



MONIKA WASILEWSKA-BŁASZCZYK*, JACEK MUCHA**

Geochemical modeling of the Cu-Ag deposits from the Lubin-Głogów Copper District (Poland) supported by lithological modeling

Introduction

The geostatistical modeling of the spatial distribution (3D) of the main and accompanying metals present in the world-class Cu-Ag deposits from The Lubin-Głogów Copper District (Poland), hereinafter referred to as geochemical modeling, has been the subject of several publications in Polish journals (Mucha and Wasilewska 2009, 2010; Wasilewska-Błaszczyk et al. 2017a).

Due to the usually high or very high variability in the elemental content, a strong right-sided (positive) asymmetry of the probability distributions, and often anomalous values, estimating their content in the future areas of exploitation is a difficult task. In addition, the geostatistical description of the variability of Cu and Ag content based on semivariograms has revealed a relatively weak, non-random component of variability (metal content autocorrelation) in the horizontal plane, disappearing after crossing a distance of several tens/hundreds of meters between the points of the deposit.

In light of the unfavorable statistical characteristics (the probability distribution) and the geostatistical structure of the variability of metal content, it is possible to increase the accuracy of the estimation by reducing the sampling interval in mine workings, increasing the weight of samples, or using more sophisticated modeling techniques.

* Ph.D. Eng., ** D.Sc. Eng., Associate Professor of AGH, AGH University of Science and Technology, Krakow, Poland; e-mail: wasilews@agh.edu.pl; mucha@geol.agh.edu.pl

The main aim of the study, presented in this article, was to examine the possibility of increasing the reliability of the 3D model of Cu content (3D geochemical model). It was concluded that this objective can be achieved by supporting the proper geochemical modeling with modeling the distribution of the individual lithological units (minor, secondary ore types) in the deposit area, hereinafter referred to as lithological modeling, followed by a separate modeling of Cu content (cascade simulation). This procedure seems to be rational when there is no geochemical similarity between the adjacent lithological units (series), i.e. they show a different intensity of mineralization. The mentioned solution is reasonable also in the case of 3D geochemical modeling of the deposit carried out for the three main (major, primary ore types) lithological series: carbonate, shale, and sandstone (Mucha and Wasilewska-Błaszczyk 2010). Ignoring the division into lithological series during geochemical modeling leads to the underestimation of the Cu content in the heavily mineralized shale series at contact zones with less mineralized carbonates and sandstones and overestimation of Cu content in the carbonate and sandstone series content estimates at contact zones with shale series.

The use of different approaches for geochemical modeling (cascade simulation, joint simulation) of the world's copper deposits of different genetic types (stratabound, porphyry copper deposits) has been the subject of numerous publications (e.g. Maleki and Emery 2015; Talebi et al. 2016). Supporting this process with lithological modeling generally results in an increase in the reliability of geochemical models of copper deposits.

The similarity of empirical distributions of the Cu content in the individual lithological units determined in the recent years in the Cu-Ag deposits of the Lubin-Głogów Copper District (Kaczmarek et al. 2014, 2017) may be used in 3D lithological modeling, especially when the mentioned units are of local significance (are poorly represented in the examined deposit). The similar empirical distributions of metal content in adjacent series allows them to be considered as a single series. Reducing the number of modeled lithological series greatly simplifies and facilitates the overall lithological and geochemical model of the deposit.

1. The basic research material

The analysis was carried out using samples collected from the part of the Rudna deposit; its location against the boundaries of the mining area is shown in Figure 1A. A systematic collection of pseudo-channel samples, with horizontal spacing of 20 m, was carried out in mine workings. A series of spot (chip) samples is collected along a vertical line separately for each individual lithological unit at every single sampling site; the Cu content and, to a lesser extent, the Ag and accompanying elements contents are determined obligatory for each sample. In the study area of about 0.56 km², approximately 22,000 of spot samples were collected from 892 sampling sites (Fig. 1B).

To evaluate the accuracy of the developed 3D models (both lithological and geochemical), 71 sampling sites, where a total of 1620 spot samples were collected, were isolated from the original data set (Fig. 1B). The data from the test set was not included in the 3D model.

