Geological survey of deep-sea polymetallic nodules in the interoceanmetal exploration area

Peter Baláž, Interoceanmetal Joint Organization (Szczecin, Poland)
Pavel Kavina, Czech Geological Survey (Prague, Czechia)

Introduction

The exploration rights of the Interoceanmetal Joint Organization (IOM) are granted to an area located within the Clarion-Clipperton Zone (CCZ) in the eastern central Pacific Ocean. All activities related to exploration of minerals in the Area (the seabed and ocean floor beyond the limits of national jurisdiction) come under the United Nations Convention on the Law of the Sea (1982), the Agreement relating to the implementation of Part XI of the Convention (1994) as well as Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area – regulations established by the International Seabed Authority (ISA). The ISA currently has 168 member states, including Czech Republic and the European Union as a whole.

The ISA issues legal documents regulating the conduct of research and the future use of the seabed. The IOM´s contract for exploration of polymetallic nodules was granted for 15 years and provided the contractor security of tenure and exclusive right to explore for polymetallic nodules in the exploration area, as well as to move to a contract for exploitation (regulations for exploitation of mineral resources in the Area are under the development process by the ISA). In 2016, and 2021 respectively, the contract has been extended and is valid till 2026.

In addition to geological survey, IOM is working on research into the technology of mining and processing of deep-sea polymetallic nodules (PMN), as well as on environmental research.

Brief history of the IOM license area

The Interoceanmetal Joint Organization was established on 27 April 1987, based on the Intergovernmental Agreement between seven states: Bulgaria, Cuba, Czechoslovakia, East Germany, Poland, Soviet Union and Vietnam. IOM started its business operations in December 1987. Registered in the District Court in Szczecin, Poland, as an international company, in accordance with the Polish law it obtained the legal personality on 16 December 1987. In 1989, Vietnam suspended its membership in the organization. In 1990, after the unification of Germany, GDR (East Germany) separated from IOM. In January 1992, the USSR duties and obligations were taken over by the Russian Federation. On 31 December 1992, the liabilities of the former Czechoslovakia were taken over by the Czech Republic and the Slovak Republic.

IOM did a preliminary study of a 546,000 km^2 area located in the eastern part of the CCZ, during which a perspective area of 300,000 km^2 with the highest rate of nodule abundance was selected. On 30 July 1992, the General Secretary of the United Nations awarded IOM and its member states the Certificate of Registration, whereby IOM became the pioneer investor. The registered pioneer area of IOM covered 150,000 km^2. On 29 March 2001, IOM and the International Seabed Authority signed a contract for polymetallic nodules exploration within the 75,000 km^2 area.

Location

The IOM exploration area covers app. 75,000 km2 of the eastern part of the CCZ and consists of two sectors, B1 and B2 (Fig. 1). In B2 sector there are four exploration blocks (H11, H22, H33, H44) and preliminary delineated Preservation Reference Zone (Tab. 1, Fig. 2). Within the H22 exploration block the H22_NE exploitable block was delineated. Preservation Reference Zone (PRZ) is an area in which no mining shall occur to ensure representative and stable biota of the seabed in order to assess any changes of the marine environment. The obligation of establishing the PRZ in its license area is imposed on the contractor by the ISA. Delineation of the PRZ in the IOM exploration area is preliminary and the final location is being considered.

Adjacent properties (common borders) to the IOM exploration area belong to 4 organizations – NORI (Nauru), OMS (Singapore), BGR (Germany) and BMJ (Jamaica). The BMJ exploration area was delineated in April 2021 and reflects generally increased interest in deep sea mineral exploration in the area that has emerged during the past decade. 11 out of a total 19 exploration contracts has been signed in the 2011–2021 period.

Tab.1. IOM´s Exploration area (sectors and blocks). Areas are calculated in UTM map projection coordinate system.

Exploration area	Area (km^2)
B1 sector	11 952
B2 sector	63 234
– H11 exploration block	5 390
– H22 exploration block	4 151
– - H22_NE explotable block	957
– H33 exploration block	4 008
– H44 exploration block	1 919
– PRZ (preliminary)	2 626
Total	**75 186**

Exploration methods

Before 2001, 21 research expeditions were carried out to the CCZ area, mainly focused on regional research. Since the signing of the exploration contract between ISA and IOM in 2001, 6 expeditions have been organized. The work was carried out in accordance with the program approved by the ISA. The study included a geological survey focused on determination of PMN abundance, nodule coverage, determination of metal content and chemical composition of PMNs, as well as study of seabed sediments, their geotechnical properties. During the expeditions, basic oceanographic, meteorological and environmental data were collected.

Distance methods used during expeditions include:

- multibeam bathymetry,
- geoacoustic survey (side-scan sonar and sub-bottom profiler),
- photo and video profiling.

