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3D GEOSTATISTICAL MODEL OF THE ORE BODY IN ELATSITE PORPHYRY COPPER DEPOSIT, PANAGYURISHTE ORE REGION

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ABSTRACT

The results of three-dimensional geostatistical modeling of copper ore body in Elatsite porphyry copper deposit are present in this work. The deposit is located in NNW part of Elatsite-Chelopech Ore Field from Panagyurishte Ore Region, Bulgaria. Paleozoic granodioritic rocks are developed in northern part of the deposit and Pre-Cambrian metamorphites are located in south. Upper Cretaceous granodioritic to quartzdioritic or monzodioritic porphyrites are intruded near and along the contact between granodiorites and metamorphites.

Drillhole data from the open pit area, collected during preliminary and detail exploration of deposit and located between levels 1390 and 1045 are used for the model development. Copper contents in composite samples from each drill for each level represent primary data. Three dimensional variogram analysis, based on spherical model is used for determination of properties of spatial variability in data. Automatic routines of Least Squares method are applied for approximation of experimental variogram values, which aims precise determination of variogram models. Cross-validation for the variogram model effectivity is done and it shows that chosen model represent adequately natural variability of source data.

Smooth variation of copper content differences is typical for the Elatsite deposit, which is premise for precise determination and interpretation of variogram model. Derived ore body anisotropy is oriented along fault structures, dykes and host rock contacts, confirming their main ore-controlling role in deposit.

Three-dimensional model of ore body is designed on basis of variogram analysis results, as ordinary block kriging interpolation is used. The deposit is modeled with discrete blocks with dimension 15x15x15 m. The ore body is stockwork type, prolonged in NE direction. Digital terrain model is constructed for the modeling purposes and it is used as boundary to exclude eroded part. The constructed 3D model is proximal and generalized as the ore body development is not studied in depth and spatial characteristics of rock types are not separately analyzed.

GEOLOGICAL NOTES

The Elatsite porphyry copper deposit is located at the northern slope of Chelopeshka Baba pick, about 55-60 km east from Sofia City and about 6 km from Etropole town. It is formed within the frame of Elatsite-Chelopech Ore Field, as it is located about 6 km NW from the center of Chelopech volcano (Popov *et al*, 2001). 114.78 M.t. ore with 0.37 % copper content were extracted during the period from 1981 to 1995. Calculated in 01.01.2001 reserves are 139.57 M.t. ore with contents of 0.32 % Cu, 0.108 g/t Au, 0.004 % Mo, as well as the resources are 425.98 M.t. with 0.28 % copper content.

The Lower Paleozoic metamorphic rocks, Lower Carboniferous rocks of the Vejen pluton and Late Cretaceous rocks of Elatsite dyke-like intrusion with the associated dykes are spread across the region of deposit (fig. 1). The Lower Paleozoic metamorphic rocks are found along the southern deposit's boundary and phyllite, chlorit-sericitic schist and quartz-sericitic schist represent them. Various interpretations about their lithostratigraphic affiliation exist (Angelov *et al*., 1995; Cheshitev *et al*., 1995; Antonov *and* Jelev, 2002). They are alterated into hornfelse and knotted schist along the contact zone with the rocks of the Vejen pluton. Their main orientation is from 90 to 110° with 15-45° dip to south.

The Vejen pluton is developed in northern part of the deposit, mainly represent by granodiorite and granite. Von Quadt *et al*. (2002) determine its absolute age as 314±4 Ma by $^{206}Pb/^{238}U$ zircon method. The strike in the contact between the granodiorite and the horfelse is about 100° in the westernmost part of the deposit. The contact turns to the southeast (140°) and then rapidly turns to the northeast (60°) as shown in fig.1. The strike of the contact in easternmost part is about 80°. The general dip is 20-25° to the south near the surface, up to 45-55° in depth. Tectonic brecciation is observed along the contact as a result of younger tectonic deformations.