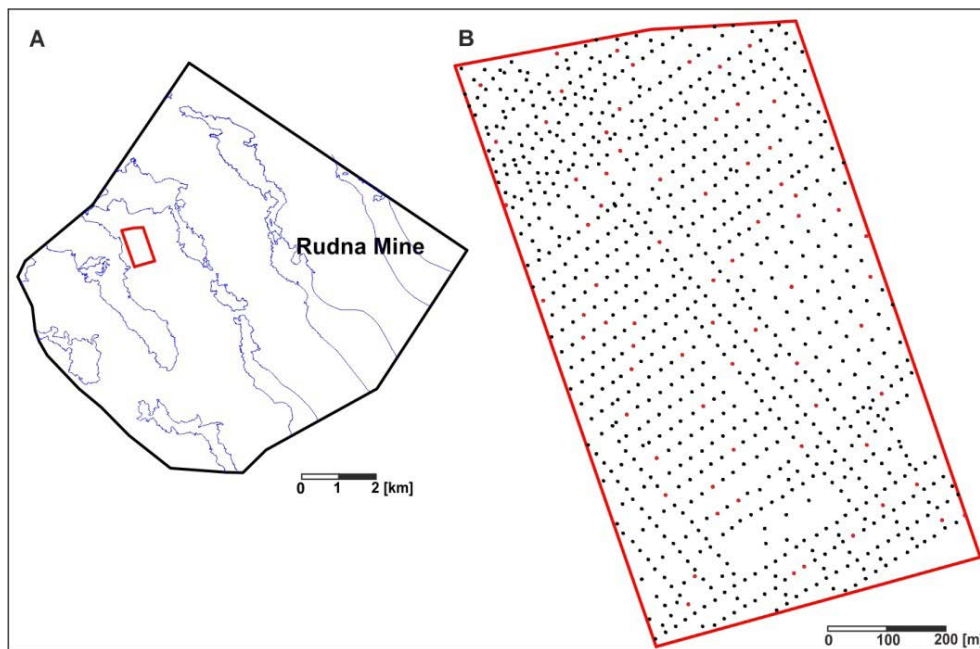


Fig. 1. Location of the research area (red line) against the background of the Rudna mining area (black line) and the elevation boundaries of the roof of the Weissliegend sandstone series (blue line) (A); the primary (black) and test (red) sampling sites in the research area (B)

Source: own work

Rys. 1. Lokalizacja obszaru badań (czerwona linia) na tle obszaru górniczego Rudna (czarna linia) i granic elewacji stropu białego spągowca (niebieska linia) (A); lokalizacja podstawowych (kolor czarny) i testowych (kolor czerwony) stanowisk opróbowania w obszarze badań (B)

Źródło: opracowanie własne

Geologically, the study area is the part of the depression zone of the roof of the Weissliegend sandstone series with a width of about 2.5 km between two elevations (Central and North) of the Rudna mining area. The geological profile of the deposit in the examined area is typical for depression areas, meaning that the copper-silver mineralization occurs within all main lithological types of ore host rocks: from the bottom, the sandstone series is represented by white quartz sandstones with clay binders, shale series, and finally, carbonate series. In the marginal parts of the depression, the shale layer undergoes a pronounced reduction in thickness until it is fully wedged out at the slopes of the adjacent elevations.

2. Geochemical characteristics of the individual lithological units

All of the three main lithological series were identified in samples collected from the majority of the deposit sampling sites. Out of 18 individual lithological units of the Lubin-

-Głogów Copper District deposits (Kaczmarek et al. 2017) only 9 were found in the research area (Table 1). The carbonate series is mainly represented by striped dolomite (48.1%) and calcareous dolomite (38.1%); the local occurrence of argillaceous dolomite (13.6%) and the marginal occurrence of sand dolomite were also confirmed. The shale series is dominated by clay shale, which is found in nearly 92% of the samples, dolomitic and pitchy shale can be observed locally (4.6 and 3.8%, respectively) while boundary dolomite occurs only marginally (0.2%). The sandstone series is composed entirely of argillaceous sandstone.

Table 1. Basic statistical parameters of Cu content within the examined individual lithological units (part of the Rudna mine)

Tabela 1. Podstawowe parametry statystyczne zawartości Cu w obrębie szczegółowych wydzieleni litologicznych (fragment ZG Rudna)

Lithological series		Count (percentage share in the base series)	Minimum	Maximum	Average	Median	Skewness
Main	Individual						
Carbonate	Calcareous dolomite	801 (38.1)	0.18	15.59	2.11	1.73	3.36
	Striped dolomite	1 011 (48.1)	0.01	15.84	2.18	1.83	2.41
	Argillaceous dolomite	285 (13.6)	0.13	22.23	2.87	1.89	3
	Sand dolomite	5 (0.2)	1.47	3.41	2.08	1.89	1.6
Shale	Dolomitic shale	72 (4.6)	0.49	21	5.03	2.7	1.62
	Clay shale	1 437 (91.5)	0.35	55.65	13.7	14.26	0.25
	Pitchy shale	59 (3.8)	1.48	33.95	14.95	14.56	0.51
	Boundary dolomite	3 (0.2)	1.75	3.5	2.49	2.22	1.22
Sandstone	Argillaceous sandstone	10 972 (100%)	0.01	29.2	2.62	2.54	2.49

Source: own work.

The distribution of individual lithological units within the deposit is variable, which is indicated by the number of collected spot samples (Table 1). The greatest thickness within the study area can be observed in the case of sandstone series in the form of argillaceous sandstone. The remaining common individual lithological units include: clay shale, striped dolomite, calcareous dolomite, and argillaceous dolomite. A large number of spot samples and the continuity of these series observed over a relatively large distance allow their separate 3D lithological and geochemical modeling. The local and often discontinuous occurrence of dolomitic shale and pitchy shale, and in particular boundary dolomite and sand dolomite, in the research area makes it difficult to use the first two and excludes the last two series

from 3D lithological modeling due to the technical limitations of the applied modeling methods. For a correct 3D modeling using geostatistical methods, a sufficiently large number of samples for the interpolation or simulation procedures and for a reliable examination of the structure of the parameter variability using semivariogram analysis is needed.

