Polymetallic Nodules Resource Estimation in the Suoi Thau-Sang Than Area, Northeastern Vietnam

Khuong THE HUNG[1,], Pham NHU SANG[1,2], Nguyen PHUONG[1], Nguyen TIEN DUNG[1], Bui HOANG BAC[1], Nguyen QUOC PHI[1], Bui VIET SANG[3]*

[1] Hanoi University of Mining and Geology, Hanoi, Vietnam; email: khuongthehung@humg.edu.vn; phamnhusang@humg.edu.vn; nguyenphuong@humg.edu.vn; nguyentiendung@humg.edu.vn; buihoangbac@humg.edu.vn; nguyenquocphi@humg.edu.vn
[2] State Key Laboratory of Marine Geology, Tongji University, Shanghai, China; email: nhusang@tongji.edu.cn
[3] Intergeo Division, Pham Van Dong street, Hanoi, Vietnam; email: buivietsang1978@gmail.com

http://doi.org/10.29227/IM-2020-02-03

Submission date: 06-03-2020 | Review date: 22-09-2020

Abstract

1,720 chemical, mineral, and petrography samples in the Suoi Thau-Sang Than area, northeastern Vietnam were collected to investigate polymetallic nodules resource. The similarity-analogy in ore geology, direct calculation method for metallization parameters, and mineral resource estimation based on cutoff grade change methods are employed to estimate polymetallic nodules resource from the Suoi Thau, Sang Than, and Ban Kep areas in northeastern Vietnam. The similarity-analogy in ore geology indicates 1,785,000 tons Cu, 12,005,000 tons Pb+Zn, and 195 kg Au in total. The direct calculation method for metallization parameters shows 2,060,000 tons Cu, 13,648,000 tons Pb+Zn, and 224 kg Au in total. These methods display that the Sang Than area contains mainly polymetallic nodules in the studied area. Following the mineral resource estimation based on cutoff grade changes, estimation results indicate potential Pb-Zn nodules resource in the Ban Kep and Cu nodules resource in the Sang Than, while no potential Au nodules resource in the Suoi Thau and the Sang Than as well as the Ban Kep. The estimation results obtained from mineral resource estimation based on cutoff grade changes are suitable with the results from the traditional geometric block methods. Our study suggests that the Sang Than area can be considered as a potential Cu nodules resource, and the Ban Kep area is potential Pb-Zn nodules resource in northeastern Vietnam for future exploitation, while there is no potential polymetallic nodules resource in the Suoi Thau area. Furthermore, the one resource estimation based on cutoff grade changes method displays an overview of the prospect on polymetallic nodules resources, indicating that this method can serve as a basis for the proposed selection of the prospective areas for effective Cu, Pb-Zn, and Au mineral exploration in the Suoi Thau-Sang Than area, northeastern Vietnam.

Keywords: *polymetallic nodules, resource estimation, Suoi Thau-Sang Than area, northeastern Vietnam*

1. Introduction

Polymetallic nodules play an important role in providing valuable metals for industry because of zinc, lead, copper, and gold can be highly found together in the nodules (Rankin, 2011; USGS, 2014; Graedel et al., 2015). Zinc is primarily utilized to make galvanized steel as well as the production of brass, bronze, chemicals, and zinc alloys for the construction and industry. Lead is widely used for the production of lead-acid batteries, cable sheaths, machinery, machinery manufacturing, shipbuilding, light industry, lead oxide, radiation protection, and other industries. Copper contains excellent properties, making it can be used predominantly in electrical power, electronics, energy, petrochemicals, transportation, machinery, metallurgy, light, and some high-tech fields. Gold is considered the most valuable of the pure metals, and it is chiefly utilized for coinage, ornaments, jewellery, and gilding.

Mineral resource estimation is a practical significance in the mineral investigation (Glacken & Snowden, 2001; Hung et al., 2016; Zhang & Huang, 2010; Revuelta, 2018; Kužvart & Böhmer, 1986). This provides a scientific and practical basis for establishing geological survey programs as well as evaluating the prospects of minerals and investment. For decades, scientists have focused on researching and proposing many methods of mineral resource estimation in processes of geologic mapping and surveying minerals. Generally, mineral resource estimations are mainly conducted according to the results of geological mapping and mineral prospecting at 1:200,000 - 1:50,000 scale. Currently, many geological and math-geological methods have proposed to estimate mineral resources. Among them, the similarity-analogy in ore geology, direct calculation method for metallization parameters, and mineral resource estimation based on cutoff grade change methods have been widely used to investigate mineral resources (Lasky (1950; Byryukov, 1962; Kogan, 1971, Snowden, 2001; Hung et al., 2016; Zhang & Huang, 2010; Revuelta, 2018). Different estimation methods have been used for different scenarios depending upon the ore boundaries, geological geometry, grade variability, the amount of time, and money available. To select the suitable methods for the research object, the stage of geological investigation, the completeness of the document, the geological structure characteristics of the object and mineral type should be investigated carefully. The northeast Vietnam is assessed to be high polymetallic nodule resources (Tri & Khuc, 2011). However, the mineral resource estimation methods have been used based on qualitative description and calculation, which used rigid formulas and parameters, suggesting not suitable for the variability of the mineral market. To have a more comprehensive and flexible view of mineral resource estimation, a model for evaluating polymetallic resources based on many different boundary content options should be studied in this area. Therefore, northeast Vietnam is

