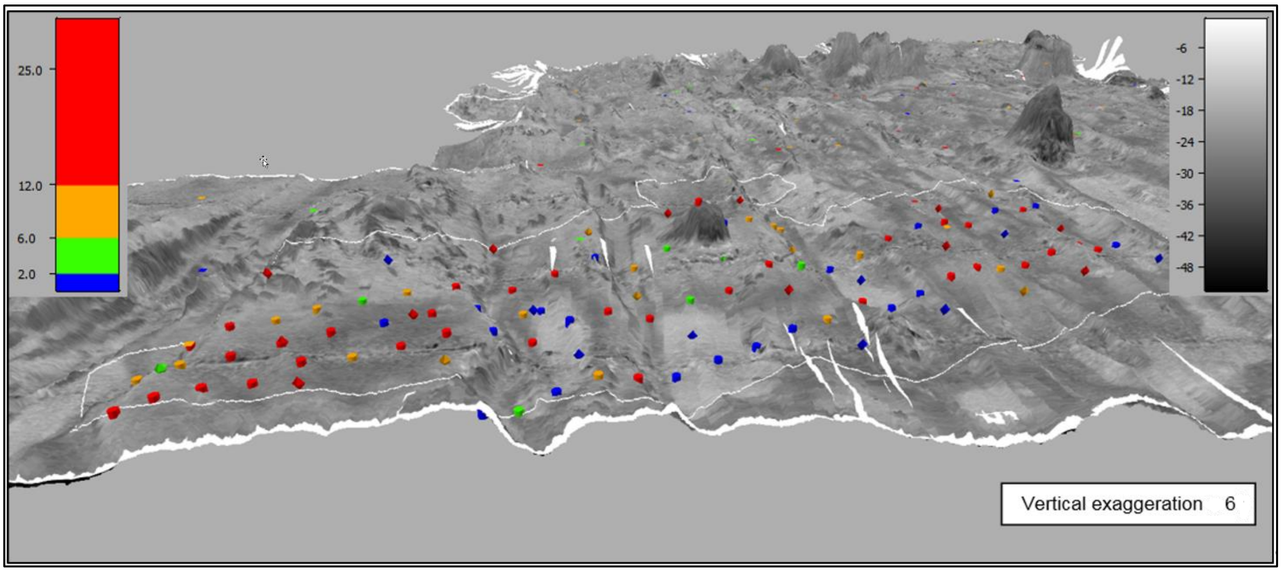


Figure 8. Nodule-rich and nodule-poor areas on a typical area of seafloor in the CCZ. The scheme shows 12-kz multibeam echosounder (MBES) backscatter based on bathymetry and sample data. For scale, the sample symbols are typically 3-km apart (refer also to Figure 9). Abundance (coloured) is given in wet kg/m^2; the acoustic absorption (backscatter; grey scale) is in dB. Very dark areas generally relate to exposed volcanics (no nodules to speak of and not sampled), very light areas generally relate to sediment drifts (some sampled), and intermediate grey areas are nodule-bearing sediments. Within the white outline is the area that was estimated to an indicated and measured level of confidence, while outside, it was estimated to an inferred level.

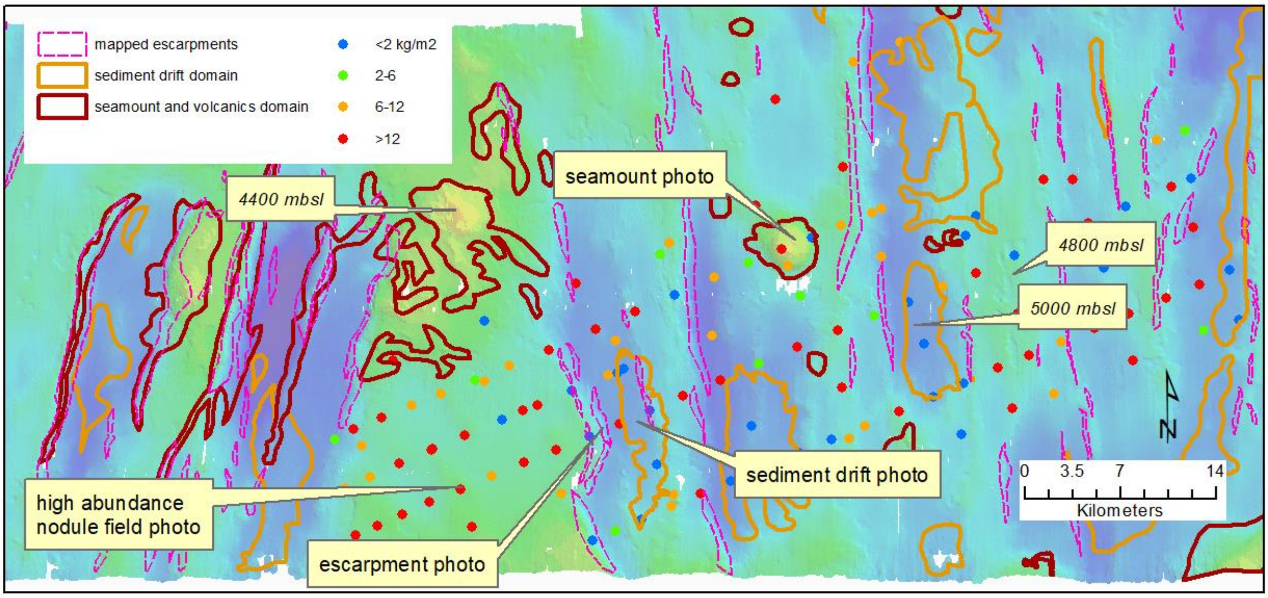


Figure 9. Resource domains in one part of the CCZ nodule deposit. The colour scale represents the seabed bathymetry with example depths for scale. The area is the fore and mid-ground of Figure 8. Photo sites are for Figures 7 and 11–13.

Lipton et al. [12] used MBES data to help define domains with low potential for nodule abundance that were excluded from the mineral resource estimate. These included volcanic areas and soft sediment drifts, where seabed photos and box core samples both confirmed that there were few, if any, nodules present.

Figures 8 and 9 show how changes in host and basement geology can relate to nodule abundance and thus help to define such domains for mineral resource estimation.

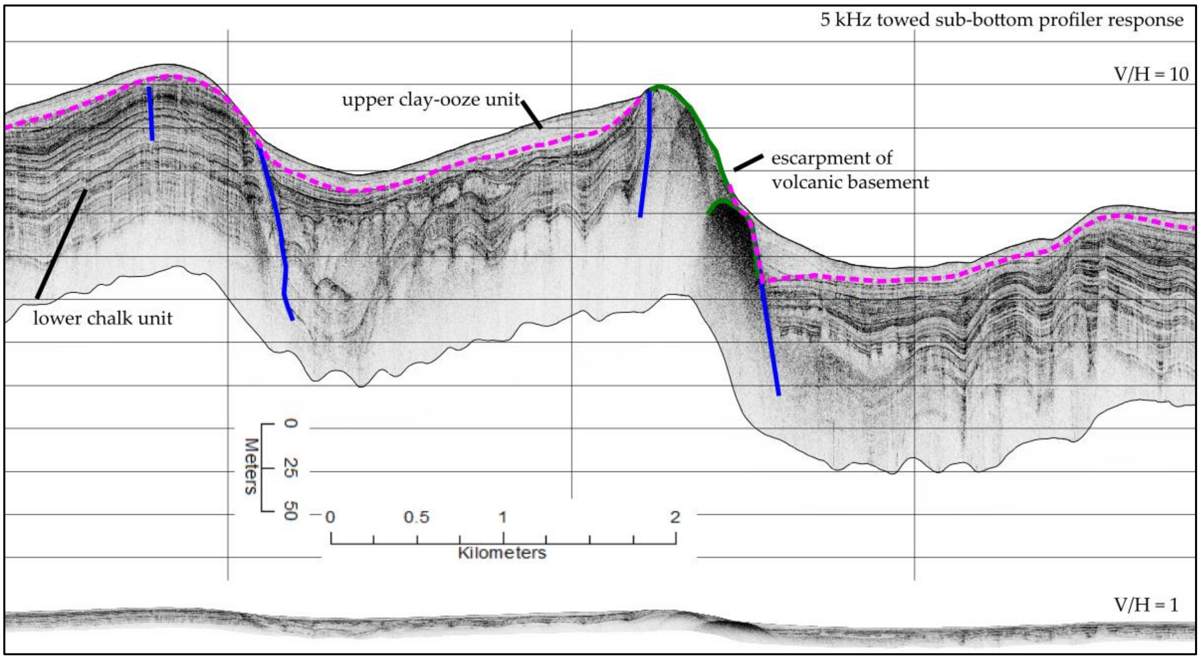


Figure 10. Example sub-bottom profiler image of the host/basement for the nodule deposit.

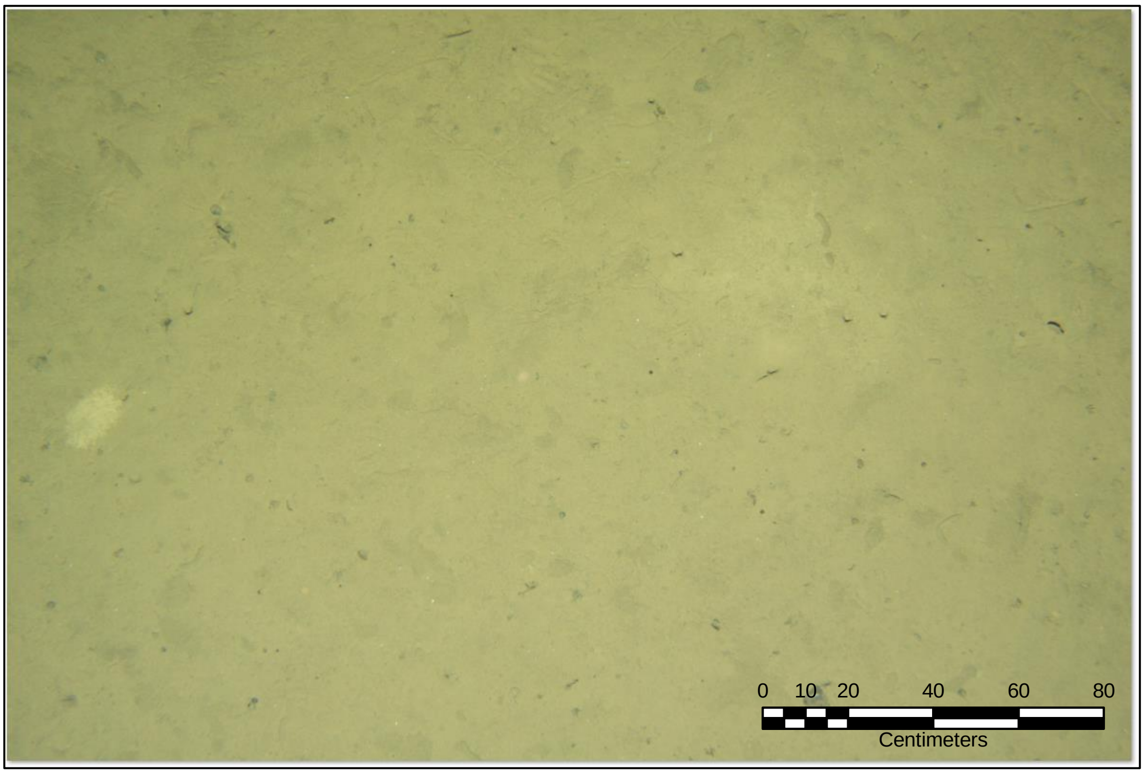


Figure 11. Sediment drift example photo. Source: TOML image 2015_08_10_225306.