The boundaries of the Cu-Ag deposit (the Lubin-Głogów Copper District) in the vertical profile are arbitrarily determined and are set based on the collected samples and the determination of the content of major elements in the spot samples. This justifies the development of 3D lithological and geochemical models, and the preliminary statistical analysis of the data used for this purpose, based on the samples collected from the excavation (between extreme spot samples in the vertical profile). Within these limits, the Cu content in approximately 1/3 of the spot samples is less than the cut-off value (<0.7%), usually close to 0. These samples are generally located outside the balance deposit, only occasionally occurring in the form of subeconomic or gangue partings in the deposit. This makes it difficult to assess the accuracy of the estimation of parameter values using a 3D model, since in the case of Cu content close to 0, even a slight overestimation of the parameter value results in a relative error of several thousand percent. For this reason, the error statistics for the estimation of Cu content were made using the spot samples of the test set with Cu content > 0.7%.

Table 2. The summary of the results of the Kolmogorov-Smirnov test for the identity of the distribution of Cu content in individual lithological units of the carbonate and shale series

Tabela 2. Zestawienie wyników testu Kołmogorowa-Smirnowa zgodności rozkładów zawartości Cu w wydzieleniach szczegółowych serii węglanowej i łupkowej

Lithological series		Calcareous dolomite	Striped dolomite	Argillaceous dolomite	Sand dolomite
Main	Individual				
Carbonate	Calcareous dolomite				
	Striped dolomite	–			
	Argillaceous dolomite	–	–		
	Sand dolomite	+	+	+	
Main	Individual	Pitchy shale	Clay shale	Dolomitic shale	Boundary dolomite
Shale	Pitchy shale				
	Clay shale	+			
	Dolomitic shale	–	–		
	Boundary dolomite	–	–	+	

[+] – No basis for rejecting the hypothesis of the identity of distributions (Kolmogorov-Smirnov test (K-S test)) at significance level $\alpha = 0.05$.

[–] – rejecting the hypothesis of the identity of distributions with an error risk lower than 5%.

Source: own work.

The Cu contents in individual lithological units were compared using the basic statistical parameters and, in particular, measures of central tendency and dispersion. The compatibility of empirical distributions of Cu content in individual lithological units at the significance level $\alpha = 0.05$ was examined using the Kolmogorov-Smirnov test (K-S test).

The preliminary analysis of statistical parameters has confirmed significant differences in the range of values and the mean values of the Cu content for various individual lithological units. Particularly clear differences can be observed in individual lithological units of the shale series; in the case of the carbonate series they are much smaller (Table 1).

The results of the Kolmogorov-Smirnov test summarized in Table 2 show generally large differences in the distribution of Cu content between the individual lithological units in the research area. They allow for classifying sand dolomite and each individual lithological unit of the carbonate series, pitchy shale and clay shale, and boundary dolomite and dolomitic shale into the same geochemical domains. From a methodological point of view, such methods used in geochemical modeling are only valid if the individual lithological units with similar levels of Cu content are adjacent to each other. The percentage share of contact zones between individual lithological units in the research area are presented in Figure 2. Sand dolomite is adjacent to striped dolomite, which justifies the combination of the two. While there are contact zones between pitchy shale and clay shale, they are less common than

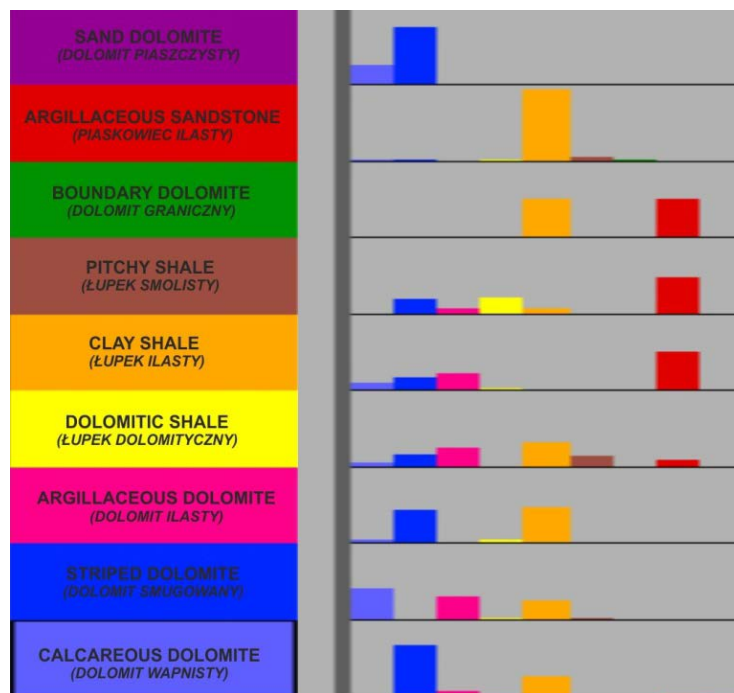


Fig. 2. Bar graphs of the share of contact zones between individual lithological units in the research area

Rys. 2. Wykresy słupkowe wielkości udziałów kontaktów pomiędzy litologiami szczegółowymi w obszarze badań

between the former and dolomitic shale, which, however, have different Cu contents. A similar situation can be observed in the case of boundary dolomite and dolomitic shale (no contact zones between them while both have similar Cu content); meanwhile, boundary dolomite is directly adjacent to clay shale. Based on the identified contact zones between the individual lithological units (Fig. 2), boundary dolomite (found in only three samples) was modeled with clay shale, despite large differences in their mean Cu content, in order to facilitate 3D modeling (Table 2).