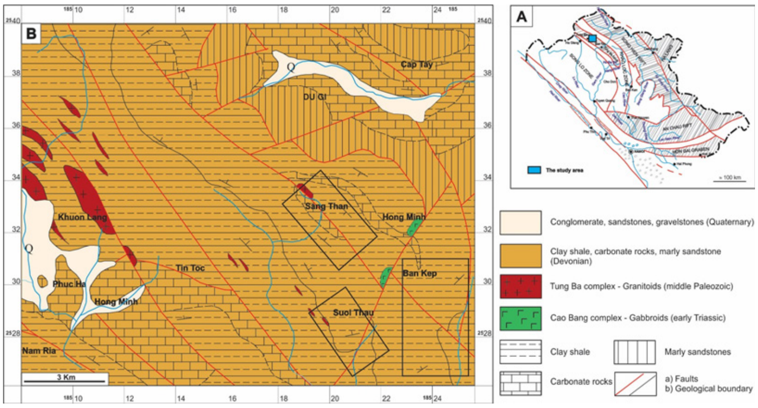

Fig. 1. (A) Tectonic sketch map of northeastern Vietnam and location of the studied area (Dovjikov et al., 1965), (B) Simplified geological map of the Suoi Thau-Sang Than area, Ha Giang province (Son et al., 2003)

Rys. 1. (A) Rysunek mapy tektonicznej północno-wschodniego Wietnamu i lokalizacja badanego obszaru (Dovjikov i in., 1965), (B) Uproszczona mapa geologiczna w obszarze Suoi Thau-Sang Than, prowincja Ha Giang (Son i in., 2003)

an ideal area to apply this asymptotic approach for estimating polymetallic nodules resources.

In this study, similarity - analogy in ore geology, direct calculation method for metallization parameters, and mineral resource estimation based on cutoff grade changes methods are used to investigate polymetallic nodules resource from Suoi Thau, Sang Than, and Ban Kep areas in northeastern Vietnam.

2. Geological setting

Geology

The Suoi Thau-Sang Than area is located in Ha Giang province, northeastern Vietnam (Fig. 1). The area has mainly consisted of Devonian sedimentary rocks (i.e., clay shale, carbonate rocks, and marly sandstone), and minor Triassic gabbroid rocks and Paleozoic granitoid rocks (Minh et al., 1992; Son et al., 2003; Fig. 1A). Structurally, the studied area is Northwest part of a synclinorium complex extending from Northwest to Southeast. The Tung Ba structural block is controlled by the Duong Thuong-Du Gia overthrust/reverse fault in the north, and the Ban Coc-Minh Ngoc reverse dip-slip fault in the south (Dovijkov et al., 1965). These two faults and the faults located between them in the same direction play a key role in controlling the activities of magmatic intrusive rocks and minerals in the region (Son et al., 2003). Besides, other fault systems occurred to are developed to complicate the regional structure.

Morphological and structural characteristics of polymetallic mineralization zones

In the studied area, the Suoi Thau, Sang Than, and Ban Kep areas are investigated to be indicated containing polymetallic and gold mineralization (Bat et al., 1989; Sinh et al., 1985; Minh et al., 1992). Generally, the mineralized zones are developed along the northwest-southeast with a length of 380–3,800 m and extend beyond the study area. The mineralization zones are laid down in the distribution area of the Devonian sedimentary rocks. The concentrations of Cu, Pb, and Zn are unevenly distributed in the mineralized zone, but it is assessed to be industrial ore bodies (Son et al., 2003; Sang, 2011).

In the Suoi Thau area, there are three mineralized zones.

Mineralization zone 1 has developed along the northwest-southeast direction of about 720 m, plugged to the northeast with a slope of 10–30°, 90–115 m thick (average 95 m). The zone is located at the boundary between the marble and the quartz-biotite. Analytical sample results showed 0.31–1.06% Cu (average 0.47%), 0.63–1.31% Pb (average 1.01%), 1.32–3.85% Zn (average 2.59%). Calculation results of smelting displayed 0.10–2.10 g/t Au (average 0.53 g/t). The changes related to ore creation are skarnification and quartzization.

Mineralization zone 2 extends along the north-south about 380m, width 40–80 m (average 50 m), and it plugs in the northwest with a slope of 35°. The mineralized rock is mainly marbles. This zone contains 0.16–0.57% Cu (average 0.42%), 0.40–2.04% Pb (average 1.19%), and 0.13–3.86% Zn (average 2.82%). Calculation results of smelting indicated 0.10–1.80 g/t Au (average 0.68 g/t). The formation of this mineralization zone can be related to the skarnification and quartzization.

The mineralization zone 3 is suffered highly brittle deformation that impacted by post-ore fault activities. The zone appears mainly marbles, which were significantly broken and fractured. The mineral zone is about 1,800 m length, 230–400 m width (average 320 m), and it dips to northeast 30o. Compositional analyses of sample show 0.20–0.73% Cu (average 0.49%), 0.26–1.56% Pb (average 1.03%), and 1.08–5.56% Zn (average 2.85%). Calculation results of smelting display 0.10–1.30 g/t (average 0.52 g/t). The formation of this mineralization zone can be controlled by the skarnization, dolomitization, and quartzization.

The Sang Than area, the mineralization zone is located in the broken zone by impacting of faults. The mineralized rocks are mainly marbles that were highly crushed and fractured. This zone shows 3,900 m length, 700-900 m widths (average 380 m), and it plugs in the southwest with a slope angle of 40o. Sample analysis results indicate 0.02–3.10% Cu (average 0.59%), 0.19–2.47% Pb (average 0.96%), and 1.01–6.47% Zn (average 2.73). Calculation results of smelting show 0.10–1.50 g/t Au (average 0.63 g/t). The skarnization, dolomitization, quartzization, and chlorination can be considered forming this mineralization zone.