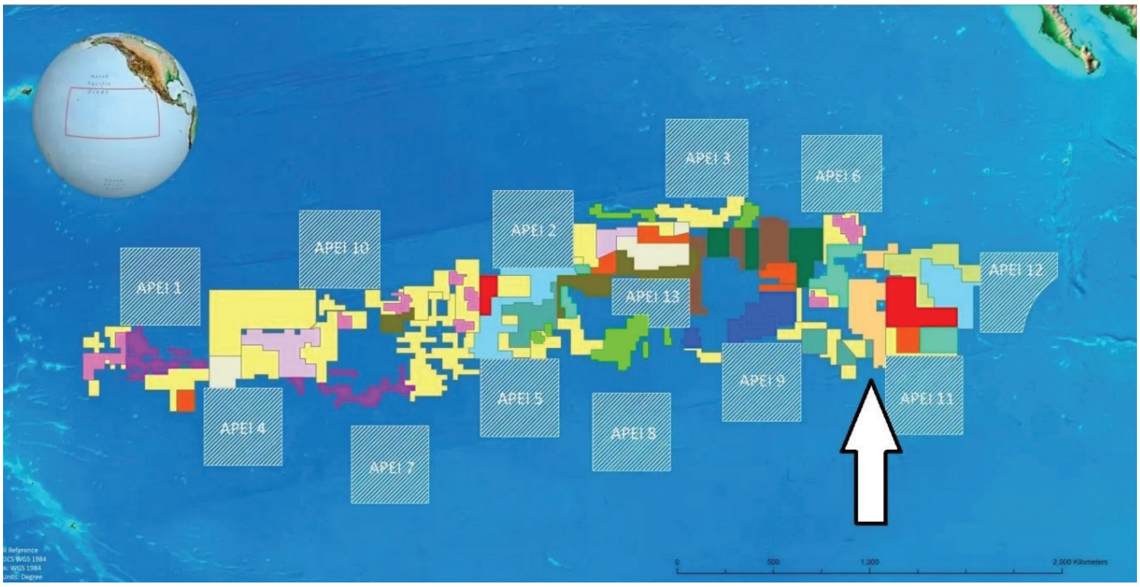

Fig. 1. The IOM exploration area (light orange colored areas) and adjacent properties in the Clarion-Clipperton Zone in the eastern central Pacific Ocean [1]

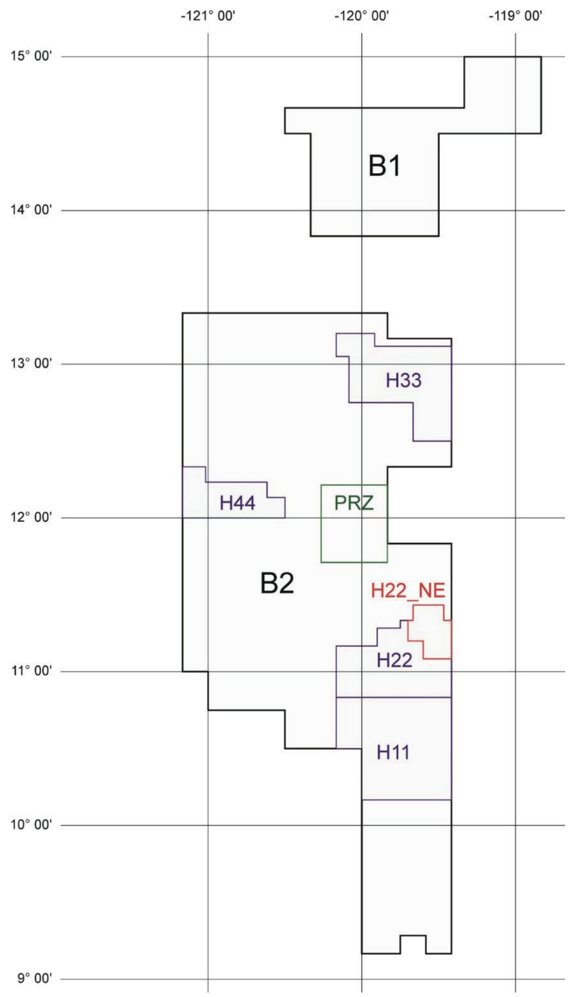

Fig. 2. IOM exploration area (B1 and B2 – sectors, H11, H22, H33, H44 – exploration blocks, H22_NE – exploitable block, PRZ – Preservation Reference Zone)

Following seabed sampling systems were applied during the exploration expeditions:
- box corer sampling,
- piston (gravity) corer sampling,
- trawling and dredging.