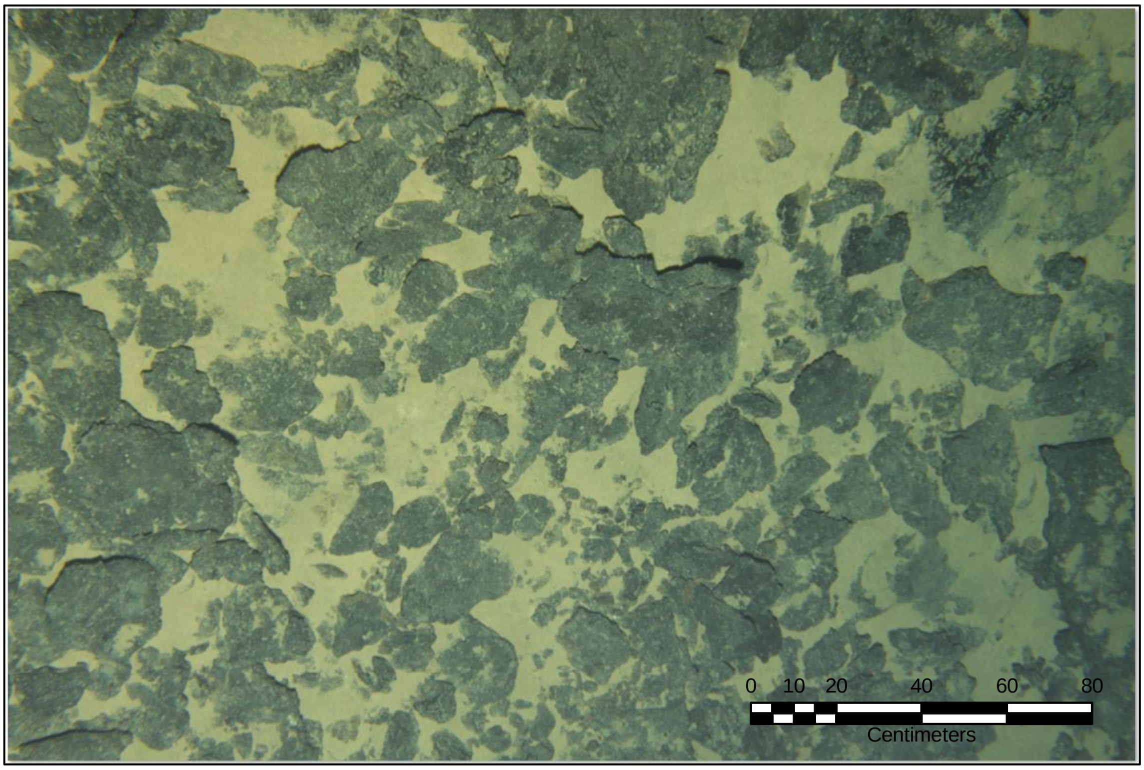


Figure 12. Volcanic knoll crest example photo. Source: TOML image 2015_08_17_094309.

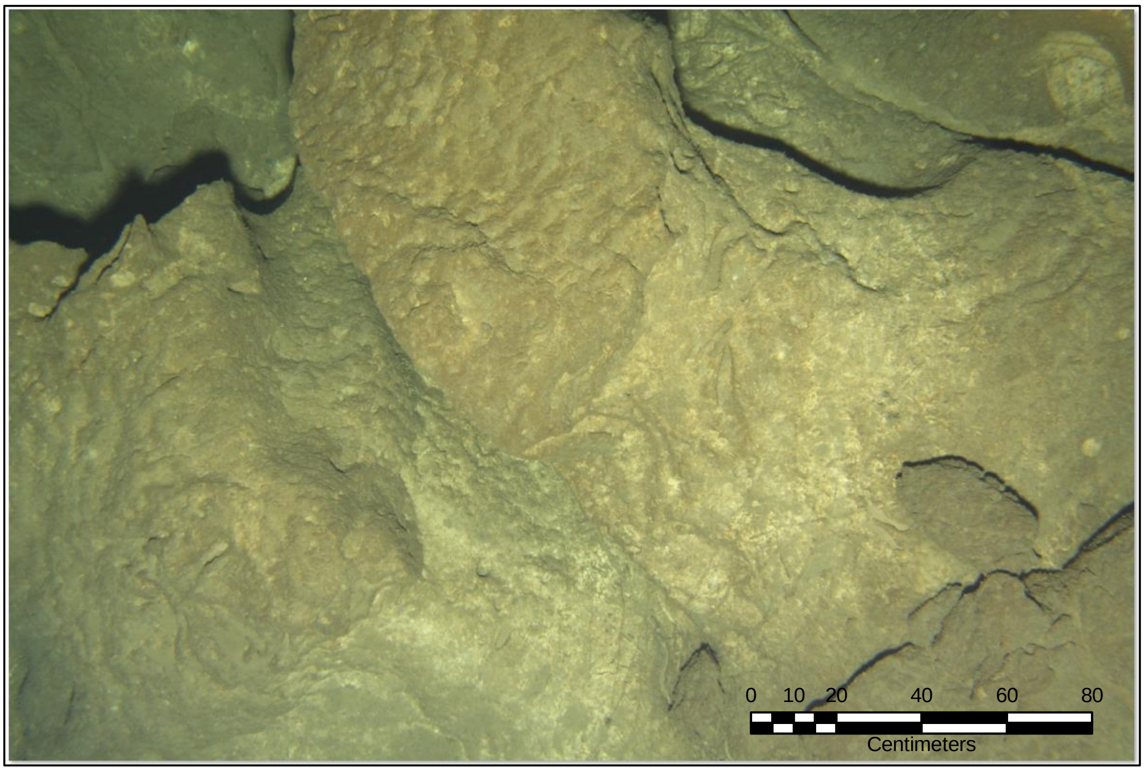


Figure 13. Chalk escarpment example photo. Source: TOML image 2015_08_10_205331.

4.3. Sampling

4.3.1. Physical Sampling

There are two main types of samplers used for the physical sampling of polymetallic nodules: free-fall grabs (FFGs) and box corers (BCs). FFG samplers are dropped over the sides of expedition ships and sink to the seafloor without any cable link to the boat (which then proceeds to drop more FFGs in nearby locations). The FFG contacts the seafloor (Figure 14) with a spring-loaded pair of clamshell net bags. This seafloor contact triggers the ejection of ballast, making the sampler buoyant, and the clamshell net bags close as the sampler starts to ascend, capturing the nodules. After it reaches the sea-surface, the FFG sampler is recovered by the boat.

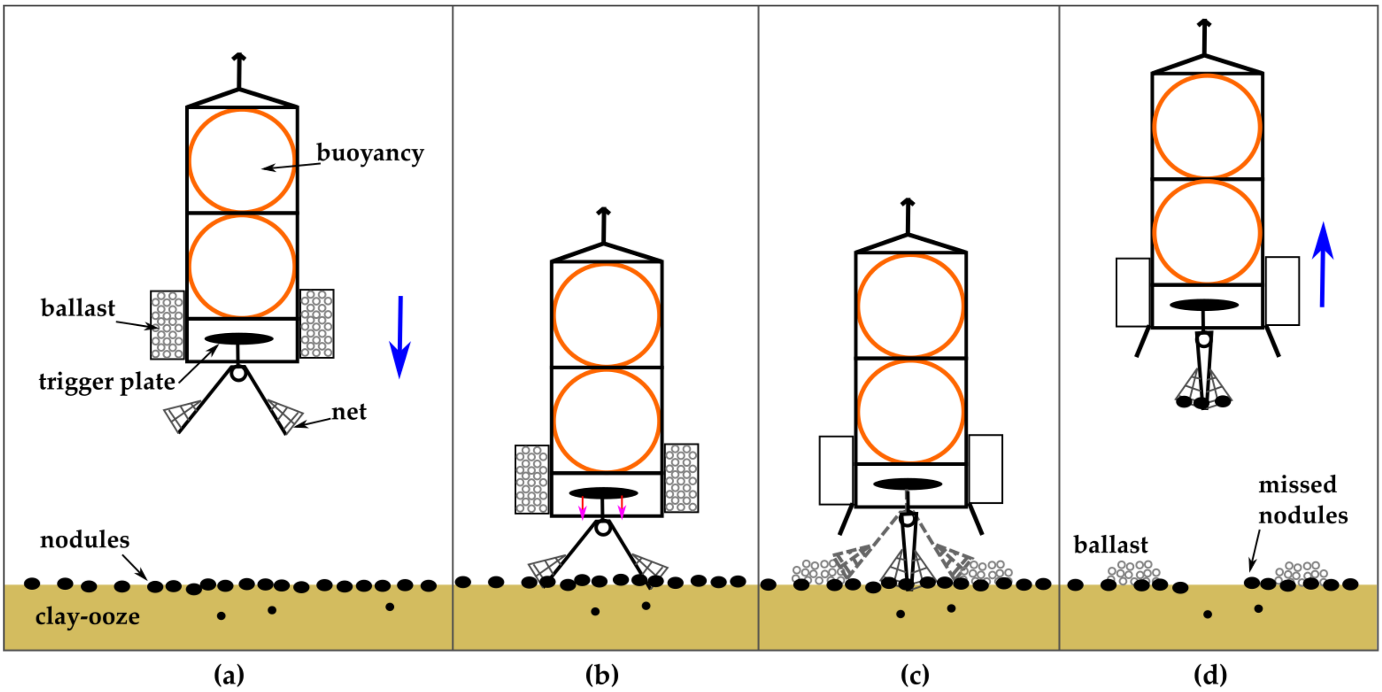


Figure 14. Schematic of the sampling process of nodules using free-fall grab (FFG). (**a**) Free-fall decent; (**b**) landing and trigger; (**c**) ballast dump and closing of grab with start of ascent; (**d**) free ascent. Modified from Lee et al. [60].