In the Ban Kep area, two mineralized zones have discovered. The mineralization zone 1, the mineralized rock consists mainly of fractured marbles. This zone is 1,300 m length,

Tab. 1. Similarity levels among estimated areas ($K.10^{-2}$)

Tab. 1. Podobieństwo między obszarami badań ($K.10^{-2}$)

K_{ij}	Suoi Thau	Sang Than	Ban Kep
Suoi Thau	100	90.539	93.020
Sang Than	90.539	100	92.526
Ban Kep	93.020	92.526	100

Tab. 2. Results of Cu, Pb-Zn, and Au resource estimations based on similarity-analogy in ore geology

Tab. 2. Wyniki szacunków zasobów Cu, Pb-Zn i Au na podstawie analogii podobieństwa w geologii rud

Area	S_{sp} (m^2)	q_c (ton/m^2)	K (10^{-2})	Q_{sp} (10^3 ton)	Metal contents (%)			Metal resources (10^3 tons)		
					Cu	Pb-Zn	Au (g/t)	Cu	Pb-Zn	Au (kg)
Suoi Thau	776,500	54.4	90.539	38,245.122	0.45	3.62	0.55	172	1,384	21
Sang Than	4,428,000	54.4	100	240,883.200	0.59	3.64	0.63	1,421	8,768	151
Ban Kep	968,500	54.4	93.526	49,275.482	0.39	3.76	0.46	192	1,853	22
Total				**328,403.805**				**1,785**	**12,005**	**195**

Tab. 3. Results of Cu, Pb-Zn, and Au resource estimations based on direct calculation method

Tab. 3. Wyniki szacowania zasobów Cu, Pb-Zn i Au na podstawie metody obliczeń bezpośrednich

Area	S_{sp} (m^2)	M_{sp} (m)	d (ton/m^3)	K_q	Q_{sp} (10^3 tons)	Metal contents (%)			Metal resources (10^3 tons)		
						Cu	Pb-Zn	Au (g/t)	Cu	Pb-Zn	Au (kg)
Suoi Thau	776,500	75	3.23	0.21	39,502.496	0.45	3.62	0.55	177	1,429	22
Sang Than	4,428,000	75	3.23	0.27	289,624.410	0.59	3.64	0.63	1,708	10,542	182
Ban Kep	968,500	75	3.23	0.19	44,577.634	0.39	3.76	0.46	173	1,676	20
Total					**373,704.540**				**2,060**	**13,648**	**224**

* Assessing the reliability of the resource estimations of category 334 resources.

Tab. 4. Results of Cu resource estimations based on cutoff grade changes

Tab. 4. Wyniki szacunków zasobów Cu na podstawie zmian zawartości granicznej

Αρεα	Ορε ρεσουρχε σ (10^3 τον)	Χβ (%)	Γαμμα φαχτορσ			γ(ζ)	1−γ(ζ)	Τοταλ ποτεντιαλ σ οφ ορε ρεσουρχ εσ (10^6 τονσ)	Τοταλ ποτεντιαλσ οφ χοππερ ρεσουρχε σ (10^3 τονσ)
			α	β	ζ				
		0.1			1.067	0.006	0.994	39.256	18
		0.2			2.133	0.077	0.923	36.462	17
		0.3			3.200	0.244	0.756	29.879	14
Suoi Thau	39,502.496	0.4	3.840	0.094	4.267	0.453	0.547	21.605	10
		0.5			5.334	0.644	0.356	14.079	6
		0.7			7.467	0.880	0.120	4.745	2
		1.0			10.667	0.984	0.016	0.636	0.3
		0.1			0.078	0.339	0.661	191.345	113
		0.2			0.156	0.456	0.544	157.433	93
		0.3			0.235	0.538	0.462	133.875	79
Sang Than	289,624.410	0.4	-0.538	1.278	0.313	0.600	0.400	115.753	68
		0.5			0.391	0.651	0.349	101.133	60
		0.7			0.548	0.728	0.272	78.757	47
		1.0			0.782	0.807	0.193	55.798	33
		0.1			1.324	0.009	0.991	44.172	17
		0.2			2.647	0.114	0.886	39.514	15
		0.3			3.971	0.338	0.662	29.499	12
Ban Kep	44,577.634	0.4	4.155	0.076	5.295	0.582	0.418	18.612	7
		0.5			6.619	0.769	0.231	10.285	4
		0.7			9.266	0.947	0.053	2.370	0.9
		1.0			13.237	0.996	0.004	0.168	0.1