Multibeam bathymetry

Multibeam sonar is used to map the seafloor. The multiple physical sensors of the sonar send and receive sound pulses that map the seafloor or detect other objects. Multibeam collects two types of data: seafloor depth and backscatter. The seafloor depth (bathymetry) is computed by measuring the time it takes for the sound to leave the array, hit the seafloor, and return to the array. Backscatter is a measurement of the intensity of the sound echo that reflects back to the multibeam array. Multibeam sonar is usually mounted directly on the ship's hull [2].

Bathymetric mapping of the whole exploration area (B1 and B2 sectors) was performed during expedition in 1999. New high resolution bathymetric survey, carried out in 2018, was focused on exploration blocks H11, H22 (Fig. 3), H33 and H44. The bathymetric survey was performed according to the design profile scheme (system of parallel profiles and perpendicular control profiles).

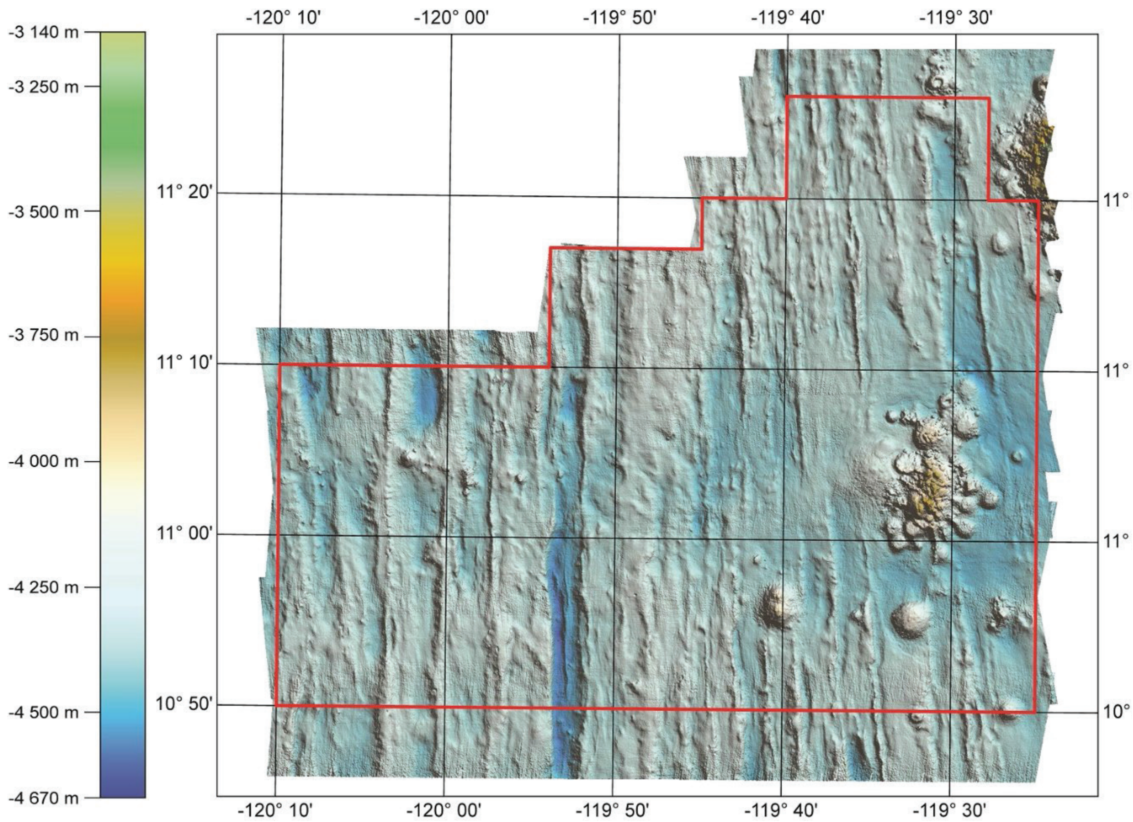

Fig. 3. Ocean depths in the H22 exploration block are in the range from –3,692 m to –4,673 m

Side-scan sonar

Side-scan sonar is an active sonar system for detecting and imaging objects on the seafloor. The multiple physical sensors of the sonar send and receive the acoustic pulses that help map the seafloor or detect other objects. Side scans search at constant speeds and in straight lines. With side scan sonars, the sea bottom is mapped from directly beneath the device to either side. This device is usually placed on a tow-fish. It is an underwater vehicle, that is towed behind a surface vessel [3].

Side-scan sonar was used to map sediment types, nodule coverage, obstacles (information for future mining operations) and detailed seabed morphology (slopes and their orientations). The sonar registration ranges are 1,000 m on each side of the survey (Fig. 4).