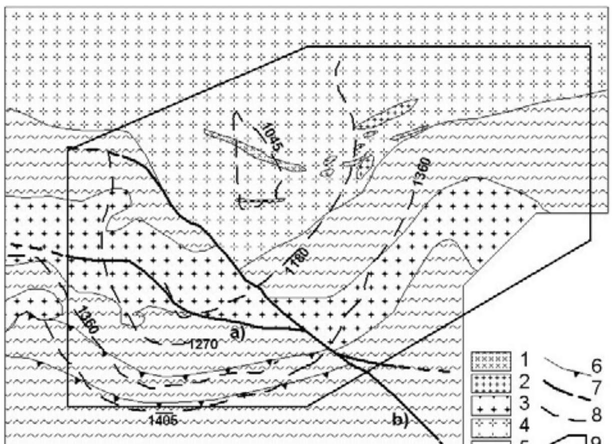


Figure 1.Geological map of the Elatsite deposit deposit (by G. Georgiev, unpubl.)
1 - microdiorite, micro-gabbro-diorite, microgabbro, 2 – granodiorite porphyrite, granite porphyrite, 3 - quartz-monzodiorite porphyrite, quartz-diorite porphyrite, 4 – Vejen pluton - granodiorite, granite, quartz-diorite, aplite, 5 - hornfelse, knotted schist, schist, 6 – Kashana reverse slip - overthrust, 7 - faults: a) Elatsite, b) Murgana, 8 – open pit horizons, 9 – boundary of designed 3D model

The Elatsite intrusion (The big dyke) consists of quartz-monzonitie intruded in the contact zone between metamorphites and Vejen pluton. The wide fracturing zone of the Kashana reverse slip - overthrust obviously defines its position. This intrusion is represented by a long plate-like body with over 3.3 km length, as its width varying from several meters up to 200-400 m. In the western part of the deposit the strike of that body is about 90°, in the central part - 110-120°, than it turns sharply to the northeast (50°), and finally turns to the southeast. The intrusion's dip is 20-45° to the south in upper parts, while in depth it's probably increasing up to 55°-70°.

A great number of dykes represent by quartz-monzodiorite porphyrite, granodiorite porphyrite, granite-porphyries and aplite associate with Elatsite intrusive. Microdioritic, micromonzonitic, diorite porphyritic and quartz-diorite porphyritic dykes are also observed (Trashliev *and* Trashlieva, 1964; Von Quadt *et al*., 2002).

The U/Pb zircon method dating determines the age of igneous rock bodies between 92.1±0.3 Ma – 91.84±0.31 Ma (Von Quadt *et a*l., 2002), which is very close to the Cenomanian – Turonian boundary. Velichkova *et al*. (2001) determines 88-90 Ma age of the subvolcanic bodies near Elatsite and Chelopech villages by $^{40}Ar/^{39}Ar$ analysis on biotite. Besides, these intrusions are most probably formed by the end of Turonian or in the beginning of Coniasian ages, according to geological data (Popov *et al*., 2001).

Examining the structure of Elatsite deposit, Kalaydjiev *et al*. (1984) suggest the development of a dense net of rectilinear faults with E-SE, N-NW and NE direction. The recent study (Georgiev, *unpubl*.) does not confirm this assumption. Practically, there are three main fault structures, traced across the deposit: Elatsite fault, Murgana fault and Kashana reverse slip - overthrust (fig. 1). The Elatsite fault posses a strike, varying from 85° to 125°. It lengthwisely crosses Elatsite intrusion in the western part of the deposit, while to the east it passes along the intrusion's southern contact. Its dip is 70-85° to the south. Movements, typical for right normal-slip fault are accomplished. This fault basicly coincides "The first Elatsite fault", defined by Kalaydjiev *et al*. (1984). The Murgana fault possesses a strike about 125-150°. It diagonally intersects the deposit as it's dip is subvertical 80-90° to SW mainly. It is nominated by Kalaydjiev *et al*. (1984) as "Central Elatsite fault". Right-slip movements with amplitude about 200-250 m and collaps of 50-200 m are accomplished. It is turning in southeastern part, where it is noted by Popov *et al*. (2001), as the strike is 150-155^0. The Kashana fault is registered for the first time by Trashliev (1961), and later it is traced out and described by Kouykin *and* Milanov (1970) and Kouykin *et al*. (1971). These authors determine its age as Austrian in first mentioned paper, while in second paper they assign Laramian (or Post-Turonian) age to it. A thrust fault zone with width of 80-150 m, composed by anastomosing subordinate fault surfaces is observed in southwestern part of the Elatsite deposit, within the Late Paleozoic metamorphic rocks. It passes along the contact between the Early Paleozoic and Triassic rocks to the west. The zone probably represents the appearance of Kashana thrust in this part of the deposit. The partial intrusion within this zone of Elatsite intrusive, as well as the intrusion at Kashana and some other smaller bodies, point to its Austrian age. Younger post-ore movements most probably with Laramian age are established as well. It should be mentioned that Georgiev (*unpubl*.) determines radial-concentric development of the jointing and small faults within the deposit.