Tab. 6. Results of Pb-Zn resource estimation based on cutoff grade changes

Tab. 6. Wyniki szacowania zasobów Pb-Zn na podstawie zmian zawartości granicznej

Area	Ore resources (10^3 ton)	C_b (%)	Γαμμα φαχτορσ			γ(ζ)	1−γ(ζ)	Total potentials of ore resources (10^6 tons)	Total potentials of Pb-Zn resources (10^3 tons)
			α	β	ζ				
		3.0			5.285	0.636	0.364	14.381	52
		3.5			6.166	0.759	0.241	9.506	34
		4.0			7.047	0.848	0.152	5.995	22
Suoi Thau	39,502.496	5.0	5.379	0.568	8.809	0.946	0.054	2.134	8
		6.0			10.571	0.983	0.017	0.679	3
		8.0			14.094	0.999	0.001	0.055	0.2
		10.0			17.618	1.000	0.000	0.004	0.01
		3.0			2.207	0.968	0.032	9.165	33
		3.5			2.575	0.979	0.021	5.951	22
		4.0			2.943	0.987	0.013	3.892	14
Sang Than	289,624.410	5.0	1.677	1.359	3.678	0.994	0.006	1.691	6
		6.0			4.414	0.997	0.003	0.747	3
		8.0			5.885	0.999	0.001	0.150	0.6
		10.0			7.356	1.000	0.000	0.031	0.1
		3.0			2.202	0.062	0.938	41.805	157
		3.5			2.569	0.103	0.897	39.972	150
		4.0			2.935	0.155	0.845	37.671	142
Ban Kep	44.577.634	5.0	1.757	1.363	3.669	0.281	0.719	32.041	120
		6.0			4.403	0.421	0.579	25.812	97
		8.0			5.871	0.673	0.327	14.585	55
		10.0			7.339	0.840	0.160	7.126	27

Tab. 5. Total potentials of copper resources based on cutoff grade changes
Tab. 5. Całkowity potencjał zasobów Miedzi na podstawie zmian zawartości granicznej

Cutoff grades (%)	Total potentials of ore resources (10^6 tons)	Total potentials of copper resources (10^3 tons)
0.1	274.8	148
0.2	233.4	125
0.3	193.3	104
0.4	156.0	86
0.5	125.5	70
0.7	85.9	50
1.0	56.6	33

Tab. 7. Total potentials of Pb-Zn resources based on cutoff grade changes
Tab. 7. Całkowite potencjały zasobów Pb-Zn na podstawie zmian zawartości granicznej

Cutoff grades (%)	Total potentials of ore resources (10^6 tons)	Total potentials of Pb-Zn resources (10^3 tons)
3.0	65.4	243
3.5	55.4	206
4.0	47.6	177
5.0	35.9	134
6.0	27.2	102
8.0	14.8	56
10.0	7.2	27

Tab. 9. Total potentials of Au resources based on cutoff grade changes
Tab. 9. Całkowite potencjały zasobów Au na podstawie zmian zawartości granicznej

Cutoff grades (g/T)	Total potentials of ore resources (tons)	Total potentials of Au resources (kg)
0.2	169.2	95.5
0.3	142.8	78.9
0.5	113.8	60.8
0.7	99.1	51.7
1.0	86.7	44.4
1.5	72.0	36.6

70–120 m width (average 80 m). Results of sample analysis show 0.16–0.70% Cu (average 0.41%), 0.10–3.11% Pb (average 0.75%), and 0.60–7.29% Zn (average 2.65%). Calculation results of smelting display 0.10–2.00 g/t Au (average 0.44 g/t). The formation of this mineralization zone can be strongly related to the skarnization, dolomitization, and quartzization.

The mineralization zone 2 extends along the east-west, and it is mainly surrounded by the Devonian marbles. The zone shows 1500 m length, 60–130 m width (average 100m). Results of sample analysis display 0.10–0.57% Cu (average 0.38%), 0.12–2.03% Pb (average 0.92%), and 1.06–4.80% Zn (average 1.97%). Calculation results of smelting indicate 0.10–1.00 g/t Au (average 0.45 g/t). The formation of this mineralization zone can be formed by the skarnization, dolomitization, and quartzization.

3. Materials and methodologies

This study was carried out based on the results of geological surveying and mapping the Geological and mineral resources map of Vietnam at 1:50,000 scale of the Phuc Ha map sheet group (Son et al., 2003). 518 samples in the Suoi Thau, 503 samples in the Ban Kep, and 699 samples in the Sang Than were collected by the Intergeo Division for analyzing chemical, mineral, and petrography at the Center for Experimental Geological Analysis in Vietnam Institute of Geosciences and Mineral resources and the Intergeo Division. The mineralization zones have been investigated by surface works such as openings and ditches. Based on geological characteristics and level research in the study area, the similarity-analogy in ore geology, direct calculation method for metallization parameters, and mineral resource estimation based on cutoff grade change methods are chose to study the mineralized zone of category 334 resources in the Suoi Thau-Sang Than area.

Similarity-analogy in ore geology:

Similar-analogy in ore geology was developed based on similar geological environments in different areas, which are similar mineralization characterization (Byryukov, 1962). This method is created by using a similar model for other ore deposits, which are similar geological characterization. According to the method, resource estimations are calculated as the formula (Byryukov, 1962).

$$Q_{tn}=K.q_c.V_n' \quad (1)$$

where Q_{tn}-resource estimation, K-a similar factor among estimated areas regarding the standard area, q_c-ore resources in an area unit, volume or length of the standard area, V_n'-volume, area, or existed depth of mineralized zone.

Metal resources in the studied area are determined by the formula.

$$P_{tn}=Q_{tn}.\overline{C} \quad (2)$$

where Q_{tn}-ore resources of a mineralized zone (10^3 ton); C -average contents in the mineralized zone (%).

The similarity factor (K_{ij}) between areas is determined by the comparative method of ore-forming criteria, which are evaluated by using the information on mining geological characteristics of surrounding rocks as well as the composition of each area. The information is digitized and calculated following the formula.

