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UNLOCKING EUROPE'S RESOURCES: THE STRATEGIC POTENTIAL OF IOM DEEP SEA POLYMETALLIC NODULES FOR CRITICAL METALS SUPPLY

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ABSTRACT: The purpose of the paper is to investigate the potential of seabed polymetallic nodules in the Clarion-Clipperton Zone (CCZ) as a sustainable source of critical metals such as rare earth elements (REEs), cobalt, manganese, lithium and scandium. The methodology involves extensive geological surveys and sampling within the Interoceanmetal Joint Organization (IOM) exploration area, followed by the analysis of the mineral composition, metal content, and assessment of metallurgical processing possibilities. The importance of critical metals is discussed on the basis of literature analysis. The research confirms that polymetallic nodules in the CCZ are rich in critical and strategic metals with economic potential. Further research is needed to assess the environmental impacts and economic feasibility of deep-sea mining. Practical implications are that the development of deep-sea mining could be a viable alternative to traditional land-based mining, potentially reducing Europe's reliance on imported critical metals. Social implications of the project are in the sustainable supply of critical metals for advancing green technologies, combating climate change and the goals of the society energy transition. The study provides an evaluation of the potential of polymetallic nodules as a strategic resource, and contributes to the discourse on sustainable mining and resource security in the context of global supply challenges.

KEYWORDS: critical metals, polymetallic nodules, strategic resources, deep sea mining

Introduction

Recently, increasing attention has been given to the potential supply risks of critical metals, such as rare earth elements (REEs), cobalt, manganese, lithium and scandium. Critical metals are recognised by two factors (European Commission, 2023): their importance for the economy and the risk of disruption of supply. They are indispensable to modern society and the global economy, playing a crucial role in a wide range of industries, including technology, energy, and defense. These metals are characterised not only by their essentiality in maintaining economic stability and societal functionality but also by their susceptibility to create chain disruptions. Such disruptions can arise from geopolitical tensions, environmental constraints, limited geographic availability, or challenges in extraction and processing. As a result, the secure and sustainable supply of critical minerals is of paramount importance to ensuring the resilience and continuity of both economic development and technological advancement.

Seabed mineral resources, such as polymetallic nodules, have been identified as a possible source of critical metals. Seabed mineral deposits are considered a large but least explored source of metals on Earth (Sakellariadou et al., 2022).

In 2001, the International Seabed Authority (ISA), the UN agency responsible for administering ocean mineral resources beyond the limits of national jurisdiction, granted Interoceanmetal Joint Organization (IOM) an exploration license of the area of 75.000 km^2, located within the Clarion-Clipperton Zone (CCZ) in the Eastern Central Pacific (Figure 1). Two sectors (B1 and B2), four exploration blocks (H11, H22, H33 and H44) and one exploitable block (H22_NE) (Figure 2) have been delineated as a result of the IOM exploration activities.

Currently, the IOM is carrying out the advanced geological survey of the polymetallic nodule deposit in the license area as part of its exploration activities under contract with the International Seabed Authority. All the activities related to the exploration of minerals in the area beyond the limits of national jurisdiction (referred to as the Area) fall under the provisions of the United Nations Convention on the Law of the Sea (UNCLOS) and related regulations.

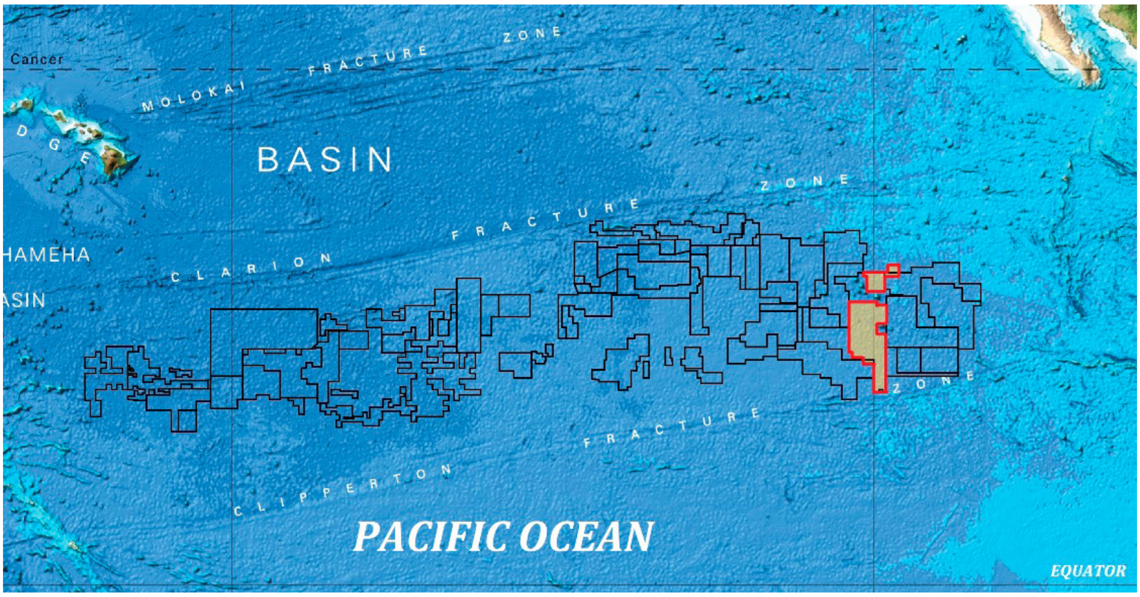

Figure 1. The IOM exploration area (red line colour) located in the Clarion-Clipperton Zone of the Eastern Central Pacific

Compared with terrestrial reserves, nodules in the CCZ contain more Tl, Mn, Te, Ni, Co, and Y, and significant amounts of Cu, Mo, W, Li, Nb, and REEs. The share of heavy REEs (HREEs) in the total REEs contained in the CCZ nodules amounts to 26% compared to only 1% share in large terrestrial REE deposits. This is crucial because the HREEs have versatile applications in multiple technological sectors, which in turn results in their high economic value (Sakellariadou et al., 2022). The main metals present in polymetallic nodules (PMN) are manganese, nickel, copper, cobalt, zinc and REEs.