The Elatsite deposit is spatially and genetically related to the Upper Cretaceous Elatsite intrusion and associated dykes (Hadjyiski *et al*., 1970; Kalaydjiev *et al*., 1984; Dimitrov, 1988; Popov *et al*., 2001). This is determined according to circumstance that it is intensively affected together with the Paleozoic rocks by the post-ore hydrothermal alterations and by the ore mineralisation. The hydrothermal alterations are represented mainly by K-silicate (*Ksp+bi+qtz+il+pl+calc* or *Ksp+chl+qtz+il+ab*), propyllitic (*Ep+act+ab+bi+qtz+calc* or *Ep+chl+ab+bi+qtz*) and sericitic (Il+qtz+py) alterations (Strashimirov *et al*., 2002). The copper is primary economic element in the Elatsite deposit and the Au is secondary one. The molybdenite concentrate was extracted during some exploitation periods as well. Several consecutively formed mineral associations represent the ore mineralization: magnetite-bornite-chalcopyrite, quartz-pyrite-chalcopyrite, quartz-molybdenite, quartz-pyrite, quartz-galena-sphalerite and quartz-calcite-zeolitic associations (Strashimirov *et al*., 2002). The development of the magnetite-bornite-chalcopyrite mineralisation is quite irregular, as it includes native gold and some minerals, containing elements from the PGE (Dragov *and* Petrunov, 1996). The major economic interest takes the quartz-pyrite-chalcopyrite association, which comprises the main content of copper, gold (electrum) and molybdenum. The quartz-pyrite and quartz-galena-sphalerite associations are developed mainly in outlying parts of the deposit.

The ore mineralisation forms a big stockwork, which is developed within intensively jointed Paleozoic granodiorite and hornfelse, as well as within the rocks from Elatsite intrusive and associated dykes (fig. 1). This ore body posses an ellipse-like shape in plan, elongated to the northwest. Its length is about 1200 m and the width varies from 200 to 750 m. The area of its horizontal projection is about 0.616 km^2 (Hadjyiski *et al*., 1970). The stockwork is outcropped by the erosion on level 1400 m (before the beginning of exploitation), as the ore mineralisation reaches level 550 m in depth. Its main axis posses a general strike of 40-50° to south, as in general it follows the contact between Lower Paleozoic rocks and granodiorite of the Vejen pluton. The ore stockwork is not outlined in depth, as most of drills do not reach its boundaries. It has continuous strike and dip. The ore body boundary within host rocks is gradual and it is defined by copper content of 0.18 %. The transition is more sharply-outlined within metamorphites, along their contact with granodiorite. The ore mineralisation is represented by multiple veinlets and impregnations within intrusive rocks, while veinlets predominate in metamorphites. Small quartz-pyrite veins are rarely observed.

DATA USED

Drillhole data from preliminary and detail exploration of Elatsite deposit (Hadjyiski *et. al*., 1970), between horizons 1390 and 1045, are used in this study. The preliminary exploration is realised on 100x100 m grid, down to level 805. The drill grid is chessmate condensed up to 71x71 m in the central parts and up to 50x100 m in the periphery during detail exploration. Outlining boreholes placed at 200 to 300 m from the base exploration network are drilled around ore body. This exploration network geometry is preserved down to level 1000, as in deeper levels it is destored due to borehole inclination. The deposit is studied in deep below level 802 with 12 drills, located in central part at intervals of 200 m. The drill core is sampled by section samples with average length of 2.38 m and the copper content is determined by chemical analyses. Composite core samples are used for the developing of geostatistical model, where every composite sample represent the copper content, which is averaged from section samples of