Tab. 8. Results of Au resource estimations based on cutoff grade changes
Tab. 8. Wyniki szacowania zasobów Au na podstawie zmian zawartości granicznej

Area	Ore resources (10^3 tấn)	X_β (γ/T)	Γαμμα φαχτορσ			γ(ζ)	1−γ(ζ)	Τοταλ ποτεντιαλσ οφ ορε ρεσουρχεσ (τονσ)	Total potentials of Au resources (kg)
			α	β	ζ				
Suoi Thau	39,502.496	0.2	-0.226	0.709	0.282	0.000	1.000	39.50	21.70
		0.3			0.423	0.000	1.000	39.50	21.70
		0.5			0.705	0.001	0.999	39.46	21.68
		0.7			0.987	0.005	0.995	39.32	21.60
		1.0			1.410	0.018	0.982	38.78	21.30
		1.5			2.115	0.075	0.925	36.55	20.08
Sang Than	289,624.410	0.2	0.560	0.402	0.497	0.706	0.294	85.12	53.40
		0.3			0.746	0.797	0.203	58.72	36.84
		0.5			1.244	0.896	0.104	29.99	18.81
		0.7			1.741	0.945	0.055	16.06	10.07
		1.0			2.487	0.977	0.023	6.59	4.13
		1.5			3.731	0.994	0.006	1.59	1.00
Ban Kep	44,577.634	0.2	0.052	0.435	0.460	0.000	1.000	44.57	20.41
		0.3			0.689	0.001	0.999	44.55	20.40
		0.5			1.149	0.005	0.995	44.35	20.31
		0.7			1.609	0.020	0.980	43.70	20.01
		1.0			2.298	0.072	0.928	41.37	18.94
		1.5			3.447	0.241	0.759	33.85	15.50

$$K_{ij} = \frac{\sum_{p=1}^{m} a_{ip}a_{jp}}{\sqrt{\sum_{p=1}^{m} a_{ip}^2 \sum_{p=1}^{m} a_{jp}^2}} \quad (3)$$

where i, j-comparative objects, a_{ip}, a_{jp}-value of i or j object at p factor ($p=\overline{1,m}$).

Direct calculation method for metallization parameters:

This method is applied to estimate polymetallic nodule resources in the study area. Polymetallic nodule resource area is assessed by ore parameters or ore-bearing coefficients and calculated according to the following formula (Kogan, 1971).

$$P_{tn} = Q_{tn}.\bar{C} = V.d.K_q.\bar{C} = S_{sq}.M_{sq}.d.K_q.\bar{C} \quad (4)$$

where Q_{tn}-total potentials of a mineralized zone (10^3 ton), V-a volume of a mineralized zone (10^3 m^3), d-bulk density of mineralized zone (ton/m^3), C-average contents in a mineralized zone (%), S_{sq}-area distribution of mineralized zone (m^3), M_{sq}-thickness of a mineralized zone (m), K_q-mineralization-bearing coefficient.

$$K_q = \frac{\sum M_q}{M_{sq}} \quad (4\ a)$$

where ΣM_q- the total thickness of ore veins in the mineralized zone.

Ore resource estimation based on cutoff grade changes:

A change in cutoff content (C_b) will lead to a change in ore resource-reserves. In 1950, this method was proposed by Lasky to investigate the change of resources. The method is constructed by determining the relationship between ore resource and cutoff grade, and between ore resource and average grade content.

$$C_b = \alpha - \beta(\ln Q + 1), \bar{C} = \alpha - \beta \ln Q \quad (5)$$

where C_b-cutoff grade of metal ore (%), C-average grade of metal ore (%), αβ-factors determined by standard construction measures or calculating resource according to several options on cutoff grade.

However, the law of Lasky (1950) only ensures reliability when metal content is distributed according to the standard log distribution. However, the metal content is distributed according to the gamma function or three logarithmic parameters; the reliability of this method is reduced. Therefore, Margolin (1974) improved the Lasky method and expressed the relationship between ore resource and contents following formula.

$$Q = Q_0 \frac{\Gamma(\alpha, C_b\beta)}{\Gamma(\alpha)} \quad (6)$$

$$P = Q_0 \frac{\Gamma(\alpha + 1, C_b\beta)}{\Gamma(\alpha + 1)} \quad (7)$$

$$\bar{C} = \frac{\alpha}{\beta} \cdot \frac{\Gamma(\alpha + 1, C_b).\Gamma(\alpha)}{\Gamma(\alpha + 1).\Gamma(\alpha, C_b\beta)} \quad (8)$$

where Q_0-ore resource when C_b gradually becomes 0; Γ(α + 1, $C_b\beta$)-incomplete gamma function, Γ(α+1)-gamma function. α, β factors are determined by the formula.

$$\alpha = \left(\frac{\bar{X}}{\delta}\right)^2 - 1, \beta = \frac{\bar{X}}{\alpha + 1} \quad (8\ a)$$

where X -average grade content (%), δ -standard deviation of content.

The researcher often uses incomplete gamma functions.

$$\gamma(z) = \frac{1}{\Gamma(\alpha + 1)} \int_0^z z^\alpha e^{-z} dz \text{ where } z = \frac{C_b}{\beta} \quad (8\ b)$$

The equation for resource and reserve estimation based on cutoff changes is expressed as a function.

$$Q(\bar{C} > C_b) = Q_0\ (1 - \gamma(z)) \quad (9)$$

where Q(C >C_b)-ore resource/reserves, which has an average grade above the cutoff (ton), Q_0-ore resource/reserves of estimated areas (ton).