A BC sampler consists of an open rectangular steel box with a convex, steel base plate on a rotating arm (Figure 15). The BC is lowered down to the seafloor on a cable, with the base plate retracted. On a soft substrate, the box is typically driven up to 50 cm into the seafloor. As the BC sampler begins to be winched upwards, the base plate rotates into a position under the box, capturing the material within the box in a relatively undisturbed state.

As BC samplers are lowered to the seafloor on a cable, only one can be deployed at a time. At CCZ water depths, it takes around 4 to 6 h to deploy and then recover a BC. BC samples are thus more expensive to collect than FFG samples but generally have a much lower risk of sampling bias. A few nodules near the edge of the box may be pushed into or out of the box or may be pushed below the surface layer in the box core. Thus, a larger area-section box corer should have less primary sampling error, especially in areas of a few large nodules. A low level of disturbance is also favourable for geotechnical tests and biological sampling (Figure 16).

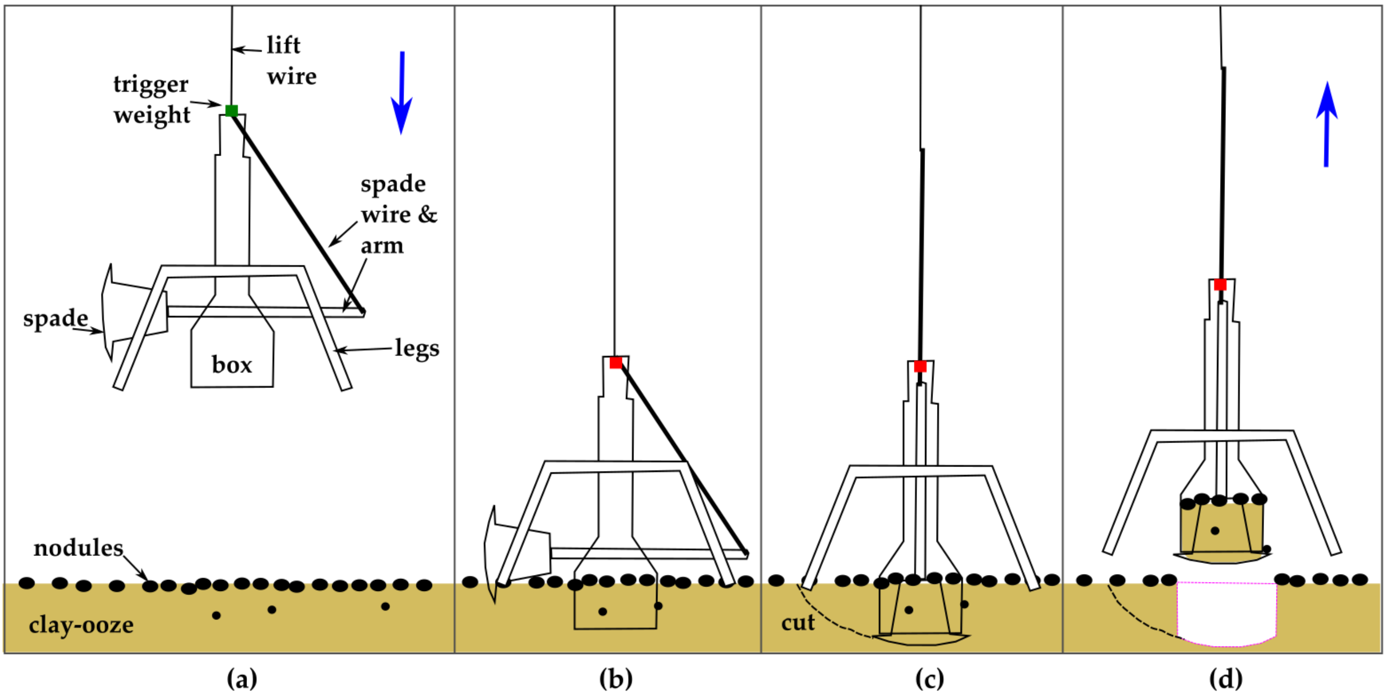


Figure 15. Schematic of the sampling process of nodules using a box corer (BC). (**a**) Descent on wire; (**b**) landing and trigger; (**c**) spade pulled to base of box by the lift and spade wire at the start of ascent; (**d**) lifted ascent. Modified from Lee et al. [60].

Figure 16. Nodules and mud in a box corer (SYMPAS). Source: Museum National d'Histoire Naturelle [61].

FFG samplers are quicker to deploy than BC samplers and are, therefore, cheaper to operate, but they tend to leave some nodules behind during collection and thus underestimate the true abundance of nodules at the sample location (Hennigar et al. [62]; Lee et al. [60]). Data collected only with FFGs have been used to estimate mineral resources at an inferred level of confidence (e.g., [22]).

Lee et al. [60] compared FFG and BC data in some detail. They found a wide range of differences between FFG and BC measurements of abundance, but with a consistent bias, with FFG under-reporting the abundance relative to BC (Figure 17) measurements. The authors attributed the biases to mechanical effectiveness. FFG samplers have been demonstrated to underestimate the actual abundance, as smaller nodules may escape some grabs during ascent, and larger nodules around the edge of the sampler may be knocked out or fall out during the sampling process. A related key issue is the size of the FFG or BC (area covered) versus the nodule diameter.

Lee et al. [60] suggested an overall correction factor of 1.4 to convert an FFG abundance to a BC abundance. However, the authors acknowledged that any simple factor lacks precision. Many workers (e.g., [12,24]) do not use any correction factors and accept that estimates of nodule abundance based on FFG samples are likely to be conservative.

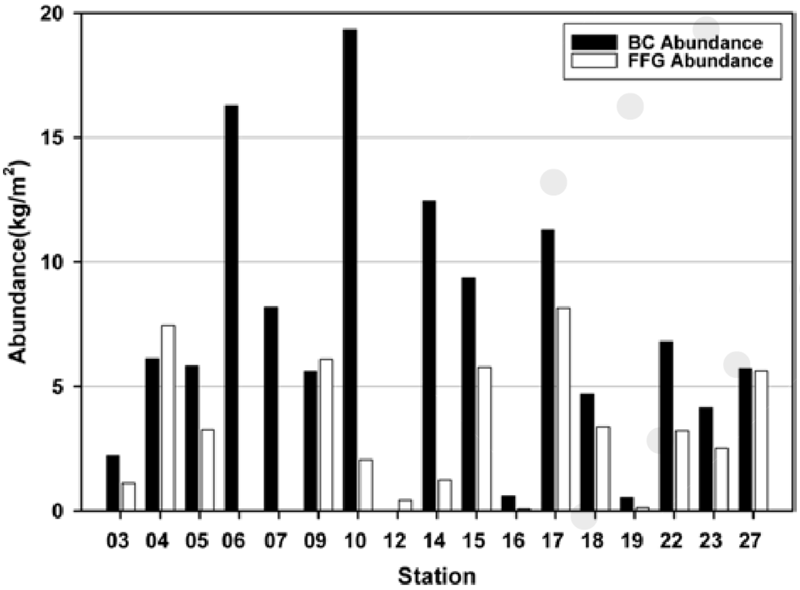


Figure 17. Comparison of returned abundances from BC and FFG at test stations within the KORDI exploration area. Source: Lee et al. [60].

As with terrestrial deposits, sampling on a reasonably regular sample grid is preferable for mineral resource estimation. Due to the high cost of FFG and BC deployment, it is desirable to optimise sampling patterns by identifying areas likely to be poorer in nodules from multibeam back scatter data and excluding (domaining out) such areas from sampling and from the mineral resource estimate. These areas include volcanic knolls and other recent volcanic rocks.

Evaluating polymetallic nodule deposits with BC samplers, or even FFG samplers, at spacings close enough to achieve a high level of confidence is a slow and expensive process. TOML achieved only slightly more than an average of four BC samples per day [12]. Consequently, alternative, lower-cost methods for measuring nodule abundance have been used to supplement physical samples.

4.3.2. Seafloor Photographs and Long-Axis Estimates of Abundance

Attempts to use simple nodule coverage to predict abundance have so far been shown to be ineffective (e.g., Sharma [63], Park et al. [64], Ellefmo and Kuhn [65]). A strong relationship between the length along the long or major axes of nodules (LA) and their weights was demonstrated in the 1970s by commercial explorers, such as Kennecott Exploration and Ocean Mining Associates (Felix [66]; Kaufman and Siapno [67]). Thus, if the nodules are mostly clear of surficial sediment, as is often the case in the CCZ, an estimate of abundance can be derived from photographs of the seafloor. The benefits of photographs over physical sampling, especially for short-range estimates, are that photographs are quicker and cheaper to capture than box-core sampling and measure a larger area.

Lipton et al. [12] successfully used such a technique. Photographs of the seafloor were taken using a camera mounted on the box core immediately before landing the box corer

(Figure 18). Upon retrieval, the long-axis lengths and masses of the nodules were physically measured. The long axis of each nodule on the seabed was also measured digitally from the photograph.

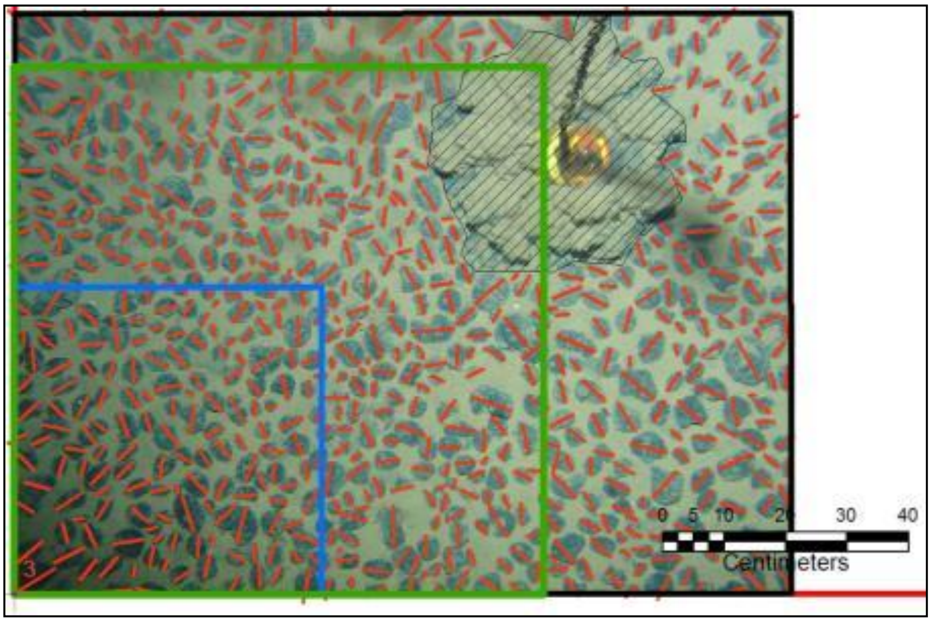


Figure 18. Example of long-axis estimate (LAE) measurements from a photograph taken from box-core-mounted camera. Source: Lipton et al. [12]. The blue frame is an example of an area that would be collected by a 0.25-m^2 box corer, and the green frame is an area that would be sampled by a 0.75-m^2 box corer.