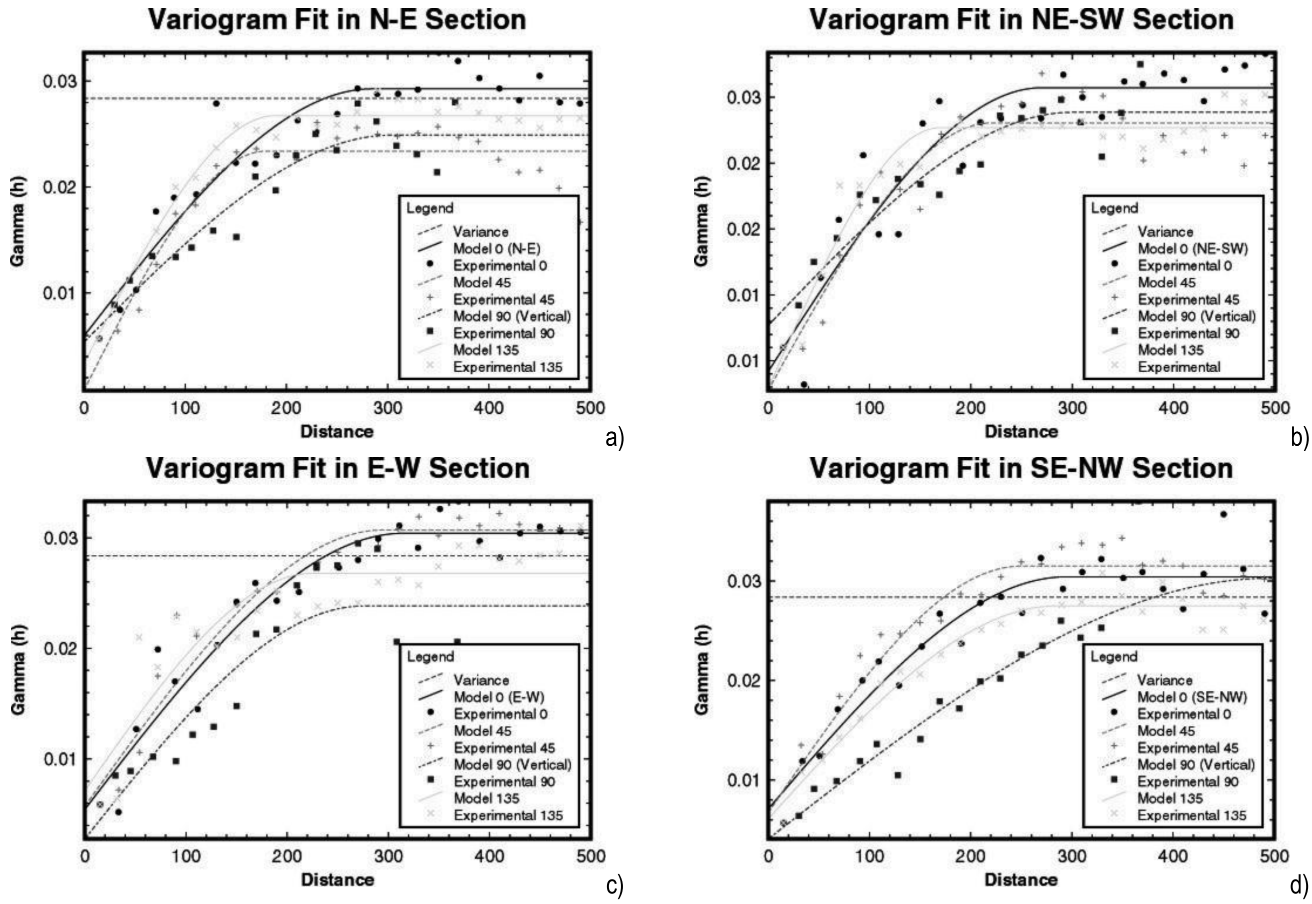


Figure 3. Experimental variograms and respective spherical models, determined for vertical sections in directions 0^o (a), 45^o (b), 90^o (c) and 135^o (d). Four variograms, calculated at dips 0^o, 45^o, 90^o and 135^o, are shown for every direction.

every drill at current level. Total number of 2819 composite samples from 24 horizons is used. Copper contents in these samples posses asymmetric statistical distribution shown on figure 2, as the statistical parameters describing their distribution low are represented below in table 2.