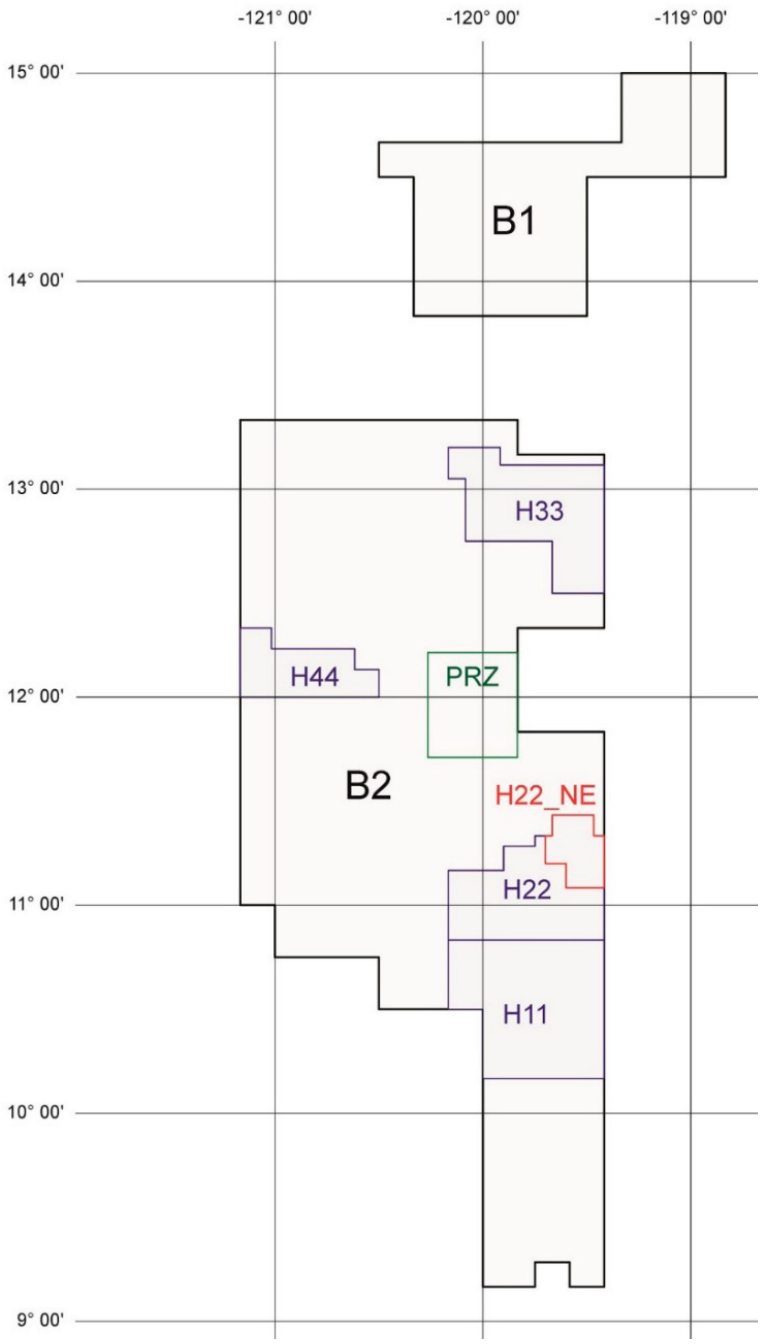

Figure 2. IOM exploration area (B1 and B2 – sectors, H11, H22, H33, H44 – exploration blocks, H22_NE – exploitable block, PRZ – Preservation Reference Zone)

The market price of a commodity is generally determined by its supply and demand. If a single country controls most of the production of a given commodity, its supply is considered to be at risk. At present, production of two commodities from land mineral resources, which are also contained in large amounts in polymetallic nodules, namely cobalt and REEs is dominated by one producer only – the Democratic Republic of Congo (DRC) and China, respectively (Cobalt Institute, 2024; USGS, 2023).

The European Commission (EC) periodically reviews the list of critical raw materials (CRM) for the European Union (the EU). Economic importance and supply risk are the two main parameters used to determine the criticality of raw materials. Economic importance is calculated based on the importance of a given material for end-use applications in the EU and the performance of available substitutes in these applications. Supply risk is calculated based on factors that measure the risk of disruption to the supply of a specific material. Combination of these factors made it possible to iden-

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tify cobalt, manganese, REEs, lithium and scandium as critical raw materials for the EU. Cobalt and REEs have been considered critical since the first assessment undertaken in 2011, scandium since 2017, and lithium since 2020. Manganese was identified as a critical metal in the 2023 EC study, due to an increase in its supply risk at the extraction stage resulting from a lower domestic (EU-based) supply, increasing reliance on import and high economic importance (European Commission, 2020, 2023).

Since 2023, copper and nickel, two other main metals present in polymetallic nodules, have also been on the list of critical raw materials. These metals do not meet the supply risk threshold, but are listed as strategic raw materials (SRM) which means that they are strategically important for green, digital, space and defence applications and are subject to future supply risks. According to the European Critical Raw Materials Act, an updated list of critical raw materials includes the strategic raw materials that reach or exceed set limit threshold for supply risk and economic importance (Regulation, 2024).

Note: A similar evaluation process was initiated in the United States. The effort began in 2017 to identify critical minerals and address supply chain vulnerabilities. The first U.S. Critical Minerals List was published by the U.S. Geological Survey in 2018. The 2022 U.S. Critical Minerals List includes following PMN metals: cobalt, manganese, nickel, REEs and zinc (USGS, 2023).

Overview of critical metals

Cobalt

World reserves are estimated at 8.3 Mt, 48% of which have been identified in the Democratic Republic of Congo (USGS, 2023). Primary production (232 kt) was the main source of cobalt supply in 2023. Cobalt is primarily mined as a by-product of copper and nickel mining, and is partially dependent on the industries of those two metals. The Democratic Republic of Congo (DRC) accounted for 76% of the global supply. Batteries accounted for 73% of the current total cobalt demand and are the dominant driver of market growth. Production of electric vehicles (EVs) continued its growth, supported by governmental subsidies and incentives. EV sales increased by 33% in 2023 (Cobalt Institute, 2024).

To ensure global e-mobility ambitions, boosting the primary cobalt supply is necessary. A cobalt shortage, anticipated between 2028 and 2033, appears inevitable, even under the most optimistic scenario. Primary supply is found to be essential to achieve supply-demand balance (Zeng et al., 2022). The domestic EU extraction of cobalt represents 12% of the total input to the EU manufacturing (European Commission, 2020). The estimated end-of-life recycling rate of cobalt is 22% (European Commission, 2023).

The potential of deep-seabed mining (DSM) as a viable alternative to alleviate cobalt supply risks in the United States is explored by Cunningham (2024). The United States faces significant supply-side risks, as most of the world's cobalt is sourced from the Democratic Republic of the Congo (DRC) and refined in China, both of which present environmental, ethical, and geopolitical concerns. The study assesses the economic viability of DSM, discussing the significant capital expenditure (CAPEX) and operational expenditure (OPEX) required for such ventures. It is recognised that mining of polymetallic nodules could significantly reduce the criticality of cobalt for the U.S. by diversifying its supply sources away from geopolitically unstable regions and could enhance U.S. economic security and reduce dependence on foreign powers like China.

Rare Earth Elements (REEs)

Rare-earth elements are a group of seventeen chemical elements in the periodic table, in particular the fifteen lanthanides, as well as yttrium and scandium. World reserves are estimated at 130 Mt (34% of which in China). In 2021, primary production (290 kt) was the main source of REEs supply, with China accounting for 58% of global supply (USGS, 2023). Permanent magnets and catalysts accounted for around 60% of total REEs consumption. Rare earths remain critical in various applications, with future demand expected to remain strongly driven by the clean energy technologies, especially the electric vehicles industry. REEs are essential for lighting and display technologies (LED

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lights, fluorescent lamps, LCD screens), magnetic resonance imaging (MRI), defence applications (precision-guided munition, laser and radar systems) and other. The recycling rate of REEs is only around 2% at present (Patil et al., 2022).