Felix [65] proposed an empirically derived formula for nodules within an unspecified part of the CCZ held by Kennecott Exploration as follows in Equation (1):

$$\log_{10} W = 2.71\log_{10}LA - 0.18 \quad (1)$$

where W is the wet mass of the nodule in grams, and LA is the long or major axis of that nodule in centimetres. Thus, the log form used in Equation (1) effectively provides a linear fit between those two characteristics.

The measurements of [12] (Figure 19) indicate small variations in the empirical regression relationship between areas:

$$\text{TOML area B1: } \log_{10} W = 2.81\log_{10}LA - 0.18 \quad (2)$$

$$\text{TOML area C1: } \log_{10} W = 2.71\log_{10}LA - 0.27. \quad (3)$$

These small variations likely relate to slight differences in the relative growth rates of nodules along their three Cartesian axes or to their bulk densities.

These formulae were then applied to LA measurements digitised from photographs of the seafloor from a towed camera system. The photographs were scaled using either parallel laser pointers or physical scales (e.g., scale annotated on camera trigger weights; Figure 18). As the measurements were done manually, which is an onerous process (including QA/QC), only every 100th photo was measured. This still enabled the estimation of weights of more than 90,000 photographed nodules. The calculated weight of the measured nodules in a given photograph was divided by the area of that photograph to derive a measure of abundance at that location.

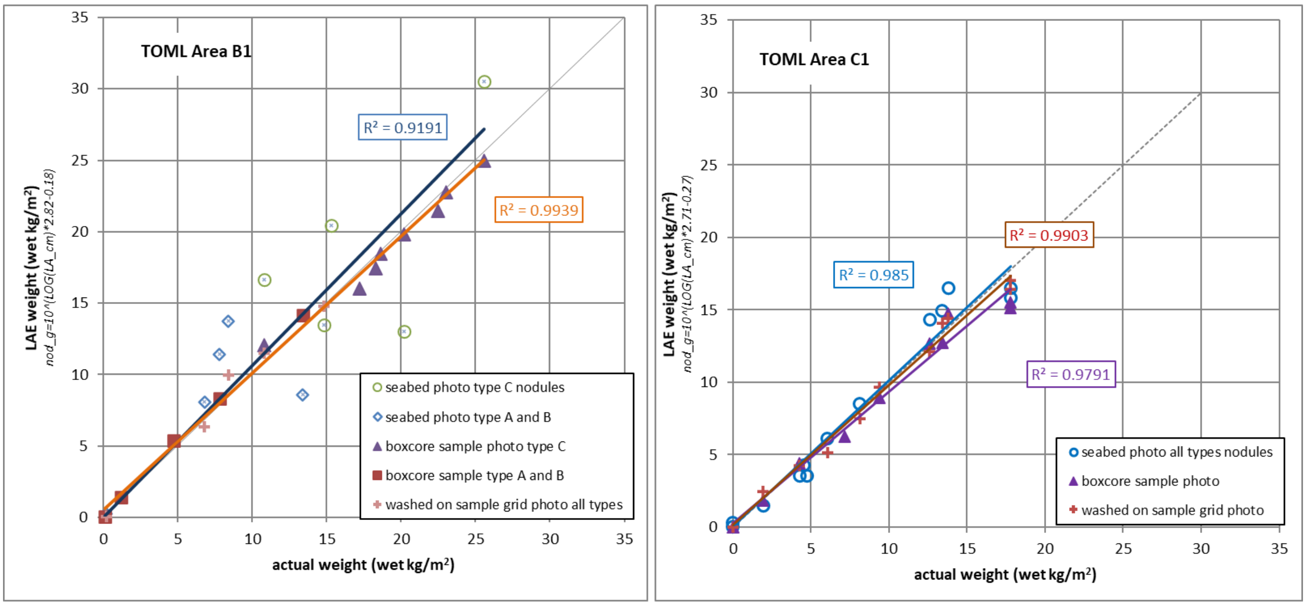


Figure 19. Correlations between total long-axis lengths and nodule sample weights, TOML areas B1 and C1. Source: Lipton et al. [12]; total sample weights and measurements were used for reasons of accuracy. Seabed photographs were taken from the box-core sampler immediately prior to landing; box-core sample photographs were taken of the undisturbed samples after landing the sampler back on the expedition vessel. Grid photo measurements are from nodules on a sample display grid after collection from the box core and washing and weighing. For TOML Area B1, the samples were also classified using a local nodule facies system to see if there was a discernible difference in the relationship. A type nodules are mostly small nodules, B type nodules are of mixed sizes, and C type nodules are mostly large nodules.

As Figure 20 shows, the system can be imprecise in some cases but is generally unbiased and sufficiently accurate for the purpose of estimating overall abundances for a mineral resource. Likely sources of imprecision include:

- Site-scale variations in the local regression relationships (mostly likely due to site-based variations in the thickness of the geochemically active layer and thus the thickness of the nodules);
- Varying scales in the towed photo images (e.g., a slightly oblique perspective when taking the photograph due to flaring of the towed systems resulting from vessel heave);
- Partial sediment cloaking or covering of the edges of nodules (Figure 5);
- Imprecision in the manual digitising process.

One issue identified by [65] may relate to bimodal or variant populations of nodules. Within the NORI D area (adjacent to the BGR eastern area considered by [65]), two distinct facies (or populations) were able to be handled separately in LAE-based estimates by [24,25]. It also remains to be demonstrated that a more accurate relationship between nodule size and weight could be determined through image analysis and even shape fitting to nodules (e.g., Schoning et al [68]). Using a single axis is simpler and may prove less error-prone than trying to use multiple geometries.

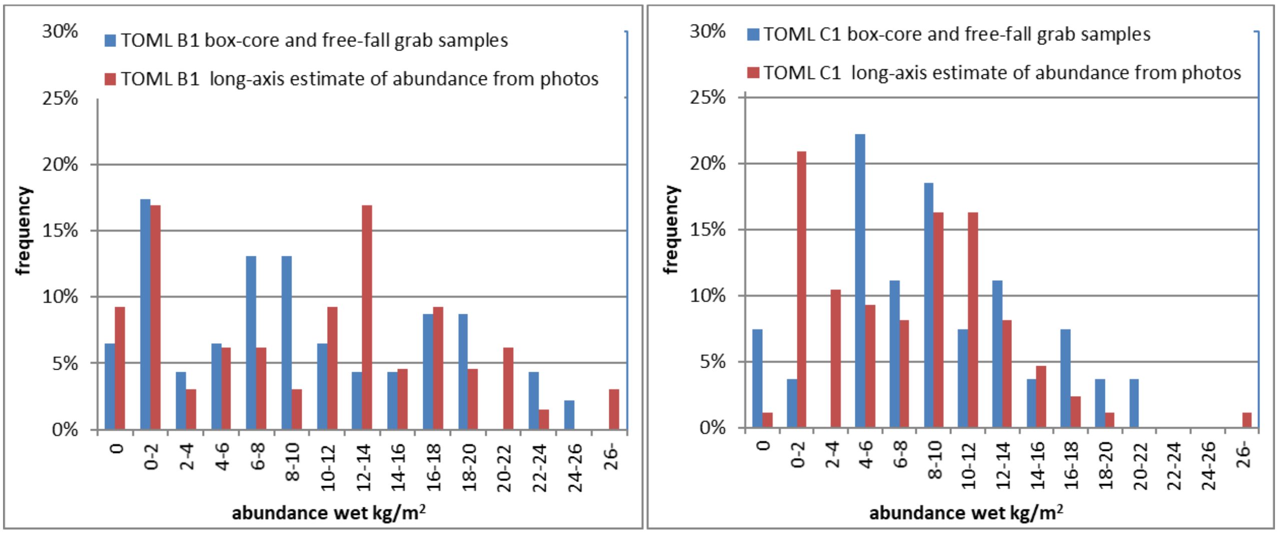


Figure 20. Histograms of abundances measured by physical sampling and the photograph-based long-axis estimate across TOML areas B1 and C1.

Ultimately, high degrees of sediment cover are a key limitation in applying photo-based abundance estimations in some areas (e.g., Figure 21; after Felix [66]), as elaborated by Mucha and Wasilewska-Blaszczyk [69,70]. Lipton et al. [12] found this to be a problem in two out of the five TOML areas that they estimated to an indicated level of confidence (namely, TOML area D1 and D2), so they relied only on box-core samples in these areas.

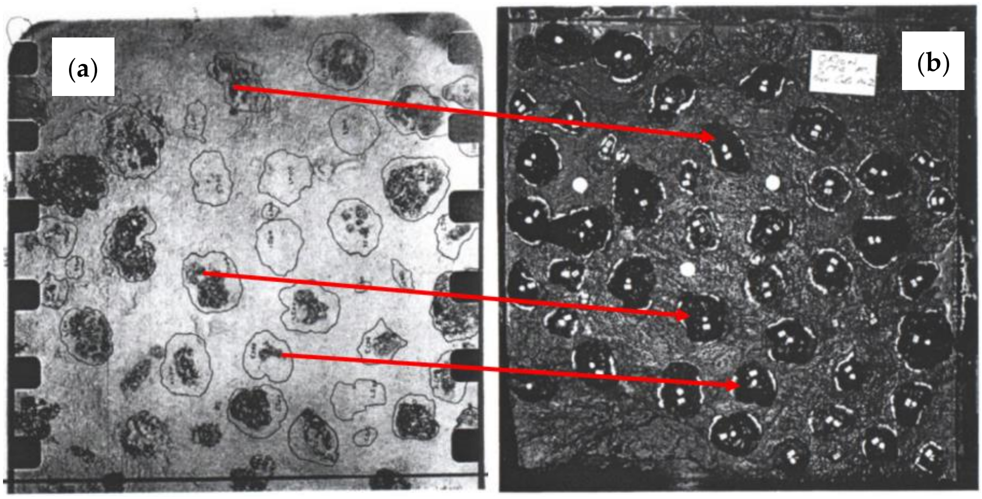


Figure 21. Seabed (**a**) and box-core (**b**) photograph pair in an area with a high degree of sediment cover. After Felix [66].