In other cases, the tests carried out have shown statistically significant differences in the distribution of Cu content between the individual lithological units, indicating the validity of individual geochemical modeling methods in the case of these series.

3. The methods and assumptions of 3D geochemical and lithological modeling

Lithological modeling was carried out using interpolation (ordinary kriging) or simulation geostatistical methods (Plurigaussian simulation). The modeling of main lithological series (carbonates, shales, and sandstones), due to their sequential nature and continuous occurrence in the research area, was carried out using a 2D ordinary kriging interpolation (Variant I, Fig. 3). Height ordinates of the following boundaries were modeled: the upper limit of sampling (usually in the carbonate series), the boundary between the carbonate and shale series, the boundary between the shale and sandstone series, and the lower limit of sampling (usually in the sandstone series). The interpolated boundaries were the basis for assigning interpolation points (hereinafter also referred to as mini-blocks) of the 3D grid to the main lithological series.

The spatial modeling of individual lithological units, with much more complex contact zones than in the case of main lithological series, used the Plurigaussian geostatistical simulation method (Yunsel and Ersoy 2011). An essential role in the development of realistic lithological models using this method is played by mutual proportions between lithological units in the vertical profile (the so-called vertical proportion curves) and two Gaussian curves describing relationships between the lithologies (Armstrong et al. 2003). The essence of modeling using Plurigaussian simulation in deposits exploited by KGHM Polska Miedź SA is presented by Wasilewska-Błaszczyk et al. (2017b).

The 3D lithological modeling using Plurigaussian geostatistical simulation method was carried out in two variants:

Separately for all 7 individual lithological units (striped dolomite, calcareous dolomite, clay dolomite, dolomitic shale, clay shale, pitchy shale, and argillaceous sandstone), not taking the division into main lithological series into account (Variant II, Fig. 3),

Separately for 3 individual lithological units within each of the main series: carbonate (calcareous dolomite, striped dolomite + sand dolomite, argillaceous dolomite) and shale (dolomitic shale, clay shale + boundary dolomite, pitchy shale) series; in the sandstone

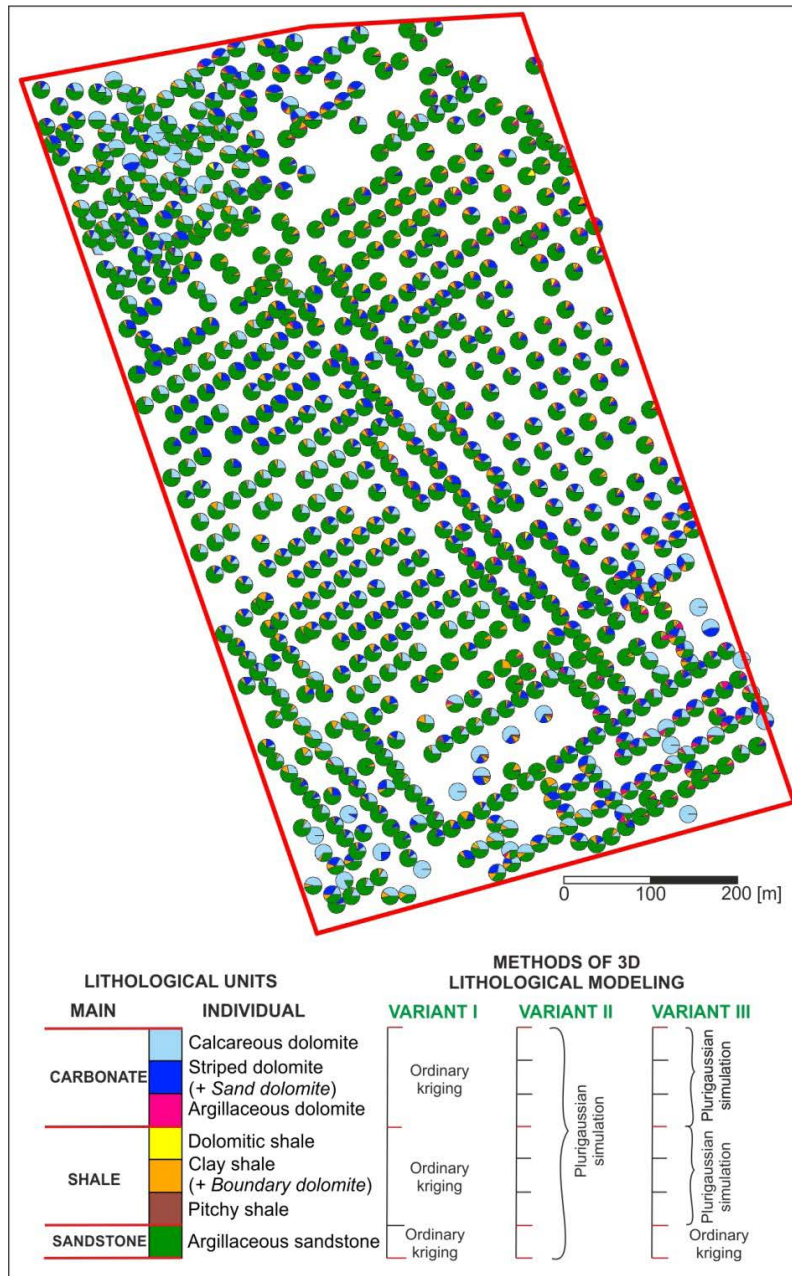


Fig. 3. Location of sample collection points with pie charts of individual lithological units in the research area; variants of three-dimensional lithological modeling
Source: own work