Manganese

World reserves are estimated at 1,700 Mt, 38% of which are found in South Africa (USGS, 2023). Primary ore production (21.1 Mt) was the main source of supply in 2022. South Africa accounted for 40% of the global supply, with other important producers being Gabon (22%) and Australia (14%). Manganese has no satisfactory substitute in its major applications in steelmaking and alloys production (over 90% of consumption). The main non-metallurgical application of manganese is in the production of batteries, which represents about 2-3% of consumption (IMnI Annual Review, 2022). Manganese is used in cathodes of batteries, such as the nickel-manganese-cobalt (NMC) cells, which are used in the majority of electric vehicles at present. The demand for battery-grade manganese is expected to grow. The domestic EU extraction represents 15% of the total input to the EU manufacturing (European Commission, 2020). The end-of-life recycling input rate of manganese is about 9% (European Commission, 2023).

Lithium

World reserves are estimated at 26 Mt (36% of which in Chile). Primary mine production reached 107 kt in 2021, Australia accounting for 52% of global supply (USGS, 2023). Batteries accounted for around 74% of total lithium consumption. Lithium consumption for batteries has increased significantly in recent years due to the extensive growth of the electric vehicle market. The domestic EU extraction of lithium represents 9% of the total input to the EU manufacturing (European Commission, 2020). The recycling rate of lithium is negligible at present (Church & Wuennenberg, 2019).

Scandium

Technically, scandium is not a rare earth element, although it is commonly included in this group. Scandium rarely concentrates in commercial-grade stand-alone resources and is mostly produced as a by-product. Estimated global scandium oxide production is about 30 tonnes per year. China is the largest known producer of scandium products, followed by the Russian Federation. The single largest use for scandium in commercial applications is in solid oxide fuel cells (SOFC). The most significant forward-looking market opportunity for scandium is as an alloying agent for aluminium. The transportation industry is where aluminium-scandium alloys hold very good promise for application (Scandium International Mining Corp, 2024). The recycling rate of scandium is negligible at present (European Commission, 2023).

Polymetallic nodules in IOM exploration area

Seafloor polymetallic nodules (PMN) in the IOM exploration area typically occur on the surface of the deep seabed. They are embedded in the semi-liquid surface sediment layer and are often partly covered (blanketed) by a thin layer of unconsolidated sediment. Locally reported buried polymetallic nodules (Kotliński & Stoyanova, 2007) have not been included in the resource estimates.

Macroscopic characteristics

The seafloor polymetallic nodule is built of a nucleus and concentric layers of iron and manganese hydroxides and oxides. The nucleus is usually composed of volcanoclastic debris, lithified sediment, and bioclasts or fragments of older nodules. Nodules vary in size, ranging from microscopic to large pellets of more than 20 cm in diameter. Most of the nodules are between 5 and 10 cm in diameter. There are several morphotypes of nodules, typical for different occurrences (e.g. spheroidal, ellipsoidal, tabular, discoidal, irregular, fragments). Within the IOM exploration area, nodules appear at a depth range of 3,800–4,750 m, with the highest abundance and sea floor coverage recorded at the depth range of 4,300–4,500 m.

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The classification adopted by ISA for the CCZ area (International Seabed Authority, 2010) defines three main nodule types, taking into account their surface features (S – smooth surface, R – rough surface, S-R – mixed). Those refer to the three main genetic nodule types, namely hydrogenetic (H), diagenetic (D) and mixed hydro-diagenetic (HD), each characterised by different mineralogical and chemical composition and different rates of Mn accretion. Nodule genotype can be determined using the Mn/Fe ratio, as well as the productivity index ΣNi-Cu-Co. Preliminary classification takes place on board just after nodules are collected, and is based on their visual features. The classification is further verified by the results of chemical analyses.

Mineral composition

According to Kuhn et al. (2017), in terms of mineralogy, polymetallic nodules are mainly composed of phyllomanganates such as vernadite, birnessite, and buserite, with negligible amounts of tectomanganates (todorokite). Metals occur in phyllomanganates either as substitutes of manganese in octahedral layers or as hydrated cations in the interlayers. The MnO_6 octahedral layers of phyllomanganates can contain abundant isomorphic substitution of Mn^{4+} (for example by Mn^{3+}, Ni^{2+}, Cu^{2+}, Co^{3+}). In general, phyllomanganates (birnessite, buserite, vernadite) have a higher layer charge and accordingly a higher potential to sorb metals than tectomanganates (todorokite).

The major iron component is X-ray amorphous iron oxyhydroxide (δ-FeO(OH)), reported to include goethite, ferroxyhyte, lepidocrocite, akageneite, hematite or ferrihydrite (Kotliński, 1999; Hein & Koschinsky, 2014).

Nodules also contain microscopic detrital silicates, feldspar, plagioclases, quartz and phillipsite. The cement components include clay minerals and zeolites (Kotlinski, 1999).

Nodule grades

Polymetallic nodules in the CCZ are characterised by high abundance and high metal content (especially Mn, Ni, Cu, Co, Mo, Zn and REE). Nodule abundance and metal grades for the IOM exploration area are comparable with other contracted areas in the CCZ. The mean grades of main metals are shown in Table 1.

Table 1. Mean grades of Mn, Ni, Cu, Co, Zn and REE within the IOM exploration area for cut-off abundance 10 kg/m^2 of wet nodules (nd – not determined)

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

With the depth of the ocean in the IOM license area increasing from the north to the south, the contents of Mn and Cu in the polymetallic nodules increase, while the Ni and Co content decreases. As reported (Abramowski & Kotliński, 2011), a higher content of Co is typical for genetic types H and D in the northern part of the IOM area. A higher grade of Mn, Cu and Ni is reported in the D-type nodules collected from the central part, while southwards an increase in the amount of Mn (D-type nodule) is observed.

Although iron (Fe) is neither rare nor critical metal, together with Mn it is a major component of PMN and is the main antagonist to Mn (it reveals a reverse concentration pattern). It conditions the presence of heavy rare earth elements (HREE) in the nodule composition (Halbach & Jahn, 2016), and the Mn/Fe ratio of about 5 is a precondition for the highest concentrations of Ni and Cu (Halbach et al., 1981). The mean Fe concentration in the CCZ is close to 6%, and the Mn/Fe ratio is 5.1 (see Table 4 for more details).

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Chemical composition of nodules in H22_NE exploitable block

The H22_NE exploitable block (957 km^2) is the most researched part of IOM exploration area and, as such, is anticipated to be designed for test mining. A total of 32 sampling stations with D-type nodules, 5 stations with HD-type nodules and 6 stations with H-type nodules were selected for the assessment. The arithmetic mean values of the main metals content for the three nodule types are presented in Table 2. The data presented in this article combine results of chemical analyses of polymetallic nodules conducted in multiple research vessel (R/V) laboratories in the period from 1988 to 2014 (23 sampling stations), as well as analyses performed in the stationary laboratories of the University of Chemistry and Technology (UCT) in Prague and State Geological Institute of Dionyz Stur (SGIDS) in Spisska Nova Ves, Slovakia on the IOM samples collected in 2019 (20 sampling stations).