VARIOGRAM ANALYSIS

The variogram analysis is an essential part from the geostatistical modeling of deposits. Its aim is a determination of the spatial variability nature for studied geological feature (Matheron, 1967; Rendu, 1981). The variogram function is defined as the relation of average differences between measured values towards distances between samples:

$$\gamma(\vec{h}) = \frac{\sum_{i=1}^{n_h} (x_i - x_{i+h})^2}{2n_h},$$

where x_i-x_{i+h} are n_h of number differences between values (e.g. element's contents), measured in samples at average distance h between samples and situated along given direction. The main advantage of variogram analysis is average estimation of different natural features, as anisotropy, character and degree of correlation between neighbor samples at different distances, value of general variability, continuity, etc., which are typical for the object studied. After calculation of

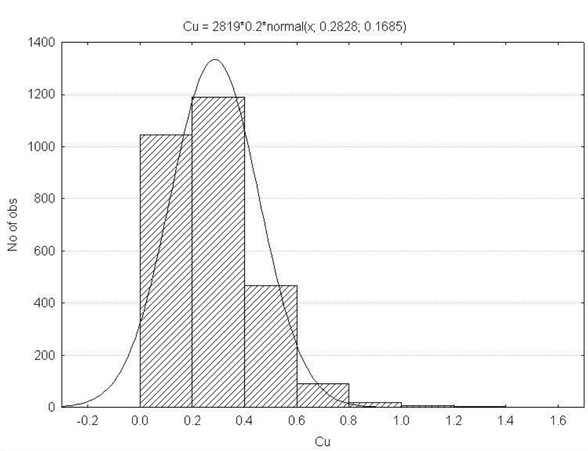


Figure 2.Histogram presenting copper distribution in used composite core samples.

average differences in separate directions, represented by experimental variograms, it is very important to select an appropriate theoretical model, to describe adequately natural structure in variability of data used.

The experimental variograms in plane and in four vertical directions with azimuth 0°, 45°, 90° and 135° are calculated in this variogram modeling of Elatsite deposit. Sixteen experimental variograms are calculated in general – four variograms at 0°, 45°, 90° and 135° directions in plane, as well as at four variograms with 0°, 45°, 90° and 135° slopes in every vertical direction. Variograms are calculated by three-dimensional searching of neighbor samples, in following conditions: from 20 to 500 m distance between samples with lag 20 m, horizontal and vertical bandwidth 200 m, horizontal and vertical angle tolerance 22.5°.

Experimental variograms are approximated with spherical model, represented in general form as:

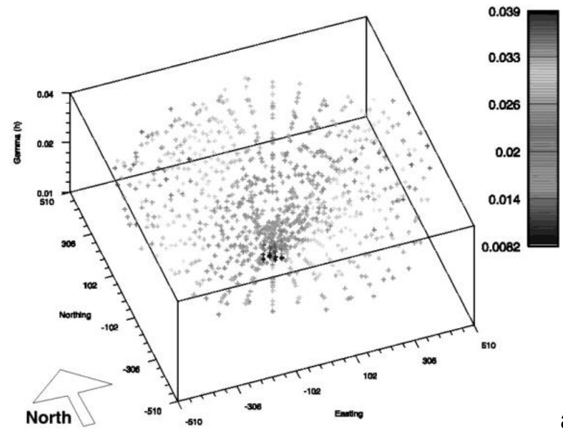
$$\gamma(h) = C\left(\frac{3h}{2a} - \frac{h^3}{2a^3}\right) \quad \text{for } h \leq a,$$

$$\gamma(h) = C \quad \text{for } h > a,$$

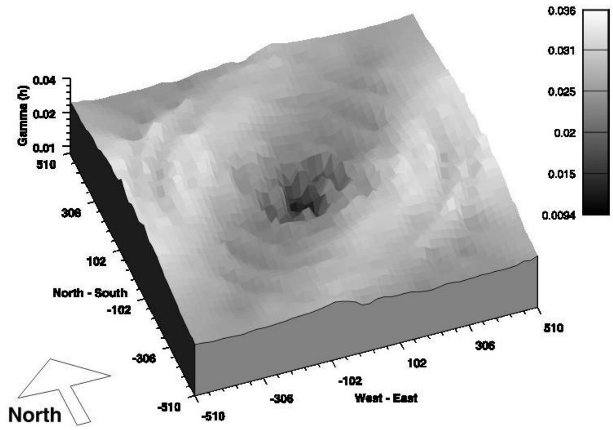
where C and a are variogram's sill and range respectively, while h is distance between samples.