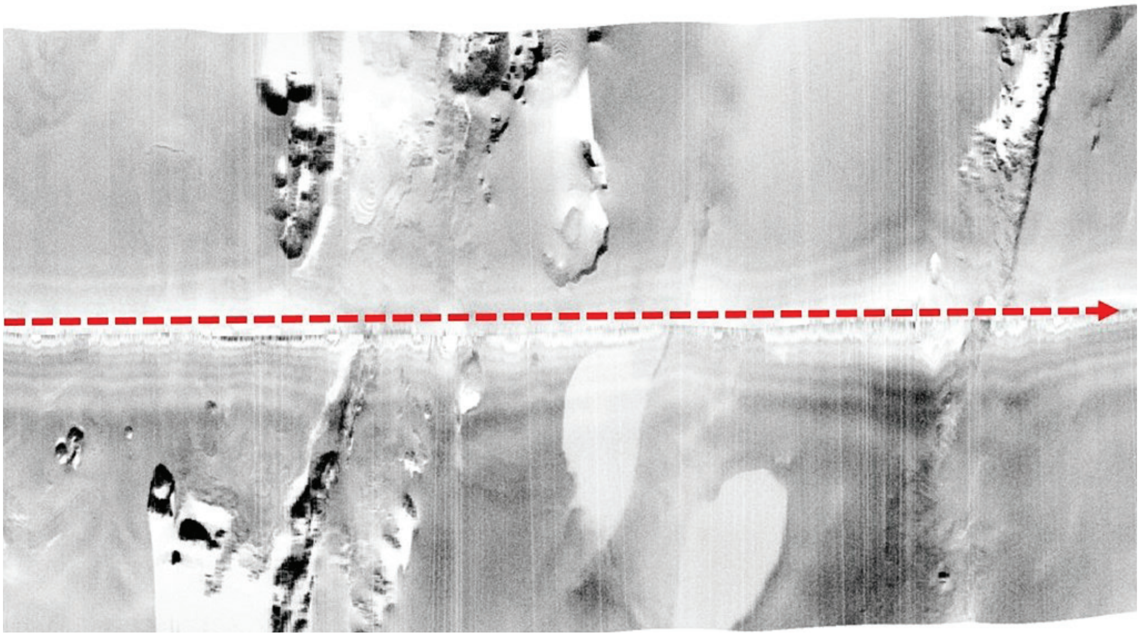

Fig. 4. An example of side-scan sonar data processed into a sonogram. The red arrow shows the direction of the vessel's movement and towing.

Sub-bottom profiler

A sub-bottom profiler is a sonar system that uses sound to map beneath the seafloor. It emits low-frequency sound pulses that are directed vertically at the seafloor. When pulses hit substrate, they may penetrate layers of seafloor and reach horizons of various sediment types. By calculating the time taken for a sound pulse to return to the device, it is possible to determine sediment and layer composition, thickness and other characteristics. This device is usually placed on a tow-fish (alongside with the side-scan sonar) and towed behind a surface vessel [4].

The distance of the towed device from the sea bottom can be 30 to 200 m, usually about 120 m. The depth range of the profiler is up to about 170 m. An example of the sediment profile under the bottom surface is shown in Fig. 5. Interpretations of geoacoustic profiling data allow us to study the internal structure of the sedimentary cover of the study area. In total, 667 km of geoacoustic profiling was completed during the contract period (from 2001).

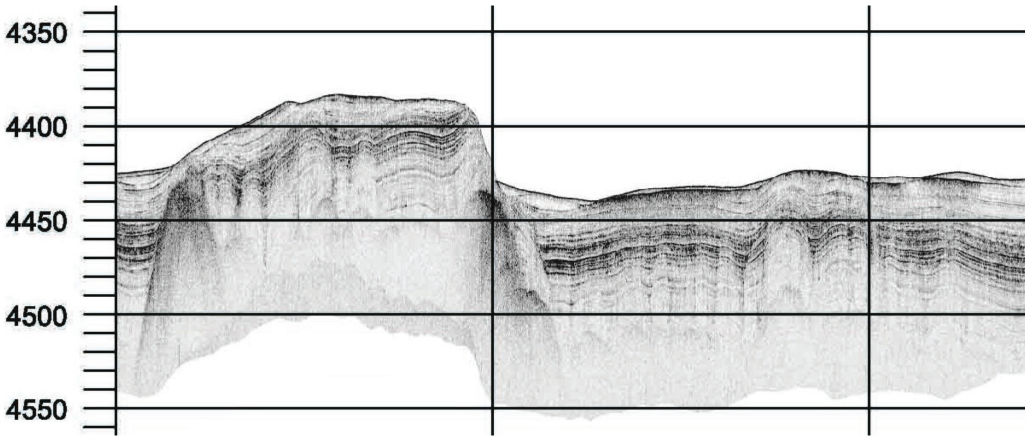

Fig. 5. An example of side-scan sonar data processed into a profilogram (depth data in meters)

Photo and video profiling

Photo and video profiling was carried out by the device placed on a tow-fish, an underwater vehicle towed behind a surface vessel. The distance of the photo-video device from the bottom was about 3.5 m, each photo of the seabed covered an area of about 4 m^2 (Fig. 6). The frequency of photography was about every 20 meters of the profile. At the same time, continuous video recording of the seabed in digital format in the colour image mode was conducted across all profiles. For each photo profile, graphs with coverage data were constructed. In total, 1,609 km of photo/video profiling (over 89,000 images) was completed during the contract period (from 2001).