4. Results and discussion

Similarity-analogy in ore geology

The combination of information used to evaluate the zones of the Suoi Thau-Sang Than area includes 29 information. The information is classified into four groups and standardized according to the corresponding quantitative principles: Very common-3, common-2, less common-1 and absent-0. Based on the standardized results of research information, a similar coefficient was created in the studied area (Tab. 1). The Kij similar coefficient between subdivisions is very high, indicating a similarly combined characterization

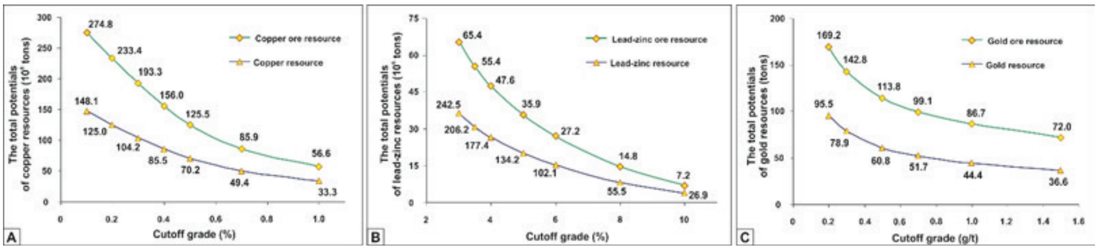

Fig. 2. Diagrams describe the relationship between ore resources and cutoff grade contents of Cu (A), Pb-Zn (B), and Au (C) in Suoi Thau-Sang Than area, respectively
Rys. 2. Diagramy opisujące zależność między zasobami rudy a zawartościami granicznymi Cu (A), Pb-Zn (B) i Au (C) odpowiednio na obszarze Suoi Thau-Sang Than

of indicator elements, mineral composition, geological representation, and variation of surrounding rocks. These suggest that the Suoi Thau, Sang Than, and Ban Kep areas are similar geological conditions and factors controlling mineralization. Therefore, polymetallic nodules resource estimation can be trustworthily guaranteed by using similarity - analogy in ore geology method.

The total estimation results are 1,785,000 tons Cu, 12,005,000 tons Pb+Zn, and 195 kg Au and the Sang Than area highly contains potential polymetallic nodules resource (Table 2). Cu nodules resource is highly in the Sang Than area (1,421,000 tons), less in the Suoi Thau (172,000 tons), and the Ban Kep (192,000 tons). Pb+Zn is mainly in the Sang Than area (8,768,000 tons), less amount in the Suoi Thau (1,384,000 tons), and the Ban Kep (1,853,000). Au is primarily in the Sang Than (151 kg), minor in the Suoi Thau (21 kg), and the Ban Kep (22 kg).

Direct calculation method for metallization parameters

Calculation results show a total of 2,060,000 Cu, 13,648,000 Pb-Zn, 224 kg Au in this studied area, and the Sang Than area consists mainly of polymetallic nodules resource. Cu is mainly in the Sang Than area (1,708,000 tons), minor in the Suoi Thau (177,000 tons), and the Ban Kep (173,000 tons). Pb-Zn is highly in the Sang Than (10,542,000 tons), less in the Ban Kęp (1,676,000 tons), and the Suoi Thau (1,429 tons). Au shows principally in the Sang Than (182 kg), minor in the Suoi Thau (22 kg), and the Ban Kep (20 kg). According to the similarity-analogy in ore geology and the direct calculation method for metallization parameters methods, estimation results show 1,785,000–2,060,000 tons Cu, 12,005,00–13,648,000 tons Pb-Zn, and 195-224 kg Au.

To evaluate the reliability of these resource estimations above, this study uses one formula.

$$\Delta = \frac{|P_1 - P_2|}{P_1} . 100\% \qquad (10)$$

where P_1-an estimation result of similarity-analogy in ore geology method, P_2-an estimation result of the direct calculation method for the metallization parameters method.

The calculation results display 3,2% in the Suoi Thau, 9,6% in the Ban Kep, and 20,2% in the Sang Than, suggesting high reliability of polymetallic resource estimation in the Suoi Thau-Sang Than area.

Ore resource estimation based on cutoff grade changes

Based on polymetallic module resource estimations in the Suoi Thau-Sang Than area, and assessing the reliability of the resource estimations which are mentioned above, we chose results of the direct calculation method for metallization parameters as basis of polymetallic resource potential based on cutoff grade changes.

* Cu nodules resource estimation.

Content thresholds are selected to be 0.1%; 0.2%; 0.3%; 0.4%; 0.5%; 0.7%, and 1.0%.

Based on selected boundary content (C_b), the estimation results show 300 tons in the Suoi Thau, 33,000 tons in the Sang Than, 100 tons in the Ban Kęp with C_b> 1,0%; 6,000 tons in the Suoi Thau, 60,000 tons in the Sang Than, 4,000 tons in the Ban Kep with C_b> 0.5%; 14,000 tons in the Suoi Thau, 80,000 tons in the Sang Than, 12,000 tons in the Ban Kep with C_b> 0.3%; 18,000 tons in the Suoi Thau, in 113,000 tons in the Sang Than, 17,000 tons in the Ban Kep with C_b> 0.1%. This indicates that decreased boundary contents will increase resource estimation results. The total resource estimation will be increased 221.7% with reduced C_b from 1% to 0.5%, 154% with reduced C_b from 0.5% to 0.3%, 142.2% with decreased C_b from 0.3% to 0.1%. Based on Vietnamese industrial contents of Cu (C_b=0.5), the Cu resource is mainly concentrated in the Sang Than area.

* Pb-Zn nodules resource estimation

For Pb-Zn, content thresholds are selected to be 3%, 3.5%, 4%, 5%, 6%, 8%, and 10%.

