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Deep-sea polymetallic nodules as opportunity for future supply with critical raw materials

Дълбокоморски полиметални конкреции като възможност за бъдещо снабдяване с критични суровини

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Abstract. The renewed importance of polymetallic nodules in the context of forecasted increasing demands for metals are discussed. Based on the Interoceanmetal Joint Organization's (IOM) site-specific data obtained during the exploration activity in the Clarion-Clipperton Fracture Zone, a total of 272.5 Mt of nodules were estimated as economically reasonable for future mining for Ni, Cu, Co, and Mn. Additionally, data for REE and other critical elements in nodules as potential by-products are presented.

Keywords: critical raw materials, polymetallic nodules, manganese, REE, Clarion-Clipperton Fracture Zone.

Introduction

Rapidly increase of interest to explore deep seabed mineral resources (in particular polymetallic nodules) is seen in the last decade although the deep-sea mining is not commercially viable at present. Nowadays, the International Seabed Authority (ISA) has entered into 31 contracts for exploration for deep-sea minerals, thus 19 of these contracts are for exploration of polymetallic nodules in the Clarion-Clipperton Fracture Zone (CCZ), NE Pacific Ocean (17), Central Indian Ocean (1) and Western Pacific Ocean (1) (ISA, 2021). The richest nodule deposits and consequently most exploration claims registered with the ISA are located in the CCZ. A conservative estimate of the dry tonnage of nodules in the CCZ is 21 100 Mt (Hein et al., 2013). These deposits are considered alternatives to depleting land resources of strategic metals such as Cu, Ni, Co, Pb, Zn, Mo, Pt, and REE that are required for various industrial purposes (Kuhn et al., 2017). Many of metals found in polymetallic nodules (Bi, Co, HREE, LREE, Li, PGE, Sr, Ti, W, and V) are defined as critical raw materials for the EU in 2020 (COM(2020) 474).

Mining of polymetallic nodules from the seabed is still in uncertain terms; perhaps the most important barrier is economic. However, the recent research indicates that deposits of polymetallic nodules have the potential to be economically feasible for exploitation in the presence of favorable metal prices, as well as in accordance with the technological improvement of the mining and processing systems (Volkmann et al., 2018; Abramowski et al., 2021a).

This study presents results based on the currently available synthesis of knowledge on the valuation of polymetallic nodule deposits of the Interoceanmetal Joint Organization (IOM). The IOM, an intergovernmental consortium sponsored by governments of six countries (Bulgaria, Cuba, the Czech Republic, Poland, the Russian Federation, and Slovakia), was among the first "pioneer investors", which in 2001 concluded with the ISA a contract for exploration for polymetallic nodules in 75 000 km^2 seafloor claim area, situated in the eastern part of the CCZ, NE Pacific ocean (Fig. 1). The structure of the IOM investment project in general contains the analysis of the financial flow and technological developments of commercial phases of the project implementation,