UCT analytical methods (Mn, Co, REE): the chemical composition of the nodules was evaluated using an acidic decomposition method. The samples were digested in a mixture of HF and HNO_3, followed by dissolution in HCl and subsequent dilution. For analysis, the samples were further diluted, using a matrix of 2 vol.% HNO_3. The concentrations of Co and Mn in the resulting solutions were determined using a GBC 932Plus atomic absorption spectrometer with flame atomisation (FA-AAS). The concentrations of Mn and Co in the solution were measured, ranging in the order of single-digit mg/L. The detection limit for both metals was at the level of 0.001 mg/L. The concentrations of REEs were measured by inductively coupled plasma mass spectrometer (ICP-MS) Perkin Elmer Elan DRC- e. The concentrations of REEs in the solution were determined, ranging from single-digit to hundreds of µg/L. The detection limit for all measured elements was at the level of 0.0001 µg/L. All samples were analysed in duplicate, and to validate accuracy, the reference material GeoPT23A was analysed alongside the samples.

SGIDS analytical methods (Sc, Li): The samples were decomposed by mixture of acids HNO_3, HCl and HF. The stock solution was aspirated into the plasma torch of Inductively Coupled Plasma Mass Spectrometer (Bruker – Aurora M90) with the argon. Concentration was evaluated by calibration curve. Limit of quantification (LOQ) for both elements was 0.5 ppm.

Table 2. Chemical composition of nodules by genetic types in the H22_NE exploitable block

Average	Mn [%]	Fe [%]	Ni [%]	Cu [%]	Co [%]	Zn [%]	Mo [%]	Pb [%]	Mn/Fe	ΣNi-Cu-Co [%]
D (n=32)	30.36	5.49	1.354	1.285	0.172	0.154	0.056	0.028	5.54	2.81
HD (n=5)	27.53	6.11	1.306	1.222	0.178	0.153	0.055	0.031	4.52	2.71
H (n=6)	23.20	7.33	1.066	0.989	0.202	0.117	0.049	0.033	3.22	2.26

Cobalt

Cobalt content in the nodule samples collected during IOM expeditions (1988-2019) to the H22_NE exploitable block is shown in Table 3. Chemical analyses were performed in the laboratories of the University of Chemistry and Technology (Prague, the Czech Rep.). The samples were chemically decomposed using a mixture of acids. Co content was determined using an atomic absorption spectrometer (AAS) with a flame technique of atomisation.

Table 3. Cobalt content and productivity index (ΣNi,Cu,Co) in polymetallic nodules in all samples collected from the H22_NE exploitable block

n=43	Co	ΣNi,Cu,Co
Average [%]	0.177	2.72
Median	0.172	2.78
Min	0.140	1.99
Max	0.327	2.98
Standard deviation	0.026	0.22
Coefficient of variation [%]	15	8

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Manganese

The content of manganese in the nodule samples collected during IOM expeditions (1988-2019) to the H22_NE exploitable block is shown in Table 4. Chemical analyses were performed in the laboratories of the University of Chemistry and Technology (Prague, the Czech Rep.). Mn content was determined using flame atomic absorption spectrometers (AAS).

Table 4. Manganese content and Mn/Fe ratio in polymetallic nodules in all samples collected from the H22_NE exploitable block

n=43	Mn	Mn/Fe
Average [%]	29.03	5.10
Median	29.31	5.40
Min	19.90	2.25
Max	33.79	6.16
Standard deviation	3.07	0.90
Coefficient of variation [%]	11	18

Rare earth elements

The content of 14 rare earth elements (excluding scandium and yttrium) in the nodule samples collected during the IOM-2019 expedition is shown in Table 5. Chemical analyses were performed in the laboratories of the University of Chemistry and Technology (Prague, the Czech Rep.). An inductively coupled plasma mass spectrometer (ICP-MS) was used to determine rare earth elements content.

Table 5. Arithmetic mean values of REEs content analysed in 20 samples collected from the H22_NE exploitable block (LREE – light rare earth element, HREE – heavy rare earth element)

LREEs [ppm]						HREEs [ppm]							
La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
96.5	235	28.7	125	32.0	8.46	29.8	4.81	24.9	4.82	13.3	1.89	12.4	1.88

Lithium and scandium

Lithium and scandium content in the nodule samples collected during the IOM-2019 expedition is shown in Table 6. Chemical analyses were performed in the SGIDS laboratory (Spisska Nova Ves, Slovakia). Li and Sc content were determined using an inductively coupled plasma mass spectrometer (ICP-MS).

Table 6. Arithmetic mean values of lithium and scandium content analysed in 20 samples collected from the H22_NE exploitable block

n=20	Li	Sc
Average [ppm]	116.3	10.3
Median	121.0	9.8
Min	64.9	8.0
Max	150.0	16.4
Standard deviation	17.2	2.1
Coefficient of variation [%]	14.8	20.2

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IOM resources of critical metals

IOM deposit resources estimates are based on data collected during marine expeditions. Four reports using geostatistical data analysis have been prepared so far in 2007, 2011, 2015 and 2020, and two validations performed by a competent person in 2016 and 2020, have been executed.

Estimating the resources of polymetallic nodules implies a multi-stage process involving various exploration ativities both conducted during marine expeditions and in land laboratories or research facilities. The process is composed of planning, prospecting, data collection, samples analysis and actual statistical resource estimation. In the case of the IOM research the process begun with the prospecting phase, where potential sites were selected based on at-sea geological surveys. These surveys focused on deep-sea environments in region of the Clarion-Clipperton Zone in the Pacific Ocean. Once promising areas were identified, the next step involved mapping of the seafloor using side scan sonar and multi-beam echo sounders to create detailed maps of the seafloor topography and the density of deposit distribution. This helped to recognise areas where nodules are likely to be concentrated.

Exploratory sampling of the seabed was conducted to gather physical samples from the seafloor. IOM has been using grab sampling, box core sampling, piston core sampling and trawling/dredging. Grab sampling and box coring involved the direct collection of nodules and geolocalized portions of the seafloor, box and piston core sampling provided a vertical profile of sediment layers and nodule distribution. Trawling involves pulling a trawl along the seafloor to collect nodules along a projected line. Visual surveys are also carried out using deep towed photo cameras. Selected photo documentation from IOM exploration activities is presented in Figure 3.

Figure 3. IOM exploration activities, a) box corer operations onboard of a research vessel, b) portion of seabed with polymetallic nodules on the surface – view inside a box corer (black and white stripes on the inner sides of box corer are 5 cm wide), c) polymetallic nodules on the seabed – picture from deep sea photo camera (the red-white circle scout on the seabed has a diameter 10 cm), d) collection of approximately 600 kg sample od polymetallic nodules using a trawl

The data collected during sampling and surveys was then subjected to detailed analysis. In laboratories, the composition of the nodules was analysed to determine the concentration of valuable metals being the subject of interest of this paper. The size, shape, and abundance of the nodules was also assessed to categorise them and understand their distribution on the seafloor.

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Geostatistical methods, including spatial distribution models, are then applied to estimate the distribution of nodules across the exploration areas. This phase includes creating models to estimate the statistical measures of nodule abundance and the classes of resources, expressed in tons and the content of metals in the nodules. In the IOM estimation we used methods presented and developed by Mucha and Wasilewska-Bałszczyk (2020), Wasilewska-Błaszczyk and Mucha (2023).