The TOML nodule mineral resource estimate in [12] was the first to include mineral resources at a measured level of confidence, and LA estimates were a key short-range abundance data source crucial to reaching this level of confidence.

Lipton et al. [12] also trialled an automated image processing technique on photographs taken at approximately 25-m intervals along three lines in the TOML areas (prototype software by Gideon Steyl of GeoSquare Consulting). This trial demonstrated the strong continuity of nodule abundance, supported the physical measurements from box-core samples, and demonstrated the accuracy of the automated method (Figure 22). Automated image processing may be useful for the detailed mapping of nodule abundance ahead of the deployment of seafloor production systems.

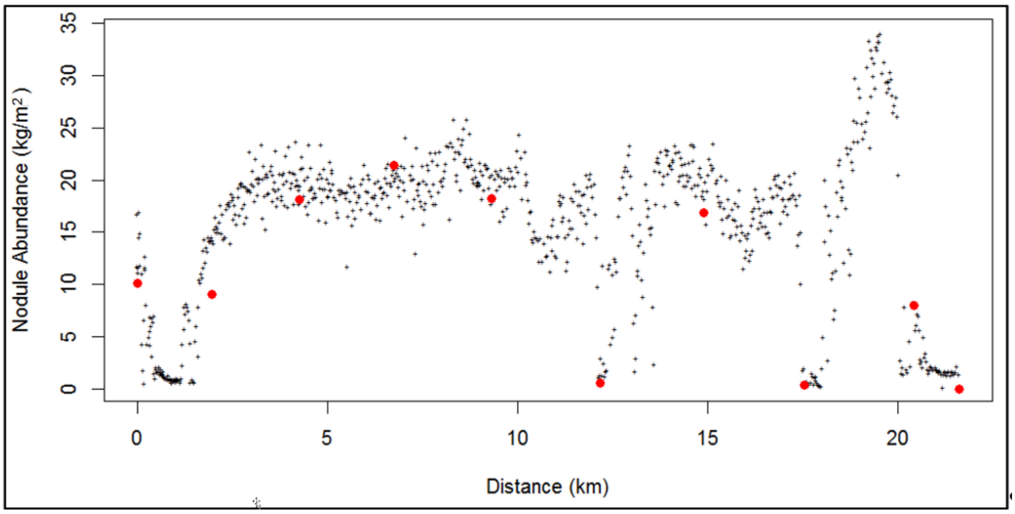


Figure 22. Nodule abundance photo-profile line CCZ15-F04 that crosses sub-area B1 for measured mineral resources. Source: [12]. Red dots—nodule coverage for seafloor photos that were used in the manual estimate of abundance using the long-axis estimation method and in the measured mineral resource estimate. Black dots—nodule abundance for all other seafloor photos derived by automated processing.

The approach of using photographs to estimate abundance has been developed further by Lipton et al. [24], who use a multiple linear regression approach that combines LA estimate and percentage nodule coverage. This approach was demonstrated to be accurate for a calibration set of samples for one particularly important facies of nodules in their estimate. As this facies has closely packed nodules, LAE alone is very difficult to do in an accurate, consistent manner.

4.3.3. Assaying

The measurement of nodule grades is carried out using the same principles and methods used for terrestrial deposits [12,23,25]. The general procedure used in [12] was as follows:

- Split the nodules into representative aliquots;
- Dry the nodules and then crush and pulverise them, reducing the sample size between each step with splitters;
- Analyse a wide range of elements using a mixture of X-ray fluorescence (XRF) and inductively coupled plasma spectrometric (ICP) methods. Measure loss on ignition using a thermogravimetric analysis furnace;
- Use blanks, duplicates, and certified reference materials not known to the laboratory to confirm the precision and accuracy of the analyses.

Polymetallic nodules are hygroscopic ([12]), which means that unless special care is taken, sample aliquots can gain weight after drying, leading to an underestimation of the grade in the analysis step.

Selection of the drying temperature is important. Two main types of water are present:

- Water of crystallisation included within the manganese and iron oxide minerals. This was determined in TOML test work to consistently be around 16% by wet weight (including the likely trace levels of other volatiles) [12]. A very small amount of water from crystallisation likely starts to be removed at temperatures as low as 50–70 °C through a transformation of the manganese mineral buserite into birnessite, but most manganese and iron oxide minerals are stable until reaching higher temperatures (115 °C and greater; Novikov and Bogdanova [71]);
- Free water included within pores and other cavities within the nodules, including water adsorbed onto mineral surfaces—this is estimated to be around 28% by wet

weight depending on the micro and macro void space in the nodules. Air-drying may remove approximately 16% (absolute) of this, with the rest removed by oven drying (up to 105 °C).

In this regard, nodules are similar to some tropical laterites which commonly have 25-30% free water and 15% water of crystallisation (Lagendijk and Jones [72]).

Estimating the water content is then complicated further because the nodules have very high porosity ([73]) and are hygroscopic. After drying to 105 °C, pulped nodules may absorb 7% of moisture by mass, or more, within a day if exposed to ambient air [12].

Lipton et al. [12] also reported experiments to understand the drying behaviour of nodules. Nodules were air-dried at ambient temperatures for extended periods and then oven-dried for several hours in increasing temperature steps. The combined drying curve is summarised in Figure 23. The tests suggest that some of the oxy-hydroxide minerals are only meta-stable and that some decomposition occurs across a continuous range of relatively low temperatures. Ultimately, the authors in [12] concluded that the industry standard drying temperature of 105 °C for rock samples provides a reasonable baseline for geochemical analysis.

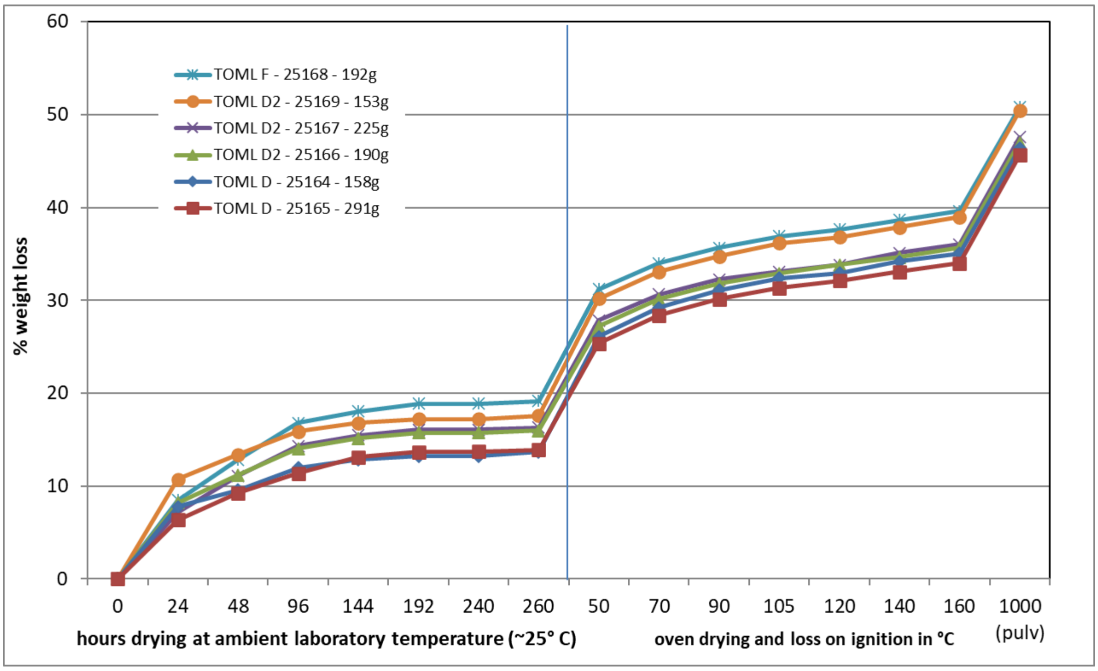


Figure 23. Three-stage drying curve for polymetallic nodule samples. Source: Lipton et al. [12].

While nodule grades are quoted on a dried basis, abundances and tonnages are usually quoted on a wet basis. This is a commonly accepted practice for similar bulk commodities containing significant amounts of free water (e.g., iron ore or nickel laterite), as the wet weight is often simpler to measure and more significant in terms of any future mining and shipping operation.

4.3.4. Historical Samples

The CRIRSCO codes require that details of sampling and assaying be included in mineral resource reports. Specifically, this involves the sampling method, sample size, assaying methods, assay quality assurance/quality control (QA/QC) data, and chain of custody of the samples. This requirement is problematic for the historical samples collected in the CCZ in the 1970s and 1980s by various groups and supplied to some Contractors by the ISA, as the required information is usually missing [22]. The historical sample results are relevant, however, to contemporary resource estimates, and they have been used previously by ISA [38] in the estimation of the inventory of the entire CCZ deposit.

Due to the very high cost of resampling, it is preferable to establish an acceptable level of confidence in the historic data rather than to simply reject it. In preparing the first CCZ mineral resource under NI 43-101, Nimmo et al. [22] carried out several statistical comparisons and were able to:

- Corroborate the ISA-supplied historical results by comparing the data between different original collection organisations and with other published data (non-ISA) from the CCZ nodule deposit. This was possible due to the large size of the CCZ deposit and the relative homogeneity of the grades across vast areas.
- Demonstrate a level of quality control by directly requesting information on sample collection and analysis from the original groups, also noting that the ISA, as an independent and accountable organisation, would need to check the data they received, as these data were used to define retained and released mineral rights under the groups' administration.
- Retain the services of an independent qualified person with direct experience in sample collection from the CCZ.

Nimmo et al. [22] concluded that historical nodule sample data are suitable for the purpose of estimating mineral resources to an inferred level of confidence. The likelihood that the historic data included free-fall grab samples that may underestimate nodule abundance was recognised but not considered to compromise the estimation of inferred resources. Subsequent authors of published mineral resource estimates (e.g., [12,23]) have reached the same conclusions.

5. Estimation Case Study—Tonga Offshore Mining Limited Contract Area

The authors were intimately involved in the first nodule mineral resource estimates completed to a CRIRSCO standard, as frequently referred to above, and as documented in publicly available technical reports (e.g., Nimmo et al. [22] and Lipton et al. [12]). The estimates pertained to a single contract area issued by the ISA to TOML. This case study serves as a synopsis of many of the above-mentioned principles with the results of the estimation exercises.