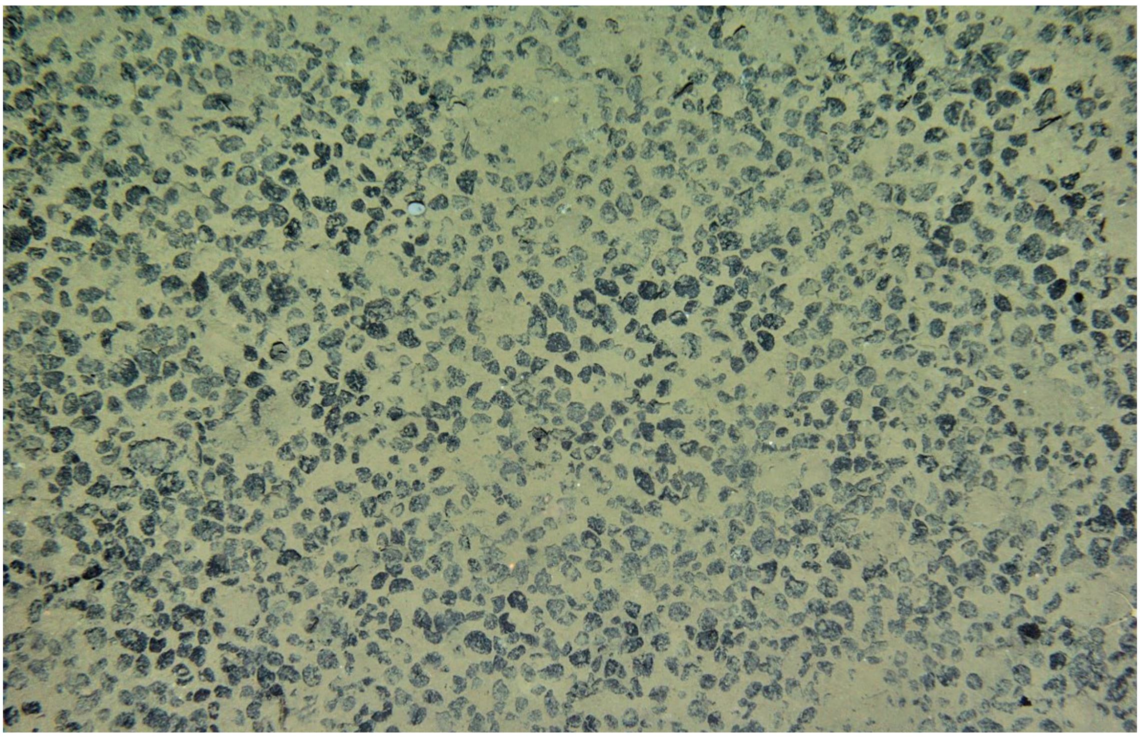

Fig. 6. Photo of the seabed taken in the H22 exploration block

Box corer sampling

Nodule and bottom sediments samples were collected using a box corer. This device has a capture area of 0.25 m^2 of the sea bottom, penetrating sediments to the depth up to 50 cm (Fig. 7). It is also equipped with a photographic system to document the sampling process. The lowering and raising operations were carried out using a winch. Box corer samples represent most important source of knowledge of the deposit, providing data on nodule and sediment characteristics, determination of nodule abundance and geotechnical measurements. In total, 396 box corer station samples were collected during the contract period (from 2001).

Fig. 7. Collected box-corer sample of sediment with polymetallic nodules after draining the water

Piston corer sampling

Sampling was carried out using gravitational tube with an internal diameter of 116 mm, a weight of 800 kg and a length of 5 m. The tube was equipped with a plastic liner with an inner diameter of 107 mm. The lowering and raising operations were carried out using a winch. The device penetrates seabed sediment to the depth up to 4 m and provides core samples (Fig. 8) for study of sediment characteristics and geotechnical measurements. In total, 11 piston corer station samples were collected during the contract period (from 2001).