Rys. 3. Lokalizacja pozycji opróbowania z wykresami kołowymi proporcji szczegółowych serii litologicznych w obszarze badań; warianty trójwymiarowego modelowania litologicznego
Źródło: opracowanie własne

series, there is only one individual lithological unit (argillaceous sandstone), which was modeled using ordinary kriging (Variant III, Fig. 3).

A two-variant approach to 3D modeling of individual lithological units was aimed at comparing the quality of the models developed with use of different numbers of lithological units (the more lithological units involved, the more difficult is the use of Plurigaussian simulation method).

The 3D models of Cu content distribution were developed using the geostatistical method of ordinary kriging (OK) and deterministic method of the squared inverse distance (ID2). In both interpolation methods, the parameters of interpolation nodes are estimated on the basis of the weighted average algorithm:

$$z^*_A = \sum_{i=1}^n w_i \cdot z_i \quad (1)$$

- ↪ w_i – weighting factor assigned to the i -th sampling point, which was in the search area,
- z_i – parameter value at the i -th sampling point,
- n – the number of data included in the interpolation (the number of sampling points located within the research area).

In both methods the weighting factors are calculated differently. In the squared inverse distance weighting method they are calculated from the following formula:

$$w_i = \frac{1}{d_{Ai}^2} \quad (2)$$

$$\sum_{i=1}^n \frac{1}{d_{Ai}^2}$$

- ↪ d_{Ai} – the distance of interpolation point A from the i -th sampling point within the research area.

The geostatistical ordinary kriging method for calculating weighting factors requires prior determination of the theoretical model of the variability structure of the parameter fitted to the empirical semivariogram. The weighting factors of kriging (w_{Kj}), minimizing errors in Cu content estimation, are determined based on the kriging system of equations (Journal and Huijbregts 1978).

Both types of 3D models were developed using ISATIS (by Geovariances) (Bleinès at al. 2017).

In lithological and geochemical 3D modeling procedures based on a 3D interpolation regular grid, a set of spot samples of varying lengths should be standardized (regularized). The length to which the spot samples are to be standardized must be identical with the vertical height of the mini-block of the 3D interpolation network. During geochemical modeling, the vertical height of the mini-block should be determined based on the average or median length of the spot samples (Sinclair and Blackwell 2002). Lithological modeling also requires taking information about the minimum thicknesses of lithological units occurring in the 3D model into account.

In the examined area, the minimum and smallest arithmetic means of thickness can be observed in the individual lithological units in the shale series (starting from 0.04 m). When determining the geometry of the interpolation grid, one should also take the computing capabilities of the computer and the time required for calculations into account. Finally, the heights of the mini-bloc and standardized sample were arbitrarily determined to be 0.05 m. Setting the distance between the interpolation points in the horizontal direction at 5m was aimed at producing an approximately ten-fold increase in the density of interpolation grid in relation to the density of the sampling network (the average distances between adjacent sampling sites are about 40 m).

The geochemical and lithological quality of 3D models was verified based on the test set. The Cu content and individual lithological units in the examined standardized spot samples were compared with the estimated Cu content and the simulated individual lithological units in those 3D interpolation points of the model that were the closest to a given spot sample.

The quality assessment of the lithological models was carried out on the basis of the percentage share of the regularized spot samples where the individual lithological units were properly classified using the 3D model (the range of values from 0 – no compatibility to 100% – perfect compatibility). The medians of absolute relative errors of the interpolation (ε_{AR_i}) of Cu content, used as a measure of the accuracy of interpolation of the Cu content, were calculated as a difference between the estimated (in the 3D model) and actual (observed) content in the spot samples of test data set using the following formula:

$$\varepsilon_{AR_i} = \frac{|z_i^* - z_i|}{z_i} \cdot 100\% \quad (3)$$

- ↪ z_i^* – the estimated Cu content in those mini-blocs of the 3D model that were the closest to a given regularized spot sample “ i ” of test data set,
- z_i – the Cu content determined in the regularized spot sample “ i ” of test data set (considered as the actual value).

4. Research results

The results of the verification of the accuracy of 3D lithological and geochemical models are presented in Table 3 and Fig. 4.