Resource estimation involves calculating the total area with nodule presence and estimating the total tonnage of nodules by considering the area and average abundance. This estimation is critical in determining the potential economic value of the nodules. The economic feasibility of extracting these resources is then evaluated by considering current and projected market values of the metals, alongside the costs associated with extraction, processing, and transportation.

The findings from the exploration process are compiled into resource reports, which are prepared according to international reporting standards. The ISA has developed its own geological reporting standard for polymetallic nodules resource assessment (International Seabed Authority, 2015).

Further information on the details of the procedures, technologies, expected results and the overall exploration process are extensively presented by Madureira et al. (2016). Similar steps activities of exploration for the German license exploration area in the Clarion-Clipperton Zone are discussed by Kuhn and Ruhlemann (2021).

The following resources were estimated in the IOM exploration area: 12.2 Mt of Measured Mineral Resources, 77.0 Mt of Indicated Mineral Resources and 183.3 Mt of Inferred Mineral Resources, a total of 272 Mt of wet polymetallic nodules (Table 7). In total, manganese resources represent 56.7 Mt, nickel 2.4 Mt, copper 2.2 Mt, cobalt 335 Kt and REE resources 6 Kt of metals contained in geological resources of the IOM deposit at 10 kg/m^2 cut-off wet nodule abundance (Table 8).

REE resources were calculated in the H22_NE block only, the area of which accounts for 1.3% of the total exploration area, the total potential resources of REE being expected proportionally higher. Similarly, the contents of Li and Sc was determined in the above-mentioned block only and, basing on the average content of those metals in H22_NE, their potential resources in the block are estimated at 1,400 and 130 tons, respectively.

The content of manganese, cobalt and REEs in basic calculation blocks (0.5x0.5 km) of the H22_NE exploitable block is shown in Figures 4, 5 and 6.

Table 7. Mineral resource estimate of wet polymetallic nodules in the IOM Exploration Area (10 kg/m^2 cut-off wet nodules abundance). Note: Sector B2 includes exploration blocks H11, H22, H33, H44 and exploitable block H22_NE

Resource classification	Mean abundance (kg/m^2)	Resources (Mt, wet)
Measured (H22_NE block)	14.60	12.2
Measured Total		12.2
Indicated (H11 + H22 blocks)	12.40	77.0
Indicated Total		77.0
Inferred (B1 sector)	13.40	62.6
Inferred (H33 block)	12.00	21.8
Inferred (H44 block)	11.50	13.6
Inferred (B2 sector other)	11.59	85.3
Inferred Total		183.3
Grand Total		272.5

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Table 8. Resources of metals in the IOM exploration area and H22_NE exploitable block for 10 kg/m² cut-off wet nodules abundance (* critical raw material, ** strategic and critical raw material according to the EU Critical Raw Materials Act 2024, nd – not determined)

Metal	Resources – metal content [t]	
	IOM exploration area	H22_NE block
Mn*	56,692,000	2,439,000
Ni**	2,417,000	109,200
Cu**	2,159,500	103,800
Co*	334,600	14,600
Zn	250,800	12,700
REE*	nd	5,916

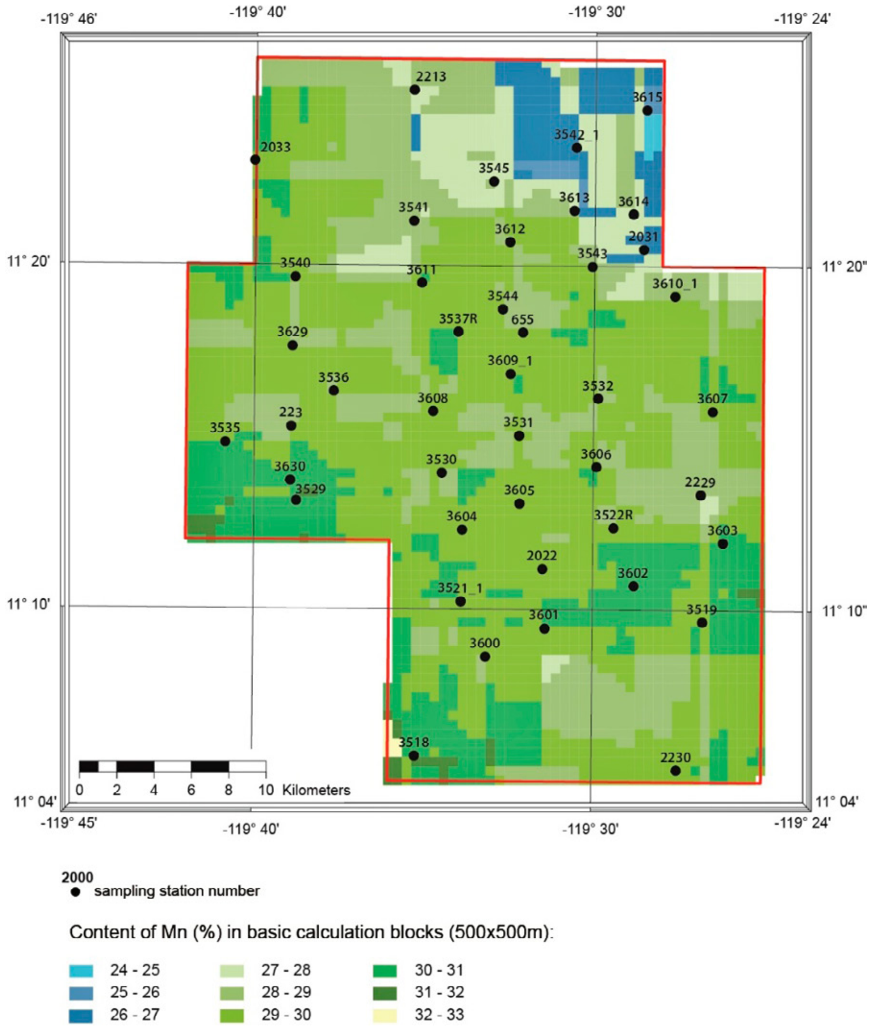

Figure 4. Manganese content in basic calculation blocks of the H22_NE exploitable block