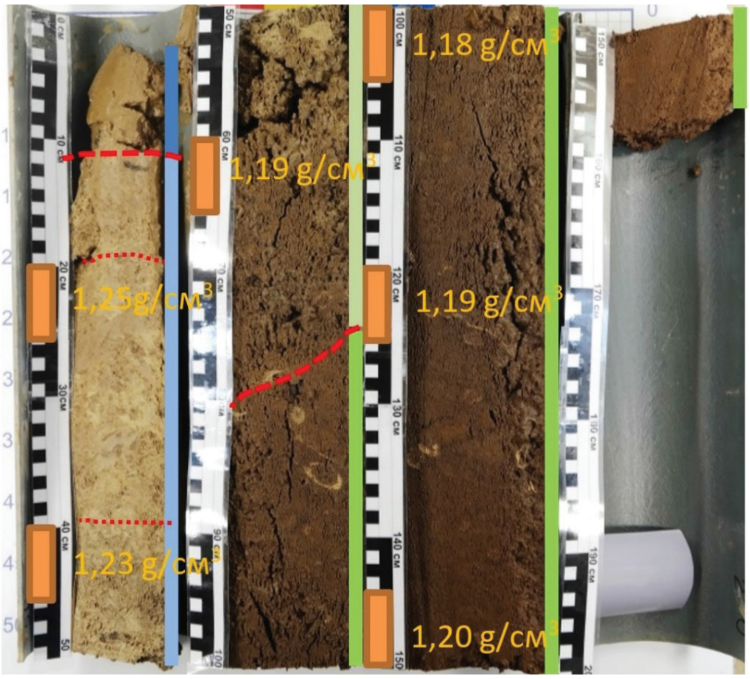

Fig. 8. An example of sections of sediments exposed by piston corer

Trawling and dredging

A large-volume nodule samples were collected using trawl, having an inlet of 40 × 140 cm dimensions. A basket of general capacity equalling 1,000 kg, made of polyamide fabric and 2 meters long, was attached to the body of the trawl, in order to collect nodules. Lifting

Fig. 9. A large-volume trawling sample collected in the H22 exploration block

operations were carried out using a transit winch. Trawling have been used regularly in almost every cruise. During the contract period (starting from 2001) total of 4,000 kg of polymetallic nodules were collected by trawling. Samples of nodules collected by trawl are used for chemical analyses, technological laboratory and benchmarking tests.

Hard rock type of the seabed (basalts) was occasionally sampled using the dredge – cylinder-like sampler 1 m long and 0.8 m in diameter. Two dredging samples were collected during the contract period.

Geological setting

The Clarion–Clipperton Zone is the world's largest (around 5.5 million km^2) and most perspective area of polymetallic nodules occurrence, with estimated resources of 21 billion tons of nodules [5]. The sedimentary cover is a mixture of carbonates (e.g. carbonate oozes), red brown clays, and siliceous sediments (siliceous oozes and siliceous-argillaceous oozes). Sediment accumulation in the area does not exceed the rate of 10 mm/1,000 years [6].

Lithology and stratigraphy

Based on the origin and composition, the bottom sediments within the IOM exploration area can be divided into four litho-stratigraphic units (Kotliński, 2010):

- F_{MI} (Oligocene-Miocene) – biogenic calcareous ooze, Marquise Formation;
- F_{MII} (Miocene) – X-ray amorphous radiolarian silty clay, Marquise Formation.
- F_{ClIII} (Miocene-Pliocene) – zeolitic clay or reddish brown clay and denser zeolitic crusts, Clipperton Formation;
- F_{ClIV} (Pleistocene-Holocene) – siliceous silty clay, ethmodiscus clay and calcareous silty clay, Clipperton Formation.

The sedimentary cover within the IOM exploration area is about 100 m thick [7]. Four seismic complexes (A, B, C and F) were identified:

- A - corresponds to the clay strata of Clipperton formation lying on the seabed surface and is called upper transparent layer by the nature of the seismoacoustic record;
- B – corresponds to the sequence of interbedded nano-fossil carbonates and radiolarian clays of the lower part of Clipperton formation;
- C – corresponds to nano-fossil marl oozes of the Marquesas formation and is called lower transparent layer;
- F – is identified with the acoustic basement represented by tholeiitic basalts of the second oceanic layer.

Polymetallic nodules

Occurrences of nodules with such high abundance as in the CCZ result from complex processes present on the regional and on local scales lasting for the past several millions of years. Polymetallic nodules are composed of both nucleus and concentric layers of iron and manganese hydroxides and oxides (Fig. 10). Nucleus can be composed of volcanoclastic debris, lithified sediment, bioclasts or fragments of older nodules. Beside Mn and Fe, also Cu, Ni, Co are the main metal elements present in nodules.

In some areas of the CCZ, nodules cover more than 70% of the bottom, whereas other areas are nodule-free. Nodules can occur on the seabed at any depth, but the highest concentrations have been found between 4,000 and 6,000 m.