The variogram analysis is completely done by UNCERT software (Wingle, *et al.*, 1997), as the approximation of theoretical spherical model is automatically calculated by least squares method. Resulting variogram models and parameters are presented in table 1 and figure 3, which illustrate existing anisotropy of copper ore body. Geometrical anisotropy representing elongated ore morphology is examined, as well as zonal anisotropy, which is determined by ore body location around the contact between granodiorites and metamorphic rocks. 18 variograms with angular lag 20° (half-angle solution) are used for anisotropy analysis in horizontal direction with aim to describe the structure of copper spatial variability (fig. 4). The variogram surface shows that smoothest changes of copper contents are examined in NE-SW direction, along the prolongation of ore body, while highest values of copper contents dispersion are examined in NW-SE direction. Interesting fact is that major anisotropy axis is oriented either in NE-SW or NW-SE direction due to chosen automatic approximation method, which can be explained with the strike variation of host rocks contact as well as orientation of major faults and dykes.

Cross-validation routine is performed for estimation of averaged variogram model significance, which is applied later in kriging interpolation modeling. This validation compares true copper contents measured in composite samples with their kriging estimations by neighbor samples. Popular geostatistical modeling software GSLIB (Deutsch *and* Journel, 1998) is used. The results are shown on table 2 and figure 5, where a high similarity between true values and estimates, with correlation of 0.86, is illustrated. Similarity between real and estimated values confirms the good representation of natural copper variability by variogram model, which is obvious condition for precise reserve calculation trough kriging method. Smoothing effect of kriging interpolation, espatialy for samples with higher contents, is illustrated on figure 5.



a)



b)

Figure 4. Variogram structure in horizontal direction, determined by 18 variograms (half-angle solution), shown as experimental variograms (a) and variogram surface (b).

Table 1. Spherical variogram model parameters, calculated for individual directions and vertical angles.

Azimuth	Dip	Nugget effect	Sill	Range
0	0	0.00592432	0.0233568	285
0	45	0.000786367	0.0226083	180
0	90	0.00535023	0.0195682	305
0	135	0.00332431	0.0234292	190
45	0	0.00415641	0.0215626	270
45	45	0.00273686	0.0203063	220
45	90	0.00765853	0.0161969	300
45	135	0.0028656	0.0198173	170
90	0	0.00543918	0.0249688	315
90	45	0.00573138	0.0249761	295
90	90	0.00277493	0.0210528	275
90	135	0.00713603	0.0196509	225
135	0	0.00709468	0.0233214	295
135	45	0.00673393	0.0247538	250
135	90	0.00408765	0.026182	495
135	135	0.00609529	0.0213959	285
	Average:	0.00487	0.0221	

Table 2. Statistical parameters from cross-validation, describing distribution lows of copper contents in composite core samples (Cu), their kriging estimations (Cu*), estimation variance (S_{Cu^*}) and the differences between estimations and true contents (Cu* - Cu).

	Cu	Cu*	S_{Cu^*}	Cu* - Cu
Mean.	0.282811	0.283932	0.002157	0.001121
Median	0.26	0.27	0.002	0.009
Minimum	0.007	0.01	0.001	-0.818
Maximum	1.37	0.788	0.024	0.324
Variance	0.028384	0.019908	4.16E-07	0.007325
Std. Deviation	0.168476	0.141096	0.000645	0.085585
Skewness	1.163632	0.568922	14.986	-1.5891
Kurtosis	2.70775	0.283673	469.9832	9.997335

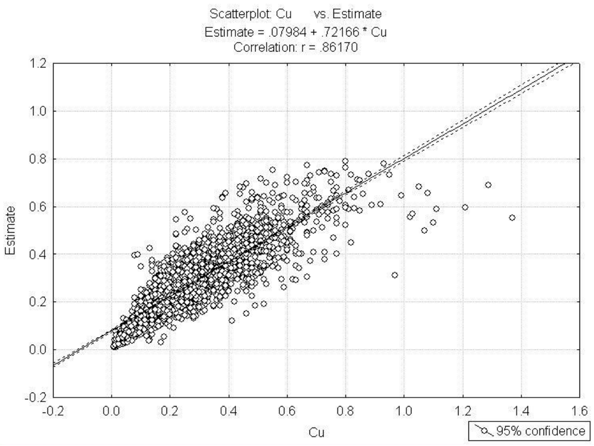


Figure 5. Correlation between true copper contents in core samples (Cu) and their kriging estimations (Estimate).