5.1. Samples and Related Data

The estimate in Nimmo et al. [22] for TOML Areas A to F was based entirely on the historical FFG and BC data in Table 2 and was thus restricted to an inferred level of confidence. The more closely spaced historical data in TOML Area B (Figure 24) did not improve the level of confidence, as QA/QC information was sparse.

The estimate in Lipton et al. [12] used data collected from two marine expeditions conducted after the estimate in Nimmo et al. [22]. These included multibeam mapping of much of the area, carefully collected and more closely spaced BC samples, and long-axis abundance estimates from a towed seafloor photo survey (Table 2, Figure 24). This additional work confirmed and extended the area that could be estimated; in some areas, this work enabled the estimation of resources to an indicated level of confidence, and in one area, it enabled estimation of a resources to a measured level of confidence (Figure 4).

The criteria for classification were assessed by the qualified person responsible for mineral resource estimations in accordance with the CIM definitions.

Table 2. Data matrix for the Tonga Offshore Mining Limited mineral resource estimates.

Data Type	2013 Inferred Estimate	2016 Inferred Estimate	2016 Indicated Estimate	2016 Measured Estimate
Historical samples from FFG and BC	Critical for grades and abundance estimates	Critical for grades and abundance estimates	Support for grades and abundance estimates	Not needed
Multibeam bathymetry and backscatter	Not available	Used in some areas for model domaining	Needed for model domaining	Needed for model domaining
BC physical samples with full QA/QC and chain of custody	Not available	Used in TOML Area F for grades and abundance estimates	Critical for grades and abundance estimates	Critical for grades and abundance estimates
Long-axis estimates of nodule abundance	Not available	Not available	Support for estimates in some areas	Critical for estimates
Higher-resolution side-scan sonar seafloor mapping	Not available	Not available	Not needed	Support for model domains

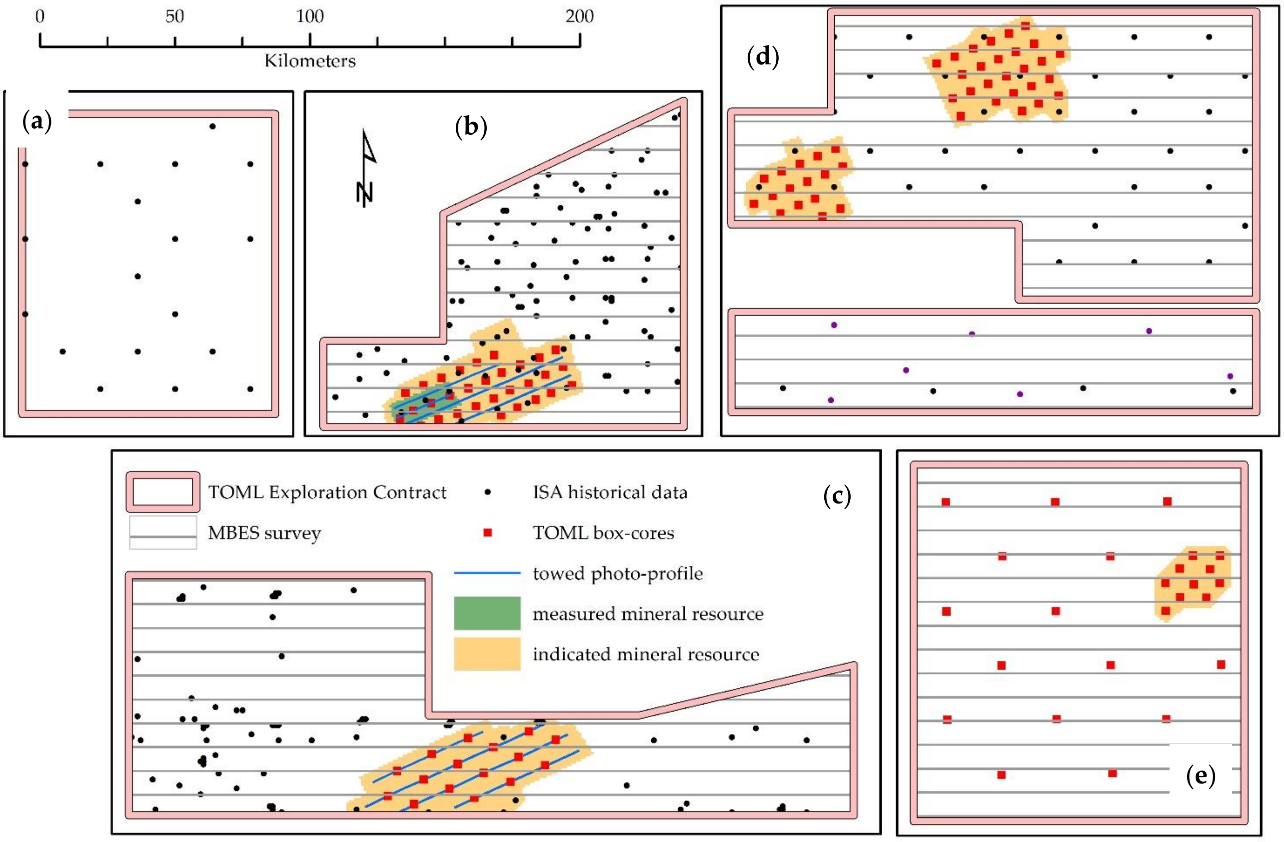


Figure 24. Key data behind the TOML mineral resource estimates. (**a**) TOML Area A, (**b**) TOML Area B, (**c**) TOML Area C, (**d**) TOML Areas D and E, (**e**) TOML Area F.

5.2. Domains and Model

The process for estimating the TOML nodule mineral resource followed a typical workflow for terrestrial deposits, with the significant difference that the estimate model was a two-dimensional grid (block model).

Geological interpretation of the seafloor defined two domains: a nodule-bearing domain (called NOD in Figure 25) and a nodule-free domain (NON).

The nodule-bearing domain featured clay-ooze-covered abyssal hills (e.g., Figure 8), typically with sampling indicating that high-grade polymetallic nodules were present with some level of supporting backscatter response. The abyssal hill escarpments were not excised as their areal extent was judged to be non-significant at the block scale used for the inferred and indicated resources (see below). There were no escarpments within the area estimated to a measured level of confidence. TOML Area A was not mapped or sampled beyond the historical data, so it was assumed to be entirely covered with the NOD domain and confidence in the estimate retained at an inferred level.

The nodule-free domain was a combination of sediment drifts and volcanic areas. These are both accurately mappable from multibeam surveys and known from photographs and box-core samples to usually have few, if any, nodules. Nodule values within this domain were set to null, and the boundaries with the nodule-bearing domain were "hard" (values were not shared across the boundaries).

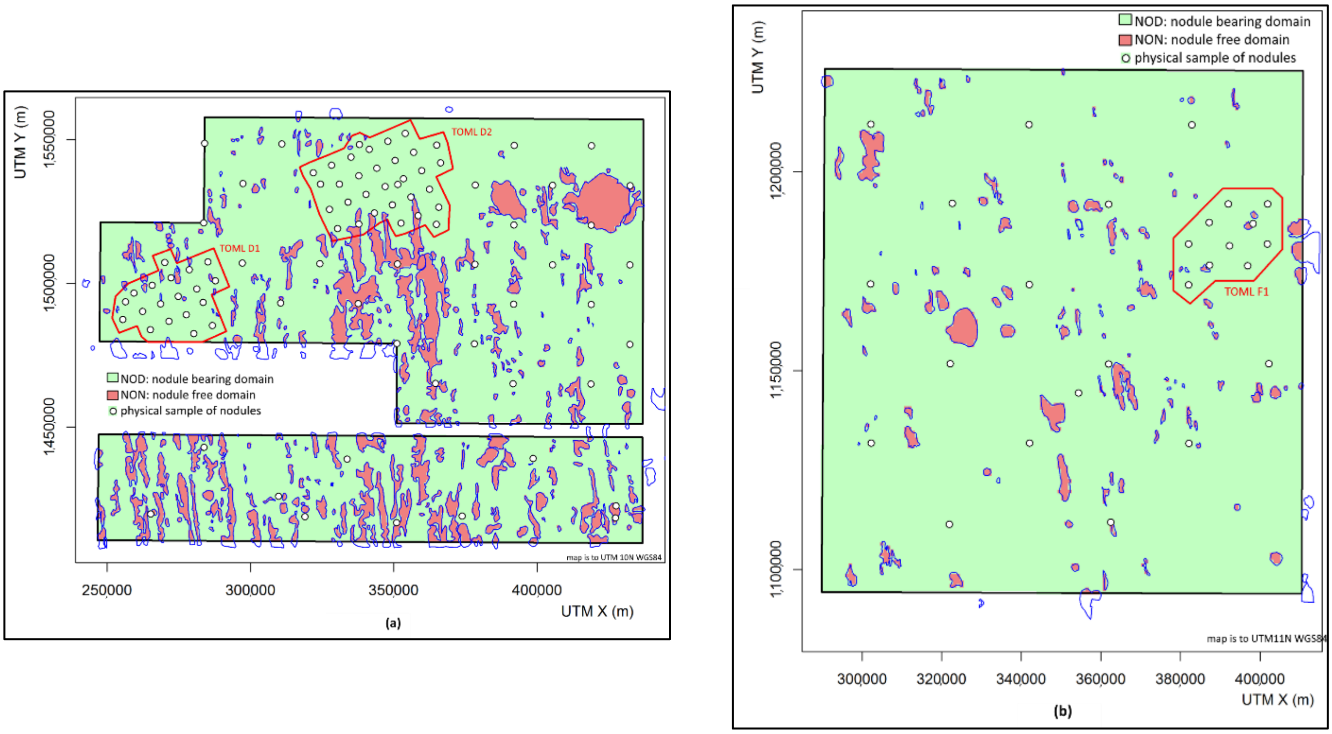


Figure 25. Example domains in TOML mineral resource estimates. (**a**) TOML D and E (**b**) TOML F. Red outlines are areas estimated to an indicated level of confidence; otherwise, these areas were estimated to an inferred level.

Six block models were constructed, one for each TOML exploration sub-area (Figure 24). Each model was blocked and based on the data spacing in Table 3.