According to the growth model for polymetallic nodules in the CCZ presented by ISA [6], six main factors control the process of nodule growth: metals supply (sea water and the bottom sediments); nucleus presence; Antarctic bottom water (the current is a supplier of oxygen and materials becoming nuclei; semi-liquid surface layer (providing chemical environment for the growth); bioturbation (the mechanism which prevents nodules from burial below sediment surface); and internal nodule stratigraphy (result of the changing geological history of deep-sea sedimentary basins).

The position of growing nodule is crucial in relation to the semi-liquid surface layer. The three accepted models of nodules growth are:

- in semi-liquid surface layer – diagenetic (D-type), called R (rough) type because of their complicated morphology;
- on the boundary of sea water and semi-liquid surface layer as a mixed type of hydrogenetic and diagenetic processes (HD-type), called R+S (rough-smooth) type because of their mixed morphology;
- above the sea bottom, on the surface sediments – hydrogenetic (H-type), called S (smooth) type because of their shape.

The IOM exploration area is dominated by D-type nodules in B2 sector and HD/H-types in B1 sector.

Polymetallic nodules in the CCZ generally grow very slowly, at rates of 1–10 mm/1,000,000 years [8]. Slow rate of growth indicates that for the nodules to reach the size of centimeters, stable environmental conditions are required. The accumulation rate of sediments within the area is three orders of magnitude higher and stays at a level of several millimeters per thousand years.

Fig. 10. Internal structure of polymetallic nodule

The CCZ nodules vary in size and range from tiny particles, visible only under a microscope, to large pellets of more than 20 centimeters in diameter. However, most nodules are between 5 and 10 cm in diameter. In the IOM exploration area, nodules are divided into fractions, where nodules within 0–4 cm refer to small fractions, 4–8 cm to medium fractions and 8+ cm nodules to large fractions. Size distribution partly depends on genetic types of nodules. No general rule was applied to size distribution due to high variability in nodule size within the IOM exploration area. For example, in the H22_NE exploitable block medium fractions prevail. On the contrary, small and large factions dominate the B1 sector.

Mineralogical composition of nodules is generally dominated by todorokite/buserite, with a lesser amount of birnessite and traces of vernadite. Additionally, the samples indicated the presence of Fe-rich clay minerals (nontronite and Fe-smectite) and mixtures of quartz, barite, zeolites, apatite, and barite.

Polymetallic nodules of the CCZ are characterized by high abundance and high metals content (especially Mn, Ni, Cu, Co, Mo, Zn and REE). Results from the B1 and B2 sectors are comparable with the results from other contracted areas in the CCZ. The mean grades of metals are shown in Tab. 2 [9,10,11].

Tab. 2. Mean grades of Mn, Ni, Cu, Co, Zn and REE within the IOM exploration area (variant for cut-off abundance 10 kg/m^2 of wet nodules)

Exploration area	Mn [%]	Ni [%]	Cu [%]	Co [%]	Zn [%]	REE [ppm]
B1	27.84	1.21	0.90	0.21	–	–
B2	30.90	1.32	1.21	0.18	0.15	–
H11 + H22	31.37	1.30	1.29	0.16	0.16	–
H33	32.35	1.41	1.20	0.18	0.15	–
H44	30.71	1.32	1.19	0.19	0.14	–
H22_NE	29.19	1.31	1.25	0.18	0.15	713

Mineral resources and reserves estimates

Seafloor polymetallic nodules in the CCZ occur typically on the surface of deep seabed, as a rule they are embedded in the semi-liquid surface layer and are, quite often, partly covered (blanketed) by a thin layer of unconsolidated sediments. Only those are included in current resource estimates for the IOM exploration area. Buried polymetallic nodules (more than 15 cm deep), locally reported within the IOM exploration area [12], have not been considered in the resource estimates.

Resources estimation is based on data collected during scientific expeditions carried out by IOM. Four reports using geostatistical data analysis have been prepared (2007, 2011, 2015 and 2020) and two validations performed by the Competent Person (2016 and 2020).

Methodology of estimation

Estimates of resources and abundance of nodules and metals were carried out in square elementary blocks with a side of 500 m using kriging and co-kriging. The estimates used

8 nearest sampling stations, two from each quadrant (quarters) into which the circular data search zone was divided. The center of the circular data search zone coincides with the center of the elementary block. In the calculation procedure, isotropic models of variograms, cross-variograms, covariance and cross-co-variance were used. The total resources of polymetallic nodules of the exploration blocks and ore fields (ore bodies), for different values of maximal the ocean-floor slopes, were obtained by summation of resources estimated for elementary blocks.

The accuracy of resource estimation in blocks H11 + H22 and in block H22_NE is high as evidenced by small, standard kriging errors in the range of 3–6%. The resources of nodules in blocks H33 and H44, expressed by standard errors from the 8–12% range, are estimated with much lower accuracy. The different size of errors is the result of the different density of the bottom sampling in individual blocks.