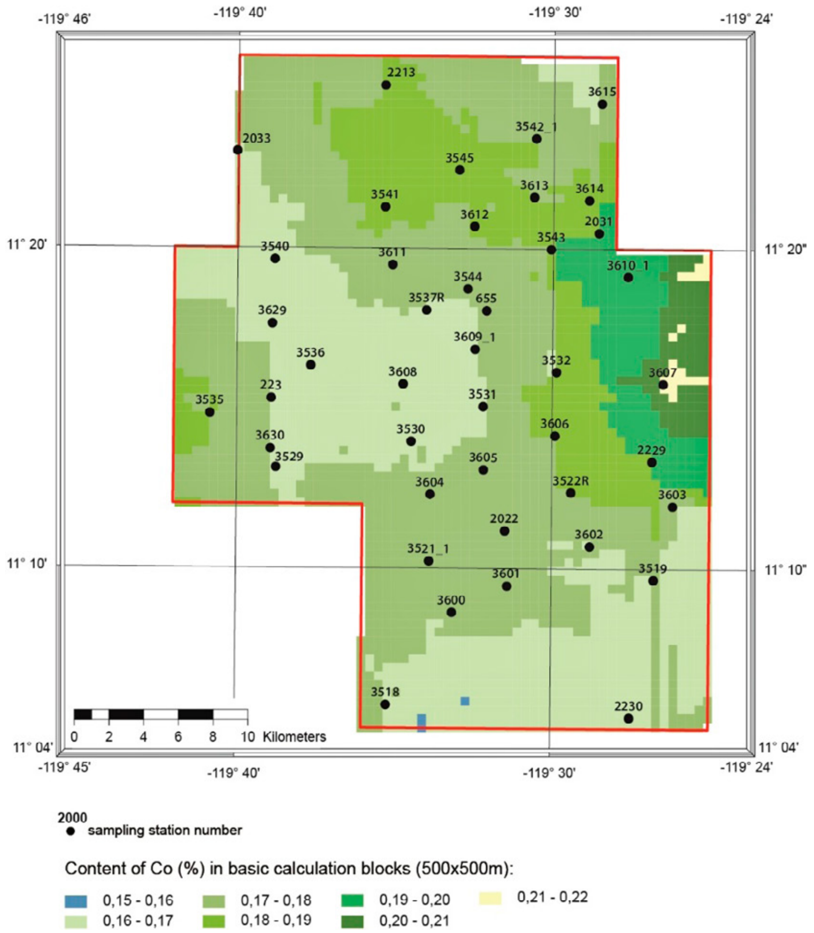

Figure 5. Cobalt content in basic calculation blocks of the H22_NE exploitable block

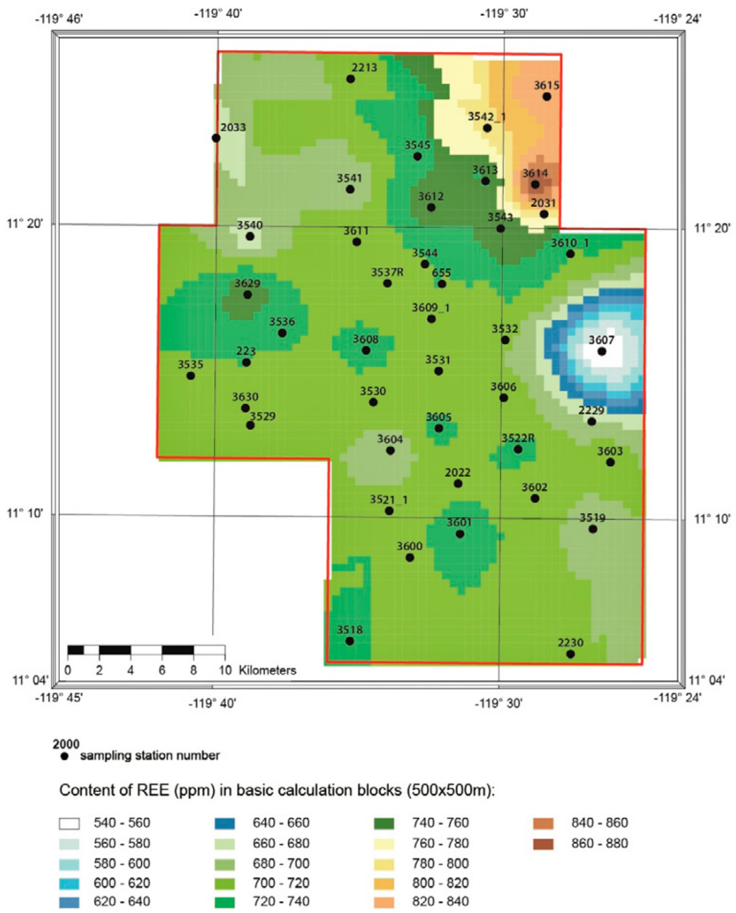

Figure 6. Rare earth elements content in basic calculation blocks of the H22_NE exploitable block

Processing possibilities

Manganese, nickel, cobalt, copper and zinc

IOM is currently testing various technologies for the processing of polymetallic nodules to identify the most optimal method. There are three main technologies for the extraction of main metals (Table 9):

1) *Hydrometallurgical technology:* leaching at atmospheric pressure using SO_2 as a reducing agent to obtain Ni and Co; obtaining Mn concentrate by drying in a rotary furnace and $(NH)_4SO_2$ as a by-product (fertilizer). This technology has been tested by IOM on a laboratory scale.
   The technological process consists of the following operations:
- preliminary grinding of wet raw material in ball mills;
- selective leaching of copper, nickel, cobalt and manganese dioxide at atmospheric pressure, thickening of the pulp after PMN leaching with the use of flocculants, and filtering of the bottom discharge thickener;
- precipitation of copper solution with powdered elemental sulphur at atmospheric pressure;
- precipitation of nickel and cobalt solution with powdered elemental sulphur and manganese;
- precipitation of manganese hydroxide in the solution's neutralisation reaction with ammonia water; thickening, filtrating, washing the filter with manganese hydroxide concentrate, drying manganese concentrate in rotating furnace, briquetting.

2) *Pyro-hydrometallurgical technology*: processing of polymetallic nodules in electric furnaces to obtain ferroalloys such as SiMn and FeMn, and hydrometallurgical processing with high-pressure sulphuric acid to separate Ni, Zn and Cu. This technology has been tested by IOM on a laboratory scale.

Pyro-hydrometallurgical processing has been studied to improve selective reduction of metals in the conditions of thermal processing (Ore-Electric Smelting Furnace), and subsequent treatment of the Cu-Ni-Co complex alloy. The process consists of the following stages:
- preliminary preparation of PN: drying, heating, sieving;
- pyrometallurgical process of selective recovery of non-ferrous metals (selective electroreduction of Cu, Ni, Co) to obtain a complex alloy of manganese and the transition to the gaseous phase;
- hydrometallurgical process of copper, nickel and cobalt selective extraction from complex alloy, including spraying of a complex alloy, two-stage dissolution of the copper sulphide concentrate, and deposition of mixed nickel-cobalt concentrate;
- neutralisation of the waste solution.

3) *Hydrometallurgical technology: high pressure leaching with sulphuric acid (HPAL technology*) using pyrite as reducing agent and the extraction of Ni, Co, Zn and Cu with Resin-in-Pulp (RIP) technology, ion exchange resin, and followed by extraction by roasting – oxide reduction from Mn. This technology has been tested by IOM on an expanded laboratory scale.
   The process consists of the following stages:
- direct preparation of PMN pulp with a high content of solid material;
- PMN pressure acid leaching with the addition of a reducing agent;
- selective separation of Cu, then Ni, Co, and Zn through the use of ion exchange resins (RIP);
- copper sulphide precipitation;
- zinc solvent extraction;
- nickel and cobalt sulphide precipitation;
- crystallization of manganese sulphate in an autoclave;
- calcination of manganese sulphate crystals to obtain manganese oxide and SO_2;
- neutralization of waste solutions.