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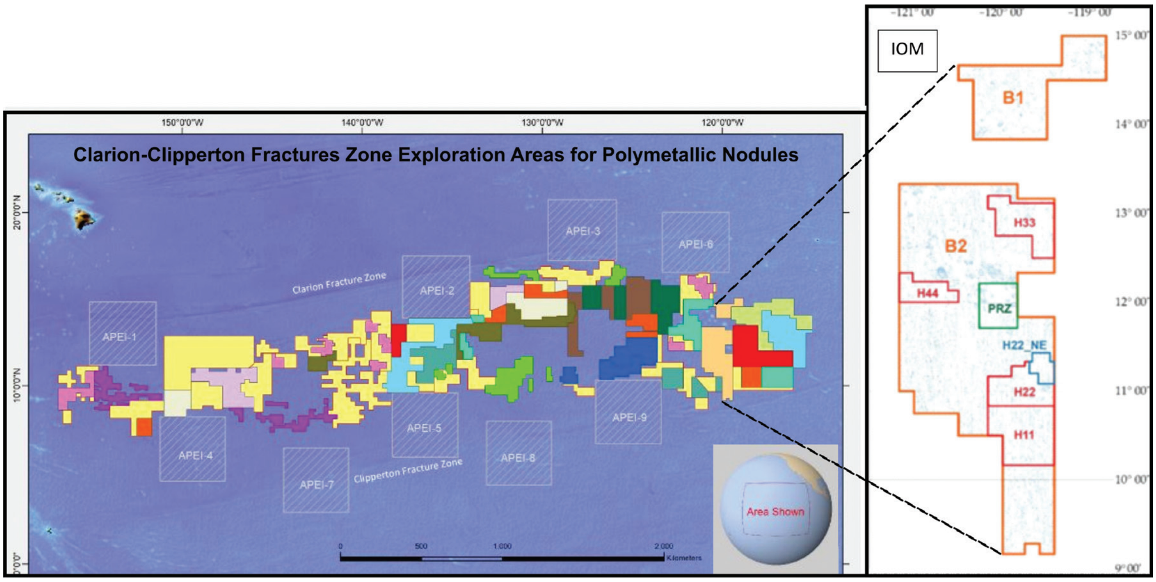

Fig. 1. Map of polymetallic nodules exploration areas in the Clarion-Clipperton Fracture Zone, NE Pacific Ocean (www.isa.org.jm); on the right, the IOM exploration area (sectors B1 and B2) with exploration and exploitable blocks, included in the resource estimation (adapted from Abramowski et al., 2021b)

namely, deep-sea mining operations, metallurgical processing, and economic criteria investigations.

Materials and methods

The source of materials for this paper is based on extensive data and information obtained from more than 25 scientific expeditions and onshore investigation carried out by the IOM in the license area (Dreiseitl, 2016; Abramowski et al, 2021b). The results of this comprehensive research, which included geological documentation, technology of nodule extraction and processing as well as research on the marine environment in the exploration area, were summarized in the IOM Preliminary Economic Assessment Technical Report prepared in 2018 (IOM fund). Resource estimation is based on geostatistical data analysis of nodule samples collected during the above-mentioned expeditions carried out by the IOM.

Geochemical studies of REE in polymetallic nodules at the Geological Institute, BAS started in 2012 (Dimitrova et al., 2014) and continued with the samples from the 2019 Interoceanmetal cruise. The concentration of 58 elements in nodules was determined by LA-ICP-MS (New Wave UP193FX excimer laser combined with a PerkinElmer ELAN DRC-e ICP-MS) at the Geological Institute, BAS. Chemical composition of bulk nodule samples was measured on pressed pellets while the *in situ* trace element composition was measured on polished sections.

IOM resources summary

According to the CRIRSCO (Committee for Mineral Reserves International Reporting Standards) directives, the resources of polymetallic nodules in the IOM license area can be categorized as „inferred” in B1 and B2 exploration sectors, as „indicated” in H11 and H22 exploration blocks, and as measured in the H22_NE exploitable block (Fig. 1).

The current status of mineral resource estimate of wet polymetallic nodules in the entire IOM exploration area and its first generation minable blocks/sites is shown in Table 1. Within the whole exploration area and blocks, the accuracy of nodule resource estimation is high, with the relative (kriging) standard error of the estimate of 3–8 %. The accuracy of Cu, Co, Mn, and Ni grade estimates is highly satisfying in areas of any size due to low variability of metal contents, resulting from stable chemical composition of polymetallic nodules. The number of geological samples is statistically important for the purpose of the resource estimation. Therefore, the subject of this economic analysis was primarily focused on the base metals, also for the IOM’s purpose of developing metallurgical processing methods. The total resources of the exploration areas and blocks were obtained by a summation of values estimated for basic calculation blocks. The 10 kg/m^2 cut-off abundance in the basic calculation blocks can be considered as economically reasonable, i.e. ensuring high probability of economic benefit from mining operation.