The accuracy of individual lithological models developed using the Plurigaussian method is variable and depends on the number of modeled lithological units. The accuracy of modeling of individual lithological units carried out separately for all 7 lithologies (Variant II) is lower than in the case of separate modeling for both the main shale and carbonate series Variant III) (Table 3). The increase in accuracy is relatively small in the individual lithological units of the carbonate series (maximally from 13% to 36% in the case of argillaceous dolomite), while in the case of clay shale more than a 3-fold increase (from 31% to 99%) is observed. The relationship between the accuracy of lithological modeling and the distribution of individual lithological units in the deposit area is evident. 3D modeling of the most commonly occurring individual lithological units with the largest share, such as argillaceous sandstone, clay shale, calcareous dolomite, and argillaceous dolomite (Table 2), is characterized by a satisfactory accuracy of estimation of their occurrence in the range of 70–99% (Table 3). The results obtained with 3D modeling of such individual lithological

Table 3. The results of quality assessment of 3D lithological models developed using the Plurigaussian simulation method based on a set of test samples (Variants II and III, Table 2)

Tabela 3. Zestawienie wyników oceny jakości litologicznych modeli 3D wykonanych metodą symulacji Plurigaussian na podstawie zbioru prób testowych (warianty II i III, Tabela 2)

Main lithological series	Individual lithological units	The number of tested samples	The percentage of properly qualified individual lithological units [%]		
			The modeled main lithological series and the total number of individual lithological units within them		
			Variant II	Variant III	
			C + Sh + S 7	C 3	S 3
Carbonate series (C)	Calcareous dolomite	182	69	72	–
	Striped dolomite	377	55	70	–
	Argillaceous dolomite	101	13	36	–
Shale series (Sh)	Dolomitic shale	16	4	–	0
	Clay shale	478	31	–	99
	Pitchy shale	16	0	–	0
Sandstone series (S)	Argillaceous sandstone	3528	97	–	–

Source: own work.

units as dolomitic shale or argillaceous dolomite were worse than expected and completely unsatisfactory. They can be associated with the discontinuous and local nature of occurrence of these units and a relatively small share in the deposit. The observed patterns partially justify the validity of combining poorly represented (as in the case of the boundary dolomite and sand dolomite) and commonly occurring individual lithological units during the process of 3D modeling.

Geochemical modeling of Cu content distribution in the deposit area was performed for:

- ◆ The lithological model taking the individual lithological units within the main lithological series into account (Variant III) due to the more accurate prediction of lithological units than in the case of the Variant II (Table 3),
- ◆ The main lithologies model without taking individual lithological units within them into account (Variant I).

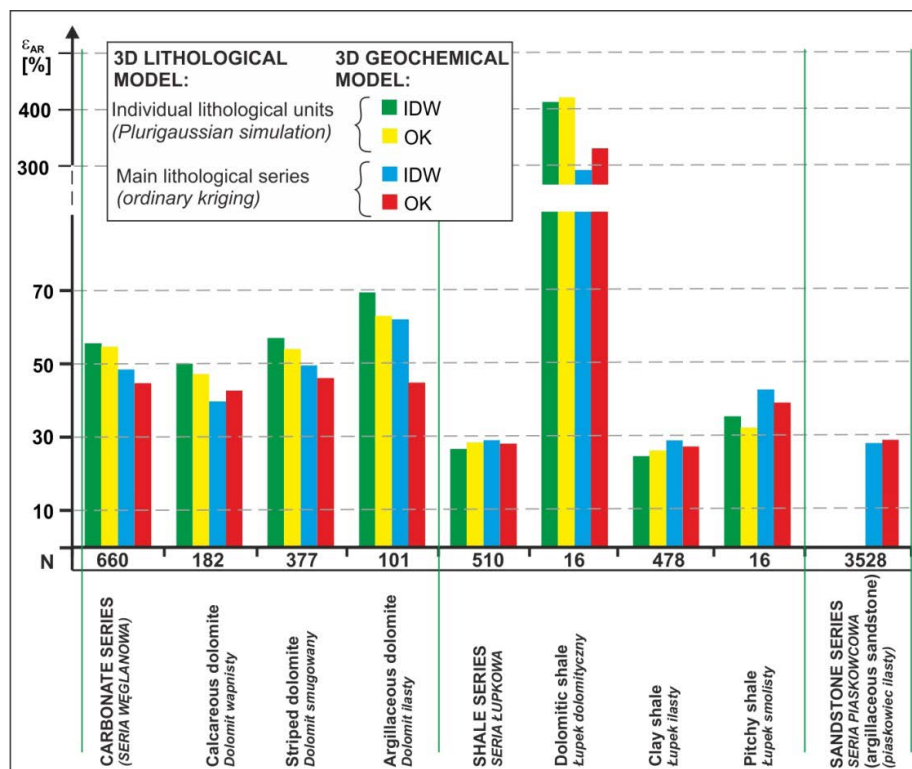


Fig. 4. The summary of medians of absolute relative errors in the estimation of Cu content in the test data set for the 3D geochemical model

IDW – the squared inverse distance weighting, OK – ordinary kriging

Source: own work

Rys. 4. Zestawienie median absolutnych błędów względnych oszacowania zawartości Cu w modelu geochemicznym 3D w punktach zbioru testowego

IDW – metoda odwrotnej odległości do 2 potęgi, OK – kriging zwyczajny

Źródło: opracowanie własne

Despite the observed variations in means, medians, and empirical distributions of Cu content between the individual lithological units (Table 2), separate 3D modeling of this metal in a lithological model distinguishing the individual lithological units within the main lithological series does not result in the expected, noticeably higher accuracy compared with estimates based on the 3D modeling of main lithological series (Fig. 4). The verification of the accuracy of Cu estimates in the 3D model based on the test dataset has shown only a slight increase in the accuracy of the estimates of Cu content within the individual lithological units of the shale series compared to the estimates of the entire shale series.