According to selected boundary content (C_b), the estimation results show 10 tons in the Suoi Thau, 100 tons in the Sang Than, 27,000 tons in the Ban Kęp with C_b> 10%; 8,000 tons in the Suoi Thau, 6,000 tons in the Sang Than, 120,000 tons in the Ban Kep with Cb> 5%; 52,000 tons in the Suoi Thau, 33,000 tons in the Sang Than, 157,000 tons in the Ban Kep with C_b> 3%. The total resource estimation results will be increased by 500.9% with reduced C_b from 10% to 5% and 182.2% with reduced C_b from 5% to 3%. Following the Vietnamese industrial contents of Pb-Zn (C_b=3%), the Ban Kep area can be a high potential Pb-Zn resource in the studied area.

* Au nodules resource estimation.

Boundary Au contents (C_b) are selected as: 0.2 g/T, 0.3 g/T, 0.5 g/T, 0.7 g/T, 1.0 g/T, and 1.5 g/T.

Following selected boundary Au content (C_b), the resource estimation results indicate 20.08 kg in the Suoi Thau, 1.00 kg in the Sang Than, 15.50 kg in the Ban Kep with C_b> 1.5 g/T; 21.30 kg in the Suoi Thau, 4.13 kg in the Sang Than, 18.94 kg in the Ban Kep with C_b> 1 g/T; 21.68 kg in the Suoi Thau, 18.81 kg in the Sang Than, 20.31 kg in the Ban Kep with C_b> 0.5 g/T; 21.70 kg in the Suoi Thau, 36.84 kg in the Sang Than, 20.41 kg in the Ban Kep with C_b> 0.1 g/T. The total resource estimation results are increased by 120.5% with reduced $C_{b.}$

from 1.5 g/T to 1.0 g/T, 131.2% with reduced C_b from 1 g/T to 0.5 g/T. According to the Vietnamese industrial contents of Au (Cb=1 g/T), the Suoi Than, Sang Than, and Ban Kep areas can be no potential Au resource in the studied area.

Generally, the combination of mineral resource estimation methods has contributed to clear up polymetallic mineralization investigation in the studied area. However, compared with the direct calculation method for metallization parameters and the similar-analogy in ore geology, the ore resource estimation based on cutoff grade changes method has shown an overview of the prospect on polymetallic nodules resources and gold mineralization in the Suoi Thau-Sang Than area according to cutoff grade changes. These estimation results can be used to serve as a basis for the proposed selection of the prospective areas for effective Cu, Pb-Zn, and Au mineral exploration.

5. Conclusions

The similarity-analogy in ore geology, direct calculation method for metallization parameters, and mineral resource estimation based on cutoff grade change methods were used to investigate polymetallic nodules from the Suoi Thau, Sang Than, and Ban Kep areas in northeastern Vietnam. Through this study, the conclusions can be drawn as follows.

The similarity-analogy in ore geology method estimates 1,785,000 tons Cu, 12,005,000 tons Pb+Zn, and 195 kg Au in this studied area, and the Sang Than area contains mainly polymetallic nodules 1,421,000 tons Cu, 8,768,000 tons Pb+Zn, and 151 kg Au. The direct calculation method for metallization parameters shows 2,060,000 tons Cu, 13,648,000 tons Pb+Zn, and 224 kg Au, and the Sang Than area is considered as a main potential polymetallic nodule in this studied area, consisting of 1,708,000 tons Cu, 10,542,000 tons Pb-Zn, and 182 kg Au. The cutoff grade changes display potential Pb-Zn nodules resource in the Ban Kep area and Cu nodules resource in the Sang Than area, while no potential Au nodules resource in the Suoi Thau and the Sang Than as well as the Ban Kep areas.

The different estimation results between the similarity-analogy in ore geology and the direct calculation method for metallization parameters methods are from 3.2 to 20.2%, suggesting high reliability of polymetallic resource estimation in the Suoi Thau-Sang Than area. Additionally, the relationship between polymetallic nodules resources and cutoff grade contents show nonlinear relation and inverse correlation. This indicates the polymetallic nodule resources in this studied area can be estimated by using each cutoff grade contents following the variability of the Vietnamese industrial contents.

Acknowledgements:

First of all, we would like to send our deepest thanks to the leaders and staff of HUMG for providing us with good facilities in research and unconditional help to carry out the study. Furthermore, the first author would like to express his sincere gratitude to Prof Jan Golonka, a great supervisor, for giving him the knowledge, indulging in geoscience, and opportunity to carry out geological research.

Literatura – References

1. Bat, T.D. (ed.) et al. (1989). Report on results of prospecting investigation of lead-zinc ore in Na Son area and preliminary prospecting lead-zinc ore in Tang Khoang-Ta Pan-Suoi Thau, Ha Tuyen area. Geological Department of Vietnam, Ha Noi (in Vietnamese).
2. Byryukov, V.I. (1962). Classification of exploration systems of solid mineral deposits (in Russian). Geologiya rud. mestorozhdenii 1, Moscow, pp. 99-121.
3. Dovjikov, A.E. (ed.), My, B.P., Vasilevskaia, E.D., Jamoida, A.I., Ivanov, G.V., Izokh, E.P., Huu, L.D., Mareitchev, A.I., Chien, N.V., Tri, N.T., Luong, T.D., Quang, P.V. & Long, P.D. (1965). Geology of North Vietnam. Explanatory note of the Geological Map of North Vietnam at 1:500,000 scale. Geological Department of Vietnam, Ha Noi, 584 pp.
4. Glacken, I.M & Snowden, D.V. (2001). Mineral Resource Estimation, in Mineral Resource and Ore Reserve Estimation - The AusIMM Guide to Good Practice (Ed: A C Edwards), pp189-198 (The Australasian Institute of Mining and Metallurgy: Melbourne).
5. Graedel, T.E., Harper, E.M., Nassar, N.T., Reck, B.K. (2015). On the Materials Basis of Modern Society. Proceedings of the National Academy of Sciences 112 (14), 4257-4262.
6. Hung, K.T., Tri, L.D., Lam, N.V., Thai, T.N. (2016). The application of logical information problems in combining with a statistical method to estimate mineral resources of the hydrothermal metasomatic kaolins in the northeastern region of Quang Ninh (in Vietnamese). Journal of Mining and Earth sciences, vol 58, issue 1: 16-23.
7. Kogan, I.D. (1971). Calculation of reserves and geological appraisal of ore deposits (in Russian). Nedra, Moscow, pp. 1-295.