KRIGING BLOCK MODEL

The geostatistical block model of copper ore body is constructed for the volume with dimensions 1560x1080 m in plan and 345 m in depth, between horizons 1390 and 1045. Outline areas with lack of data are cutted, as the contour in which the copper ore body is designed is shown on figure 1. Digital elevation model is constructed by topographic map and it is used to remove eroded parts. The studied volume is disintegrated to small blocks with dimension 15x15x15 m, which are estimated by block kriging method with 4x4x4 discretization points for every block. Kriging modeling is performed with kt3d program from GSLIB software (Deutsch *and* Journel, 1998), where 4 to 10 neighbor samples are used. Octant type searching within maximum radius is performed for declustering of drill data. Applied average variogram model, determined by variogram analysis (tabl. 1) posses nugget effect 0.00487 and sill 0.01723, as the anisotropy is described with maximum, minimum and vertical range respectively 315 (azimuth 110^{o}), 270 and 300 m. The resulting digital model represents central co-ordinates, estimated copper contents and the kriging estimation variance for each block. Detailed analysis of variability and reserves calculation conditions for separate host rocks and ore types is presented by Todorov *et al.* (2002).

Specialized module to visualize three-dimensional model of copper ore body is developed in OpenDX software, which is based on IBM Visualization Data Explorer software (IBM, 1997). The ore body morphology is illustrated by individual isosurfaces on figure 6, as the relief surface is also shown for higher reality. Constructed model could be used for reserves calculation for separate horizons as well, if the geological-economic and mining-technical conditions in the deposit would be taken into account.

CONCLUSIONS

Designed three-dimensional model describes the spatial features of copper contents distribution and ore body morphology in Elatsite deposit. The variogram analysis shows smooth copper contents variance, which is precondition for the precise model design. Invoked anisotropy posses a complicated morphology due to complex geological setting and different fault directions, as well as the variation of host rock contacts. The major anisotropy axis is oriented either in northeast or northwest direction, parallel or orthogonal to ore body length respectively, in depends of applied method for automated approximation of variogram model. Both geometric and zonal components are observed in invoked anisotropy, as the second is most obviously manifested in W-E direction. The geometrical anisotropy component reflects the differences in ore-forming process intensity at central and outern parts of stockwork and it is main controlling factor for ore body morphology. The zonal component is caused by rapid changes in lithological features of host rocks. It could be concluded that copper content variances are smoothest in NE-SW direction generally, while highest variance values are observed in NW-SE direction.

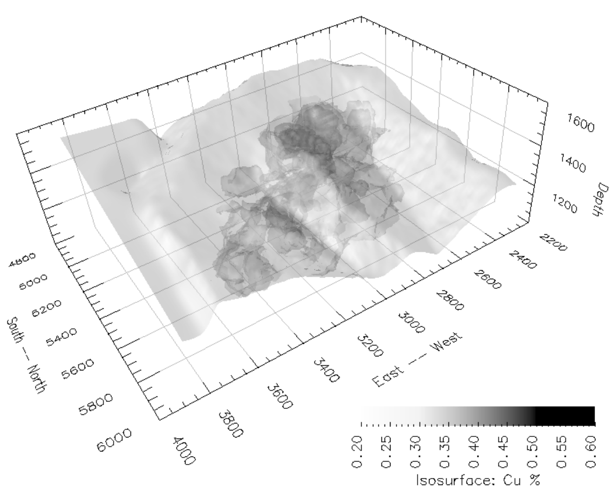


Figure 6. 3D model of copper ore body represented by isosurfaces on 0.25, 0.4 and 0.55 % Cu contents. Relief model is overlaid as transparent light-gray surface. View from Northeast.

The contact between Vejen pluton and Lower Paleozoic metamorphites as well as the sub-parallel to contact Kashana reverse slip – overthrust posses main magma-controlling and ore-controlling role within Elatsite deposit area. The intersection area of this contact, Elatsite intrusive and Elatsite and Murgana faults defines particular ore stockwork location. The last two faults obviously posses an ore-conducting role within studied depth interval. The area of intersection between separate structures is characterized by the highest permeability, which is marked by the highest copper concentration in ore body. The ore stockwork stretch in northeastern direction is obviously determined by orientation of the contact between Paleozoic granodiorites and metamorphites in this area. This contact controls the development of higher metal contents as well. It should be mentioned that the ore mineralisation within Paleozoic metamorphites is developed mainly within the zone, where they are alterated into hornfelse. The knotted schist and phyllite located out of this zone posses screening role during the ore forming, due to their plastic features.

Designed model describes in general the upper levels of deposit, as the highest contents are observed between horizons 1400 and 1200. The cross-validation performed on variogram model shows a high correlation between estimated and true contents, which represents adequate describing of real geological situation by the created model.

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