Grades of REE and other trace elements

In the IOM contract area, the nodule ores contain also other metals of economic importance. The mean contents with the number of determinations presented below included: Mo (0.061%, n = 457), Zn (0.143%, n = 520), V (0.045%; n =

Table 1. Mineral resource estimate of wet polymetallic nodules in the B1 and B2 sectors of the IOM exploration area

Mineral resource classification	Mean abundance (wet kg/m^2)	Mn (%)	Ni (%)	Cu (%)	Co (%)	Resources (Mt)*
Measured (H22_NE block)	14.6	29.19	1.31	1.25	0.18	12.2
Measured total						12.2
Indicated (H11 and H22 blocks)	12.4	31.37	1.30	1.29	0.16	77.0
Indicated total						77.0
Inferred (B1 sector)	13.4	27.84	1.21	0.90	0.21	62.6
Inferred (H33 block)	12.0	32.35	1.41	1.2	0.18	21.8
Inferred (H44 block)	11.5	30.71	1.32	1.19	0.19	13.6
Inferred (B2 sector other)	11.6	30.90	1.32	1.21	0.18	85.3
Inferred total						183.3
Grand total						272.5

*Sector B2 includes exploration blocks H11, H22, H33, and H44 and exploitable block H22_NE
Note: Cut-off abundance 10 kg/m^2 of wet nodules, without volcanoes, outcrops, seabed areas free of nodules, and areas sloped over 7° (Abramowski et al., 2021a; IOM fund)

180), Pb (0.032%, n = 517), Sr (0.067%; n = 284), Ba (0.211%; n = 279); Cr (0.0014 %; n = 91), As (0.007%; n = 256), Ti (0.37%, n= 180), Fe (5.88%; n = 531) (IOM fund data).

Results of LA-ICP-MS analyses of bulk nodule samples confirm the IOM data for Mn, Cu, Ni, Co, and the elements listed above. Furthermore, data on the presence of REE and other trace elements in the polymetallic nodules were obtained. The concentrations of characteristic elements are as follows (in ppm): Li (77–177, mean 129.7), Sc (7.7–11.7, mean 9.99), Ga (38–52, mean 44.9), Zr (204–340, mean 272.7), Pd (0.34–0.73, mean 0.58), Cd (8.6–20.8, mean 17.3), In (0.14–0.25, mean 0.21), Sb (35–65, mean 49.3), Te (4.2–8.9, mean 5.9), Hf (3.1–5.3, mean 4.35), W (51–111, mean 75.9), Tl (53–410, mean 232.6), Bi (2.5–7.1, mean 5.1), Th (5.5–15.6, mean 11.05), and U (2.6–4.6, mean 4.1). The ΣREE varies from 339.2 to 719.1 ppm (mean 594.27 ppm), ΣREY is from 380.8 to 800.8 ppm (mean 664.27 ppm), and ΣHREE is from 47.8 to 105.5 ppm (mean 87.72 ppm).

Grades of REE in the polymetallic nodules are generally lower than those for the land-based deposits, but in terms of the tonnages they are much greater (Hein et al., 2013). Additionally, relative amount of HREE in the marine deposits is quite high when compared to the land ones: up to 26 % of the total REEs (Halbach, Jahn, 2016). The different REE grades are related to different genetic types of nodules: hydrogenetic type – the highest, diagenetic type – the lowest grades. Geochemical analyses have revealed fractionation of REEs in the marine deposits (Halbach, Jahn, 2016): the δ-MnO_2-phase preferentially carries LREEs, whereas the Fe-oxyhydroxide-phase contains more HREEs.

The REE and other trace elements referred as critical raw materials are potential by-products of the major metal mining (Halbach, Jahn, 2016) as well as elements relevant to metallurgical processing. This explains the growing importance of deep-sea polymetallic nodules as a potential source for future supply with critical raw materials.

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