Results of estimation

The current status is shown in Tab. 3. The resource validation was carried out in accordance with the Reporting standard of the ISA for mineral exploration results assessments, mineral resources and mineral reserves [13]. The effective date for the estimate is August 2020. The dependency the tonnage of nodules and mean abundances in relation to the minimum abundance of wet nodules in B2 Sector is illustrated in Fig. 11.

Tab. 3. Mineral Resource estimate of wet polymetallic nodules in the IOM exploration area (variant for cut-off abundance 10 kg/m^2 of wet nodules)

Mineral Resource Classification	Mean Abundance (kg/m^2)	Resources Wet (million ton)
Measured (H22_NE block)	14.6	12.2
Measured Total		**12.2**
Indicated (H11 + H22 blocks)	12.4	77.0
Indicated Total		**77.0**
Inferred (B1 sector)	13.4	62.6
Inferred (H33 block)	12.0	21.8
Inferred (H44 block)	11.5	13.6
Inferred (B2 sector other)	11.59	85.3
Inferred Total		**183.3**
GRAND TOTAL		**272.5**

Mineral Resources were estimated at various nodule abundance cut-offs for the IOM Exploration Area. Selected base scenario is an abundance cut-off of 10 kg/m^2 (in wet condition). Assumptions will be revised in accordance with new knowledge, data and technological developments. No Mineral Reserves were estimated at this stage of the project development.

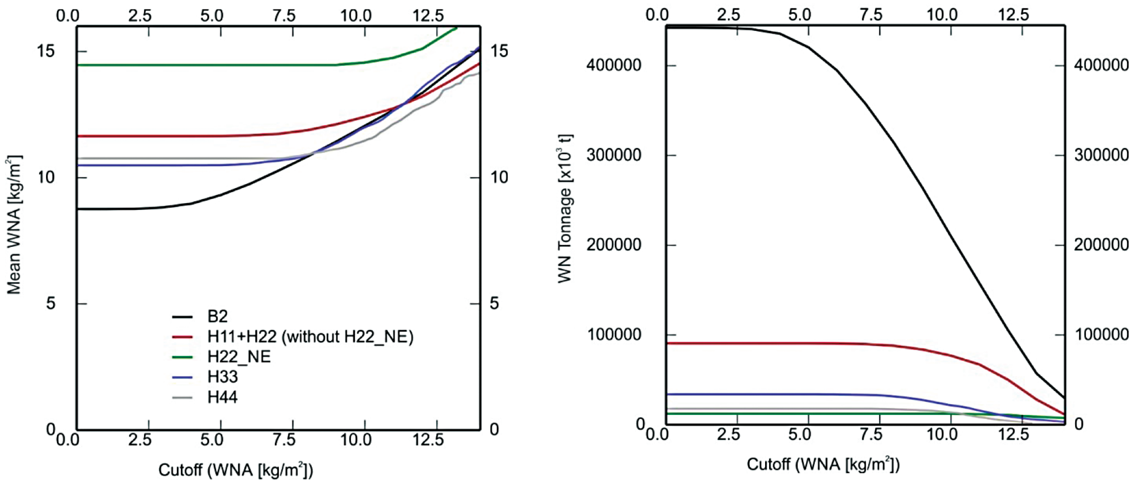

Fig. 11. Dependence of the average abundance of wet nodules (top) and the tonnage of wet nodules (bottom) on the cut-off value of the abundance of wet nodules (WNA)

Conclusions

The IOM license is under a contract for exploration of polymetallic nodules signed with the International Seabed Authority. Legal framework for mining and environmental regulations, as a fundamental condition for future deep sea mining activities, is currently under the development by the ISA.

Based on the economic evaluation, the IOM project can be described as an investment with some risk factors. It has promising economic potential due to growing market demand for battery metals which cannot be met by traditional sources (onshore, recycling, extraction from exclusive economic zones). The project possesses significant potential to contribute to the clean energy transition and expected demand of metals.

According to the European Commission´s list of critical raw materials for the EU, cobalt, manganese, and REEs are considered critical metals. From 2023, the list of critical raw materials also includes copper and nickel. These metals do not meet the supply risk threshold, but are listed as strategic raw materials, strategically important for green, digital, space and defence applications and are subject to future supply risks [14, 15]. Low supply and increasing import reliance of metals vital for European economy are a challenge for the long-term strategy of securing raw materials. This means that all major metals contained in polymetallic nodules are currently considered critically important for the EU.

Achieving of the Green Deal targets and solving the climate crisis requires extensive implementation of low-emission technologies (electro mobility, photovoltaics, wind turbines, CO_2 capture, nuclear installations, LEDs, and others). This is necessarily associated with increased consumption of specific metals. Polymetallic nodules offer a promising alternative supply of metals that can help achieve these goals.

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