Among the modeled individual lithological units, the estimates of Cu content in clay shale and argillaceous sandstone (Fig. 4) are of the highest accuracy (medians of absolute relative error of 25–30%).

The estimates of Cu content in individual lithological units of the carbonate series are characterized by higher medians of relative interpolation errors, ranging from 40% to over 70%. In the majority of units, the kriging method provides a slightly better accuracy of Cu estimation than the squared inverse distance weighting method (Fig. 4).

Unrealistically high medians of the Cu estimation errors for dolomitic shale can be associated with poor distribution of this unit in the examined part of the deposit, while the obtained results can be considered as incidental and requiring re-verification using the larger data set, taking other parts of the Rudna deposit into account.

Summary and conclusions

The results of the three-dimensional lithological and geochemical modeling of Cu content in the examined part of the depression zone of the roof of the Weissliegend sandstone series in the Rudna Cu-Ag deposit (the Lubin-Głogów Copper District) have led to the following observations and conclusions:

1. The Plurigaussian simulation method gives better results of lithological modeling of the deposit (ore type) when carried out separately for the individual lithological units within the main lithological series than when performed for all individual lithological units not taking into account the division into the main lithologies.
2. Precision and accuracy of 3D lithological modeling of the individual lithological units indicates an evident relationship between their distribution and the share in the deposit. The quality of models of the individual lithological units occurring locally or discontinuously is low and unacceptable.
3. The results of geochemical modeling limited to the Cu content are ambiguous. In general, errors in the estimation of Cu content in the tested samples are high, which masks the differences between various methods for the estimation of this metal. In the majority of analyzed cases, the kriging method provides a slightly better prediction accuracy than the squared inverse distance weighting method (IDW2).

4. The expected significant improvement of the 3D geochemical modeling of Cu content, using previously constructed 3D models of individual lithological units based on the main lithological series, has not been confirmed.
5. The presented conclusions are limited in scope and apply only to the directly examined part of the depression zone of the roof of the Weissliegend sandstone series in the Rudna deposit. There is a need for further analyses carried out in areas characterized by a different lithological and geochemical development in the profile of deposit series, particularly in the roof elevation areas (including the slope of roof elevation) of the Weissliegend sandstone in the Rudna deposit.

This study was partially funded by Statutory Research of the AGH University of Science and Technology No. 11.11.140.320 in 2017.

REFERENCES

- Armstrong et al. 2003 – Armstrong, M., Galli, A., Le Loc', H G., Geffroy, F. and Eschard, R. 2003 – *Plurigaussian Simulations in Geosciences*. Springer Science & Business Media, Berlin, 149.
- Bleinès et al. 2017 – Bleinès, C., Bourges, M., Deraisme, J., Geffroy, F., Jeannée, N., Lemarchand, O., Perseval, S., Poisson, J., Rambert, F., Renard, D., Touffait, Y. and Wagner, L. 2017 – ISATIS Software. Case Studies. Geovariances, 982.
- Mucha, J. and Wasilewska, M. 2009. Trójwymiarowe modelowanie wartości parametrów złożowych metodą krigin-gu zwyczajnego 3D. *Kwartalnik AGH Geologia* t. 3, z. 2/1, pp. 167–174 (in Polish).
- Mucha, J. and Wasilewska-Błaszczyk, M. 2010. Prognoza jakości urobku metodami geostatystyki 3D – perspektywy i ograniczenia. *Gospodarka Surowcami Mineralnymi – Mineral Resources Management* vol. 26, issue 2, pp. 57–67 (in Polish).
- Kaczmarek et al. 2014 – Kaczmarek, W., Rożek, R., Mrzygłód, M. and Jasiński, W. 2014: Litologia szczegółowa w bazie danych geologicznych KGHM Polska Miedź S.A. *Górnictwo Odkrywkowe* R. 55, nr 2–3, pp. 86–91 (in Polish).
- Kaczmarek et al. 2017 – Kaczmarek, W., Twardowski, M. and Wasilewska-Błaszczyk, M. 2017. Praktyczne aspekty modelowania litologicznych typów rud w złożach Cu-Ag LGOM. *Biul. Państw. Inst. Geol.* 468, pp. 209–226 (in Polish).
- Maleki, M. and Emery, X. 2015. Joint Simulation of Grade and Rock Type in a Stratabound Copper Deposit. *Math. Geosci.* 47, pp. 471–495.
- Sinclair, A.J. and Blackwell, G.H. 2002. *Applied Mineral Inventory Estimation*. Cambridge University Press, 381.
- Talebi et al. 2016 – Talebi, H., Sabeti, E.H., Azadi, M. and Emery, X. 2016. Risk quantification with combined use of lithological and grade simulations: Application to a porphyry copper deposit. *Ore Geology Reviews.* 75, pp. 42–51.
- Wasilewska-Błaszczyk et al. 2017a – Wasilewska-Błaszczyk, M., Kruk, M. and Mucha, J. 2017. Wiarygodność modelowania 3D zawartości Pb oraz głównych metali w złożu rud Cu-Ag Sierszowice (LGOM). *Biul. Państw. Inst. Geol.* 468, pp. 247–260 (in Polish). DOI: 10.5604/01.3001.0010.0116.
- Wasilewska-Błaszczyk et al. 2017b – Wasilewska-Błaszczyk, M., Twardowski, M., Mucha, J. and Kaczmarek, W. 2017. Model litologiczny 3D przy zastosowaniu technik interpolacyjnych i symulacji geostatystycznej (na przykładzie złoża Cu-Ag LGOM). *Biul. Państw. Inst. Geol.* Nr 468, pp. 237–245 (in Polish).
- Yunsel, T.Y. and Ersoy, A. 2011. Geological modeling of gold deposit based on grade domaining using plurigaussian simulation technique. *Natural Resources Research* Vol. 20, No. 4, pp. 231–249.