Table 9. Comparison of three PMN processing technologies optimized by IOM (SX – solvent extraction; RIP – Resin-in-Pulp technology)

Method	Material preparation	Leaching method / Metal recovery (%)					Metal separation	Remarks
		Cu	Ni	Co	Zn	Mn		
1	Wet grinding	Selective leaching with SO_2 under atmospheric pressure					• SX • S_0+SO_2 precipitation • Mn+SO_2 precipitation	• wet nodules can be used • manganese can be recovered as MnO_2xnH_2O • ammonium sulphate $(NH_4)_2SO_4$ can be produced from the solution after manages precipitation • SO_2 is a toxic gas
		92.1	96.1	92.5	–	98.5		
2	Drying (heating, sieving) Electro-smelting	Two-stage dissolution: reduction in the presence of sulphuric acid and oxidation in the presence of air and H_2O					• SX • precipitation	• drying of nodules • high temperature process • (hence energy intensive) • manganese can be recovered as SiMn; • in case of further development, for the environmental and economic reasons it is necessary to include installation for neutralizing ammonia during waste solution treatment
		89.9	83.4	84.2	–	72.6		
3	Wet grinding, pulp preparation	Sulphuric acid pressure leaching					• RIP (ion exchange resins) • SX • H_2S precipitation • Calcination (for Mn)	• wet nodules can be used • relatively low energy consumption • relatively greater selectivity to the dissolution of metals during PMN leaching, regarding Fe • high flexibility to process metals contained in the ore (particularly for Mn) • using of pyrite as reducing agent • manganese recovered as MnO_2xnH_2O or, in case of difficulties with manganese market, its extraction can be postponed without breaking the overall process
		87.1	93.2	94.1	93.5	96.6		

REEs, lithium and scandium

Laboratory study of REEs, lithium and scandium recovery from polymetallic nodules was carried out by UCT (Vu et al., 2018). Untreated nodules, thermally treated nodules and chemically treated nodules were used for a sorption/desorption experiment. Concentrations of the studied metals in solutions were determined with an atomic adsorption spectrometer (AAS) and an inductively coupled plasma optical emission spectrometer (ICP-OES).

From a technological and economic point of view, direct utilisation of untreated nodules as a sorbent for the removal of critical metals (REE, Li, Sc) at low concentrations from acidic solutions appears to be the most effective method.

Untreated nodules are highly effective to extract lithium from solutions at low pH (~0.6 mg/g)) with a high degree of desorption (~70%). Untreated nodules can remove REE metals and Sc at pH under 1.31 (~0.3–0.5 mg/g), but their desorption is limited or not possible. Desorption of Sc from untreated nodules was not carried out due to the fact that sorption of Sc takes place at pH lower than the point of zero charge. Desorption of Sc at pH 0 could dissolve the metals of interest (Co, Ni, Cu) from nodules.

An effective extraction and separation of REEs, Li and Sc from polymetallic nodules can increase the value of processed products. The biggest challenge to effective recovery of these metals is their low content in nodules, which leads to the need of processing diluted leach liquors of low metals concentration. The technology scheme (Figure 7) for recovering REEs, Li and Sc includes the following steps:

1. Leaching of nodules in mild acidic conditions to selectively extract the metals of interest while main metals (Mn, Fe, Ni, Cu, Co) remain in solid phase. Park et al. (2015) proved that selective leaching of the metals of interest was possible;
2. Increasing concentrations of REEs, Li and Sc in solutions. Based on the findings of sorption/desorption tests, sorption/desorption stages using nodules can be incorporated into the technolog-

ical scheme to concentrate the metals. Strong sorption of Co onto nodules can be utilised to increase its concentration in the main leach liquors. Concentrations of REEs can also be increased by solvent extraction (Park et al., 2015);
3. Precipitation of a mixture of REEs compounds and their decomposition to a mixture of rare earth oxides (REOs) ;
4. Precipitation of Li_2CO_3.

In practice, nodules will be leached in a mild acidic medium and the diluted leach liquor will be treated by pH adjustment and sorption to adsorb REEs, Li, and Sc on nodules. After that, the nodules will be returned to mild leaching. The cycle will be repeated (the number of cycles will be determined by experiments). When the concentration of the metals of interest is sufficient, the concentrated leaching solution will be separated and treated by solvent extraction to recover a solution with REEs and a solution with Li and Co. REOs will be obtained from the REEs solution by re-extraction, precipitation and calcination. Li_2CO_3 will be precipitated from the solution after sorption/desorption with nodules. Nodules with absorbed Co will be subjected to mild acidic leaching.

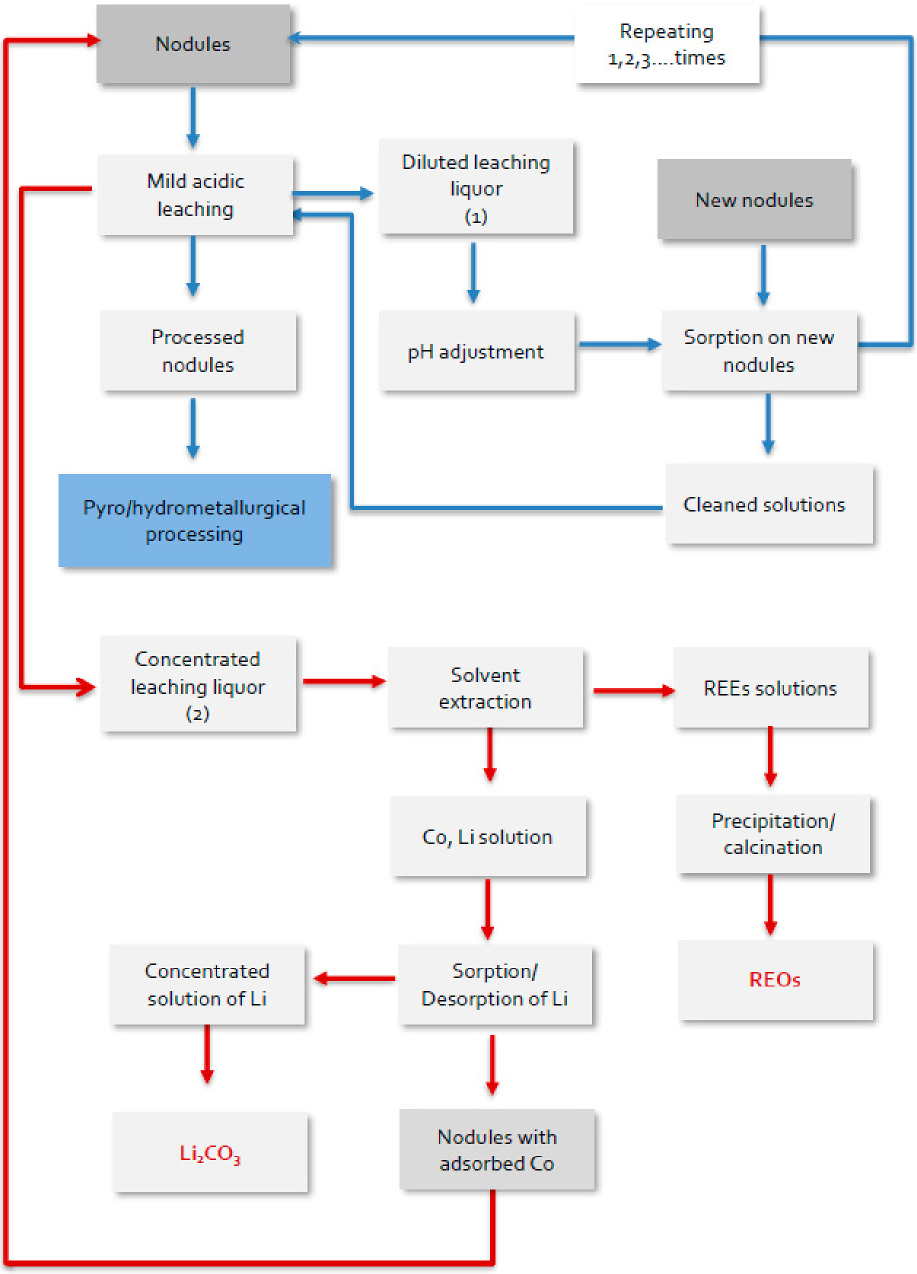

Figure 7. Technological scheme for recovering REEs and other metals from nodules

Source: Vu et al. (2018).