Table 3. Data matrix and confidence for the TOML mineral resource estimates in [12].

criterium	TOML B5338	TOML B1	TOML C1	TOML D1, D2	TOML F1	TOML F	Other areas
Level of confidence	measured	indicated	indicated	indicated	indicated	inferred	inferred
Block size	1.75 × 1.75 km	3.5 × 3.5 km	3.5 × 3.5 km	3.5 × 3.5 km	3.5 × 3.5 km	7 × 7 km	7 × 7 km
Historic sampling	referred to	included	included	included	included	referred to	generally, < 20 × 20 km
Box-core spacing	~7 × 7 km	~7 × 7 km	~15 × 15 km offset	~7 × 7 km	~7 × 7 km	~20 × 20 km offset	not needed
Photo-profile (abundance only)	relied at ~3 km × 3.5 km, (verified at ~30 m × 3.5 km)	included at ~3 km × 7 km	relied at ~3 km × 7 km	not used (clay-ooze cover)	not used (operational reasons)	not needed	not needed

Sub-cells with dimensions of 0.875 × 0.875 km were used to accurately represent the boundaries of the TOML exploration areas, the areas interpreted to contain no nodules, and the boundaries between measured and indicated levels.

Grades were then estimated into the blocks using ordinary kriging once the key statistical parameters were established.

5.3. Geostatistics and Model Estimation

Mineral resources for polymetallic nodules were estimated from measurements of nodule abundance and nodule grades at identified locations. Preparation of the data included declustering and exploratory data analysis [12]. In most of the TOML areas, the variability of nodule abundance is significantly higher than that of the metal grades (Table 4). Estimation of abundance is, therefore, the key variable of uncertainty for mineral resources.

Table 4. Declustered statistics of all polymetallic nodule samples within the TOML exploration area.

Variable	Samples	Minimum	Mean	Median	Maximum	Var	CV
Abundance (kg/m^2)	527	0	10.20	9.16	30.77	39.35	0.61
Mn (%)	338	6.54	28.09	28.71	33.79	10.414	0.11
Ni (%)	338	0.33	1.26	1.31	1.55	0.03	0.14
Cu (%)	338	0.22	1.11	1.16	1.51	0.045	0.19
Co (%)	338	0.02	0.22	0.22	0.35	0.003	0.24

Var = variance; CV = coefficient of variation. Source: [12].

Geostatistics provides a range of methods for modelling the spatial continuity of regionalised variables such as abundance and grades. The primary tool for modelling the spatial continuity of such variables is the semi-variogram (commonly abbreviated as the "variogram"). The variogram is a graph of the variance between data points as a function of distance. Variograms are typically constructed either in multiple orientations to test for spatial anisotropy, or all vectors may be considered in an omni-directional variogram. Experimental variograms are calculated for the data points and then fitted with an appropriate model selected from a range of valid mathematical functions.

Variograms were generated using the box core sample data and two-structure spherical models fitted to them (Table 5). As the variables of interest (nickel, cobalt, copper, and manganese) are unlikely to be entirely independent, the variogram models for each variable were selected with consistent parameters, where this process was determined to be reasonable. This was done to ensure that the element relationships or correlations evident between samples were respected implicitly during estimation and reflected in the resource estimate.

Manganese and nickel variograms showed greater continuity in the 150° direction (e.g., Figure 26), and cobalt showed greater continuity in the 060° direction (Figure 27). The 060° direction is roughly parallel to the broad regional trend of the CCZ, and the 150° direction is parallel to the abyssal hills. Copper showed no anisotropy.

Table 5. Model grade variogram models.

Variable	Nugget	Spherical Structure 1			Spherical Structure 2			Anisotropy Ratio
	C0	C1	Range H1		C1	Range H2		
			060° (km)	150° (km)		060° (km)	150° (km)	
Mn	0.21	0.37	5	10	0.42	15	30	0.5
Ni	0.21	0.37	5	10	0.42	15	30	0.5
Cu	0.21	0.37	22	22	0.42	70	70	1.0
Co	0.21	0.37	22	16	0.42	70	50	0.714

Source: [12].

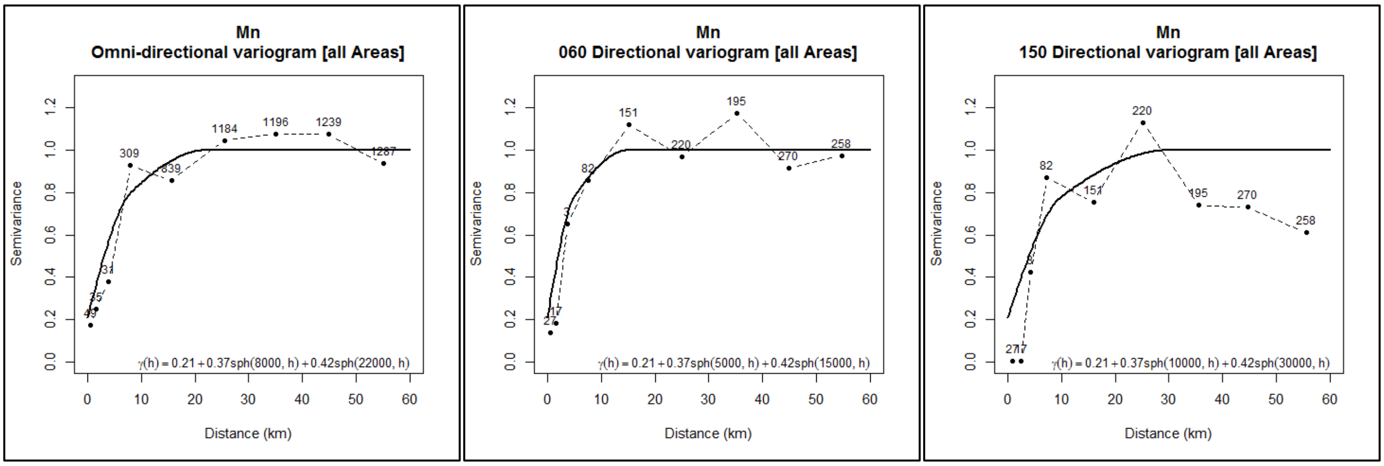


Figure 26. Mn omni-directional, 060° and 150° directional variograms. Source: [12].

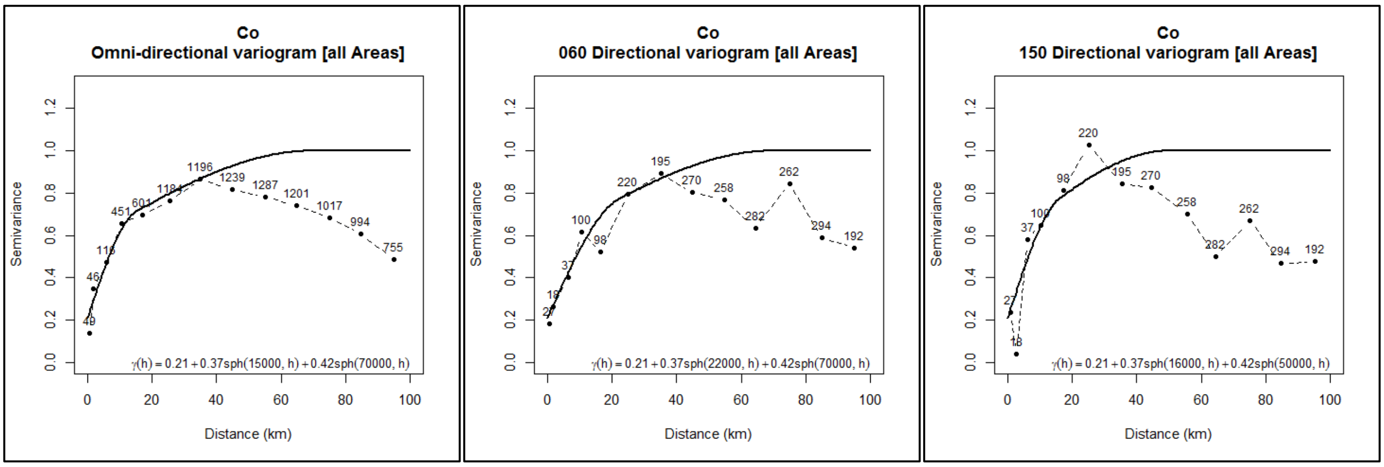


Figure 27. Co omni-directional, 060° and 150° directional variograms. Source: [12].

The variogram models for abundance generated from the box-core data were compared with variograms generated from the LAE abundance values. The variogram structures were similar. The experimental variograms combining both physical samples and LAE in [12] showed ranges of around 5 km for abundance (Table 6, Figure 28) versus 5 to 22 km for grade (e.g., Figure 26). It is noted that variograms in [25] have a range of around 3 km for abundance from the NORI D Area.

Table 6. Model abundance variogram models.

Variable	Nugget	Spherical Structure 1			Spherical Structure 2			Anisotropy Ratio
	C0	C1	Range H1		C1	Range H2		
			060° (km)	150° (km)		060° (km)	150° (km)	
Abundance	0.40	0.60	5	5	–	–	–	1.0

Source: [12]. "–" means not defined

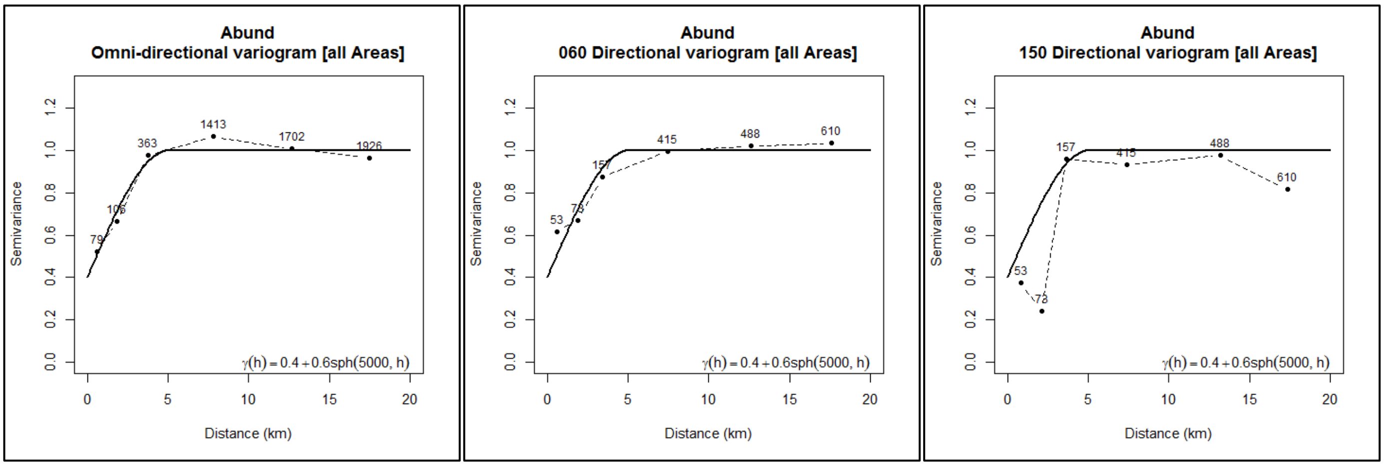


Figure 28. Omni-directional and 060° and 150° directional variograms for abundance. Source [12].