8. Kužvart, M., Böhmer, M. (1986). Prospecting and exploration of mineral deposits. Volume 21, 2nd Edition, Elsevier, Technology & Engineering, 508 p.
9. Lasky, S.G. (1950). Mineral resource appraisal by the U.S. Geological Survey., 45 (1A). Colorado School of Mines Quarterly, pp. 1-27.
10. Margolin, A.M. (1974). Evaluation of mineral deposits. Mathematical methods (in Russian). Nedra Publishers, Moscow, p. 261.
11. Minh, H (ed.), et al. (1992). Report on distribution characteristics of gold, silver, and other minor elements in the lead-zinc ore of Tung Ba - Na Son, Ha Giang area. Geological Department of Vietnam, Ha Noi (in Vietnamese).
12. Rankin, W.J. (2011). Minerals, Metals, and Sustainability-Meeting Future Material Needs. CSIRO
13. Revuelta, M.B. (2018). Mineral Resources From Exploration to Sustainability Assessment. Springer Textbooks in Earth Sciences, Geography, and Environment, Springer International Publishing AG 2018.
14. Sang, B.V. (2011). Application of geomathematic methods for prediction of polymetallic resources in Suoi Thau - Sang Than area, Ha Giang province. Master's thesis, Hanoi University of Mining and Geology (in Vietnamese).
15. Sinh, N.H (ed.), et al. (1985). Report on distributed conditions of lead-zinc ore in Viet Bac area and further prospecting. Geological Department of Vietnam, Ha Noi (in Vietnamese).
16. Son, V.M (ed.), et al. (2003). Report on results of geological mapping and mineral investigation of Phuc Ha sheet at 1:50.000 scale. Geological Department of Vietnam, Ha Noi (in Vietnamese).
17. Tri, T.V. & Khuc, V. (eds) (2011). Geology and Earth Resources of Vietnam. General Department of Geology and Minerals of Vietnam. Publishing House for Science and Technology, 645p.
18. USGS (2014). Minerals Yearbook; United States Geological Survey: Reston, VA, USA.
19. Zhang, Z., & Huang, W., 2010. Evaluation Method on Geological Deposit Potential Value. International Journal of Business and Management, Vol. 5, No. 6: 210-214.

Ocena zasobów konkrecji polimetalicznych w rejonie Suoi Thau-Sang Than, północno-wschodnim Wietnamie

W celu zbadania zasobów konkrecji polimetalicznych zebrano 1,720 próbek substancji chemicznych, minerałów i petrografii z obszaru Suoi Thau-Sang Than w północno-wschodnim Wietnamie. Podobieństwo-analogia w geologii rudy, metoda bezpośredniego obliczania parametrów metalizacji i szacowania zasobów mineralnych w oparciu o metody zmian zawartości granicznej są wykorzystywane do szacowania zasobów konkrecji polimetalicznych w obszarze Suoi Thau, Sang Than i Ban Kep w północno-wschodnim Wietnamie. Podobieństwo-analogia w geologii rudy wskazuje łącznie na 1,785,000 ton Miedzi, 12,005,000 ton Ołowiu + Cynków i 195 kg Złota. Metoda bezpośredniego obliczania parametrów metalizacji pokazuje łącznie 2 060 000 ton Miedzi, 13,648,000 ton Ołowiu + Cynków i 224 kg Złota. Te metody pokazują, że obszar Sang Than zawiera głównie konkrecje polimetaliczne na badanym obszarze. Po oszacowaniu zasobów mineralnych na podstawie zmian zawartości granicznej, wyniki oszacowań wskazują na potencjalny zasobów konkrecji Ołowiu - Cynków w Ban Kep i Miedzi w Sang Than, natomiast nie ma potencjalnego zasobu konkrecji Złota w Suoi Thau i Sang Than, a także w Ban Kep. Wyniki uzyskane z szacowania zasobów mineralnych na podstawie zmian zawartości granicznej są zgodne z wynikami tradycyjnymi metodami bloków geometrycznych. Nasze badanie sugeruje, że obszar Sang Than można uznać za potencjalny zasób konkrecji Miedzi, a obszar Ban Kep jest potencjalnym zasobem konkrecji Ołowiu + Cynków w północno-wschodnim Wietnamie do przyszłej eksploatacji, natomiast w obszarze Suoi Thau nie ma potencjalnego zasobu konkrecji polimetalicznych. Co więcej, oszacowanie zasobu w oparciu o metody zmian zawartości granicznej przedstawia przegląd perspektyw dotyczących zasobów konkrecji polimetalicznych, wskazując, że metoda ta może służyć jako podstawa do proponowanego wyboru perspektywicznych obszarów efektywnych Miedzi, Ołowiu-Cynków i Złota poszukiwanie minerałów w obszarze Suoi Thau-Sang Than w północno-wschodnim Wietnamie.

Słowa kluczowe: *konkrecja polimetaliczna, szacowanie zasobów, obszar suoi thau-sang than, północno-wschodni wietnam*