**MODELOWANIE GEOCHEMICZNE ZŁÓŻ CU-AG LGOM
WSPOMAGANE MODELOWANIEM LITOLOGICZNYM**

Słowa kluczowe

złoże Cu-Ag LGOM, litologiczny model 3D, geochemiczny model 3D, symulacja Plurigaussian

Streszczenie

Ważniejszymi przyczynami ograniczonej wiarygodności modeli geochemicznych 3D złóż Cu-Ag LGOM są niekorzystne cechy statystyczne zawartości metali podstawowych (Cu, Ag) oraz niekorzystna struktura ich zmienności ze stosunkowo słabo zaznaczonym nielosowym składnikiem zmienności. Pewne nadzieje na zwiększenie dokładności modeli geochemicznych budzi poprzedzenie jego konstrukcji modelowaniem litologicznym złoża. Wynika to ze zróżnicowania poziomów średnich zawartości metali zarówno między podstawowymi seriami litologicznymi (węglany, łupki i piaskowce) jak i pomiędzy wyróżnionymi w ich obrębie litologiami szczegółowymi, co uzasadnia wykonywanie modelowania geochemicznego oddzielnie dla każdego z nich.

W artykule przedstawiono wyniki porównania wiarygodności modelowania 3D zawartości miedzi indywidualnie w podstawowych i szczegółowych wydzieleniach litologicznych we fragmencie złoża Cu-Ag Rudna (LGOM). Modele litologiczne 3D wykonano metodami kriginu zwyczajnego (litologie podstawowe) i symulacji Plurigaussian (litologie szczegółowe). Do szacowania 3D zawartości Cu w obrębie modeli litologicznych wykorzystano metody kriginu zwyczajnego i odwrotnej odległości do drugiej potęgi. Weryfikacja dokładności oszacowań zawartości Cu w modelu 3D, wykonana punktowo na podstawie zbioru testowego, wykazała jedynie niewielki wzrost dokładności oszacowań zawartości Cu w obrębie szczegółowych wydzieleni litologicznych serii łupkowej w porównaniu z oszacowaniami zawartości Cu w tej litologii podstawowej traktowanej jako całość. W zdecydowanej większości przypadków modele 3D zawartości Cu w wydzieleniach litologicznych wykonane metodą kriginu zwyczajnego cechują się nieco wyższą dokładnością niż analogiczne modele wykonane metodą z wagowaniem na odwrotność odległości do 2 potęgi.

**GEOCHEMICAL MODELING OF THE CU-AG DEPOSITS FROM THE LUBIN-GŁOGÓW
COPPER DISTRICT (POLAND) SUPPORTED BY LITHOLOGICAL MODELING**

Key words

Cu-Ag deposit, 3D lithological model, 3D geochemical model, Plurigaussian Simulation

Abstract

The most important reasons for the limited credibility of 3D geochemical models of the Cu-Ag deposits (The Lubin-Głogów Copper District) are unfavorable statistical characteristics of the main metals (Cu, Ag), and the unfavorable structure of their variability with a relatively poorly marked non-random component of variability. It is hoped that the accuracy of geochemical models can be

increased by previous lithological modeling of a given deposit. This is due to significant differences in mean Cu content in both the main lithological series (carbonates, shales and sandstones) and individual lithological units within them, which justifies separate geochemical modeling of each.

The paper presents the results of the comparison of the reliability of 3D modeling of Cu content carried out in both individual and main lithological units of the Cu-Ag Rudna deposit (The Lubin-Głogów Copper District). The 3D lithological models were made using ordinary kriging (main lithological units) and Plurigaussian simulation (individual lithological units). The 3D estimation of Cu content within lithological models was carried out using the ordinary kriging (OK) and squared inverse distance (ID2) methods. The verification of the accuracy of Cu estimates in the 3D model using spot samples of the test data set has shown only a slight increase in the accuracy of the estimates of Cu content within the individual lithological units of the shale series compared to the estimates of Cu content in the whole main lithology. In most cases, 3D models of Cu content carried out using the ordinary kriging method are slightly more accurate than the analogous squared inverse distance weighting method.