Also interesting is the periodic effect (hole effect) evident in the variogram at ranges of approximately 7.5 and 15 km (Figure 29). This may be related to the periodicity of the spacing between the abyssal hills.

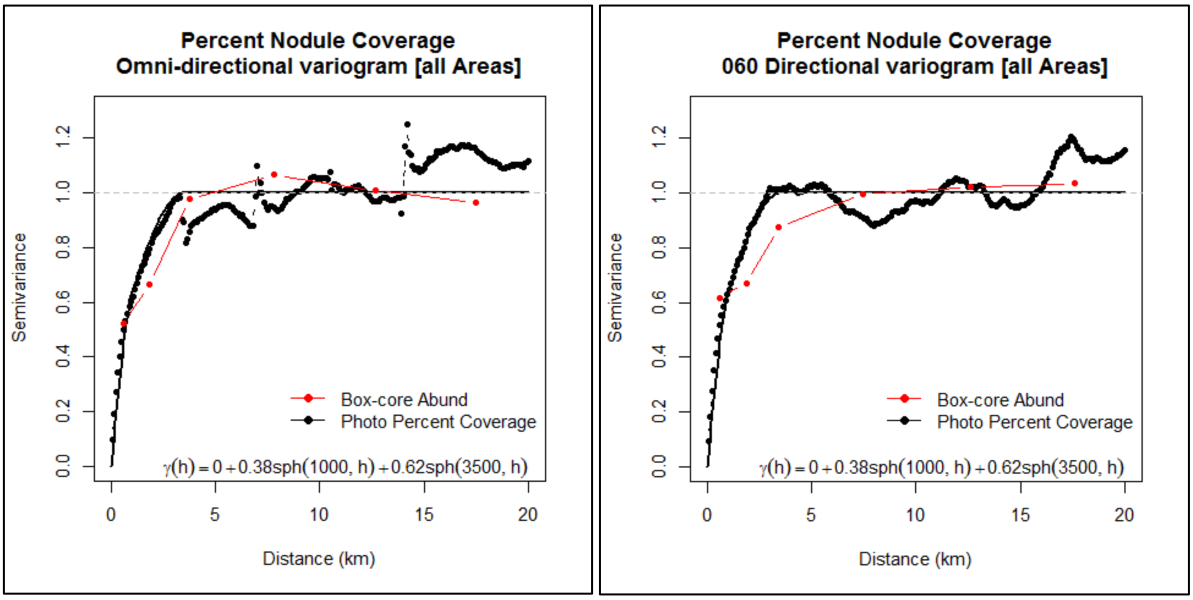


Figure 29. Omni-directional and 060° directional variograms for percent nodule coverage estimated from seafloor photos. Source: [12].

Ordinary kriging was used to estimate the nodule abundance, along with manganese, nickel, copper, and cobalt, for every cell in the block model. Panel support (volume) was approximated by estimating the values on a three by three (nine points) grid equally spaced within each block, with the point estimates averaged to give the block estimate. For each estimate, a circular neighbourhood with a radius of 30 km was used to find the closest samples (a minimum of one and maximum of 32). If no samples were found within the first 30 km, then the search radius was increased to 60 km and then 90 km to ensure that every block was estimated. The relatively large number of samples used for estimating a value for a block was chosen to ensure that the block estimates were smoothed to reflect the confidence in the estimate. Estimate checks were done using the nearest neighbour and inverse distance weighing interpolation techniques [12].

6. Discussion

6.1. Reasonable Prospects of Eventual Economic Extraction

The CRIRSCO family of codes requires that a mineral resource must have reasonable prospects of eventual economic extraction. The qualified persons in Lipton et al. [12] considered that there were reasonable prospects that:

- In the foreseeable future, mining of polymetallic nodules from the seafloor would be technically feasible.
- Processing of polymetallic nodules to extract nickel copper, cobalt, and manganese products would likely be feasible using a combination of existing extractive technologies (e.g., Haynes et al. [74]).
- The metal products would have a market because there is anticipated to be increasing demand for these metals for traditional purposes supported by increased demand for electrochemical cells (batteries).
- The entire process, from seafloor collection to the delivery of metalliferous products, could be achieved in an economically viable manner.

The mining aspects are the most uncertain because the conditions on the seafloor are unlike any on land. Lipton et al. [12] considered that the assumption of reasonable prospects for economic mining was supported by:

- Success in the pilot mining of polymetallic nodules in the CCZ by two groups in the late 1970s (e.g., Brockett et al. [51]).
- Successful sub-sea operations at similar or greater water depths, including tasks such as the installation of oil and gas production facilities at circa 2500 m; the spudding of drill holes at circa 3000 m; cable laying and retrieval at circa 5000 m; and the collection of samples at circa 11,000 m.
- Demonstration of various lift systems from water depths such as the CCZ, including cable, pumping, and airlift solutions.
- Demonstration of operating offshore production vessels including the transfer of product.
- The similarities of some proposed metallurgical processing routes to existing facilities for terrestrial ore sources.
- Higher grades than some terrestrial ore sources and upsides in terms of recoverable metals.
- Lack of overburden and no need to cut rock, at least in part, compensating for working at a depth. Reduced mine infrastructure outside of the production system.
- Transport distances for product comparable with those of other seaborne bulk commodities.
- Benefits of homogenous mineralogy in metallurgical optimisation and cost reduction.

Confidence in the prospects for the eventual economic extraction of polymetallic nodules is growing, as reflected by the increase in applications for exploration contracts in the CCZ, including many by commercial entities (Figure 2). The Contractors are also considering in detail the scale that nodule mining is likely to operate at, i.e., within the marine topography and general environment (e.g., Volkmann and Lehnen [75]).

6.2. Marine Environment

The marine environment of the region falls under the Regional Environmental Management Plan (REMP) for the CCZ established by the ISA ([76]), which includes the definition of the Areas of Particular Environmental Interest (APEIs; Figure 2). Any mineral-resource-specific Environmental Impact Statement needs to consider the REMP.

Under NI 43-101, environment studies, permitting, and social or community impact are important subjects (i.e., modifying factors) for the qualified persons to consider (CIM

[19]). This applies to all mineral deposit technical reports reported to this standard, irrespective of whether the relevant work is a marine project or not.

Therefore, consideration of the marine environment is an implied aspect of reasonable prospects of eventual economic extraction. In feasibility study level NI 43-101 reporting, consideration of the marine environment relies on compliance thresholds in addition to general commentary around environmental protection, mitigations, monitoring, and adaptive management.

Consideration of the impacts on the marine environment may ultimately result in the application of modifying factors to convert the mineral resource to a mineral reserve. For example, the ISA requires the establishment of Preservation Reference Zone(s) (PRZ(s)) within a contract area to preserve ecosystem functions and be representative of the communities and ecology of the mined area. It falls upon the Contractor to define these limits through the EIA process. There are currently no firm regulatory thresholds in this regard, but stakeholder expectations, emerging industry best practices, precedents, boundary conditions, and the appreciation of different shapes and sizes of contract areas will also come into consideration.

Ultimately, the qualified persons behind any future reserve estimate will need to determine the materiality of environmental modifying factors in a mineral reserve estimate just as they will need to do for other types of modifying factors.

6.3. Qualified Persons, Independence, and Transparency

The role of the qualified person (QP) or competent person (CP) is well-explained in the NI 43-101 and JORC member codes to CRIRSCO. Individuals with relevant skills and experience who have supervised the writing of the technical report and estimation of the mineral resources must sign off on the results and need to be prepared to defend their work to their peers. Under NI 43-101, QPs are required to provide written consent to the public reporting of their work. The CRIRSCO family of codes requires QPs to have a minimum five years' relevant experience in the matters for which they take responsibility.

It is unlikely that a single person will have all the skills and experience required to complete a mineral resource report under NI43-101, so several QPs are often required. A report is thus usually compiled under a lead QP, with other QPs contributing to key sections. The QPs may be supported in specific aspects, such as marine engineering, oceanography, and marine ecology, by "other experts" who are named but do not sign off on the report or resource estimate.

As mineral resource estimates are published and often used to raise finances for mining ventures, the independence of at least some QPs is often a requirement. Similarly, transparency in the data collection and mineral resource estimation process is strongly preferred to assist in the explanation of the results (and of any future changes to the estimate).

6.4. Property Inspection and Chain Of Custody

The CRIRSCO family of codes requires that QPs engage in a physical inspection of the deposit or explain why this inspection is not possible. This inspection is intended to provide an opportunity for independent verification of the geological features of the deposit visible in the outcrop or mine faces. For deep-sea nodule deposits, the water depth effectively precludes a physical visit, and the long (2 to 3 month) duration of exploration cruises makes short-term visits by many QPs impractical.

To address this problem, Lipton et al. [12] relied on:

- the inclusion of a QP who had actually spent 3 months working in the CCZ;
- a documented chain of custody around the collection of box core samples and seafloor images; and
- the fact that numerous other independent organisations had explored the deposit in the past and reported essentially similar results.

Demonstration of the chain of custody is also required for photographs used for abundance estimation under NI 43-101. Thus, for Lipton et al. [12], data were sent directly to the mineral resource QP from the expedition ship.

7. Conclusions

The application of established, and mostly land-based, mineral resource reporting guidelines to seabed polymetallic nodules in the CCZ has proven to be relatively straightforward. The long history of exploration and development on the deposit helps to provide important context.

The geology of polymetallic nodule deposits appears to be relatively well understood, and multiple lines of evidence, such as physical samples, seabed photographs, and multibeam echosounder survey, have led to a common view of the deposit's characteristics. The sampling methods and scales of mineralisation are unique to this type of deposit but are not an impediment to the estimation or reporting of mineral resources.

The deep-sea location of the deposits presents some challenges for mineral resource estimation, but, conversely, the extremely low variance of nodule abundance and grades form a stark and beneficial contrast with most terrestrial metalliferous deposits.

The commercial mining of polymetallic nodules has not yet been achieved; therefore, there are no precedents to draw upon for the estimation of mineral (ore) reserves. Nevertheless, successful pilot mining of polymetallic nodules in the CCZ in the late 1970s, a long history of deep-water oil and gas operations, and the apparent amenability of polymetallic nodules to various proven metallurgical processing methods, all indicate that there are reasonable prospects for defining mineral reserves and developing viable production systems on the deep seafloor.

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