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The above presented schemes of metallurgical processing of nodules, especially in relation to leaching methods, can be further extended by the alternative use of modified leach residues obtained after the processes. For example (Vu et al., 2019) presented the possible use of leaching residue from leaching deep-sea nodules in $SO_2/H_2SO_4/H_2O$ medium as a low-cost adsorbent of heavy metals (Pb(II), Cd(II), Cu(II), Ni(II), Co(II), As(V)) was studied. The leaching residue was found to be an effective adsorbent for all of the tested elements. These possible applications could further improve the efficiency and sustainability of the industrial process.

Economic model

IOM and cooperating organisations conducted several studies incorporating elements of the polymetallic nodule project, recognised as most important for commercial viability. On the basis of formulated financial flow of operating and capital expenditures, the possible market unit price of polymetallic nodules was estimated. Although assumptions related to mining costs need to be confirmed during pilot mining tests, promising results have been shown in the case of the use of high-pressure acid leaching processing technology (HPAL) as well as in the case of raw ore sales. Economic model data is regularly updated. The analysis enables assessment of business assumptions and examine the impact of changes on the results of the project. Conclusions are used to optimise the scope of the project and identify associated risks.

The knowledge on the geology of the deposit as well as mining and processing technologies are constantly in the progress of development and the technical assumptions must respond to economic circumstances. Hence there is no one final set of results giving the optimal indicators. The IOM project included two scenarios. The first scenario represents a complete greenfield project (mining–transportation–processing–sale); the second scenario represents sales of mined ore to an existing processing plant (mining–transportation–sale). Ore transportation from the mine site to the port of destination and processing plant is supposed to be chartered. Both scenarios represent two extreme possibilities for business modeling and therefore differ significantly in terms of extraction scales. (Abramowski et al., 2021).

Conclusions and Outlook

According to the European Commission´s list of critical raw materials for the EU, cobalt, REEs, scandium, lithium, manganese, nickel and copper are considered critical metals. Low domestic supply and increasing import reliance of metals vital for European economy are a challenge for the long-term strategy of securing raw materials. Many European countries have been conducting exploration in the deep-sea. Presently the EU countries that have been sponsoring ISA contractors exploring polymetallic nodules in the CCZ are: Belgium, France, Germany, Czech Republic, Bulgaria, Slovakia, Poland (last four as sponsors of the IOM contractor). UK is a sponsoring state for a contractor from Norway. These activities are carried out with a possible view to secure the additional source of critical raw materials, which are necessary to ensure the transition to green technologies (electro mobility, photovoltaics, wind turbines, CO_2 capture, nuclear installations, LEDs, and others). The recycling rate of most of these metals is extremely low at present. Moreover, copper and nickel (two other main metals present in polymetallic nodules) have been included on the list of critical raw materials (from 2023).

Demand for critical minerals experienced strong growth in 2023, with lithium demand rising by 30%, while demand for nickel, cobalt, rare earth elements (and graphite) all saw increases ranging from 8% to 15%. Clean energy applications have become the main driver of demand growth for a range of critical minerals. Electric vehicles consolidated their position as the largest-consuming segment for lithium, and increased their share considerably in the demand for nickel, cobalt and graphite. In scenarios that fully meet all national energy and climate goals, demand for critical minerals for clean energy technologies would nearly triple by 2030 and quadruple by 2040 (International Energy Agency, 2024).

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Implementation of low-emission technologies is necessarily associated with increased consumption of specific metals. Polymetallic nodules offer a promising alternative supply of critical metals that can help achieve these goals, reduce the dependence of the European economy on imports, and strategically ensure the long-term supply of critical raw materials.

The contribution of the authors

Conceptualisation, P.B. and T.A.; literature review, P.B., K.M., T.A. and E.K.; methodology exploration technologies, P.B. and T.A.; methodology processing, E.K. and G.M.G.; methodology resource assessment, P.B.; methodology metals market, P.B. and T.A.; writing, P.B., T.A., K.M., G.M.G. and E.K.; project management, T.A.; graphics and GIS systems, A.K.; conclusions and discussion, P.B., K.M. and E.K.

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ODKRYWANIE SUROWCÓW DLA EUROPY: STRATEGICZNY POTENCJAŁ GŁĘBOKOMORSKICH KONKRECJI POLIMETALICZNYCH IOM DLA ZABEZPIECZENIA DOSTAW METALI KRYTYCZNYCH

STRESZCZENIE: Celem artykułu jest pokazanie możliwości wykorzystania polimetalicznych konkrecji dna morskiego w strefie Clarion-Clipperton (CCZ) jako zrównoważonego źródła metali krytycznych, takich jak pierwiastki ziem rzadkich (REE), kobalt, mangan, lit i skand. Metodologia obejmuje obszerne badania geologiczne i pobieranie próbek w obszarze eksploracji Interoceanmetal Joint Organization (IOM), a następnie analizę składu mineralnego, zawartości metali i ocenę możliwości przetwarzania metalurgicznego. Znaczenie metali krytycznych omówiono na podstawie analizy literatury. Badania potwierdzają, że polimetaliczne konkrecje w CCZ są bogate w metale krytyczne i strategiczne o potencjale ekonomicznym. Konieczne są dalsze badania w celu oceny wpływu na środowisko i wykonalności ekonomicznej górnictwa głębinowego. Praktyczne implikacje są takie, że rozwój górnictwa głębinowego może być realną alternatywą dla tradycyjnego górnictwa lądowego, potencjalnie zmniejszając zależność Europy od importowanych metali krytycznych. Społeczne implikacje projektu dotyczą zrównoważonych dostaw metali krytycznych w celu promowania zielonych technologii, walki ze zmianą klimatu i celów transformacji energetycznej społeczeństwa. Materiał zaprezentowany w artykule dostarcza informacji do oceny potencjału konkrecji polimetalicznych jako strategicznego zasobu, przyczynia się do dyskursu na temat zrównoważonego górnictwa i bezpieczeństwa zasobów w kontekście globalnych wyzwań związanych z dostawami.

SŁOWA KLUCZOWE: metale krytyczne, konkrecje polimetaliczne, zasoby strategiczne, górnictwo głębinowe

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