Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 60, No 9, 2007

GEOLOGIE
Minéralogie

MORPHOMETRY OF ELECTRUM FROM LAYER-LIKE PERVASIVE SILICIFICATION IN STENATA OUTCROP, LOW-SULFIDATION KHAN KRUM GOLD DEPOSIT, SE BULGARIA

Irina Marinova

(*Submitted by Corresponding Member I. Velinov on June 26, 2007*)

Abstract

This work presents data on 3-dimentional measurements of 330 electrum particles from the epithermal, low-sulfidation, adularia-sericite type, sediment-hosted Khan Krum (Ada tepe) gold deposit, Eastern Rhodope Mountain, SE Bulgaria. The length, width and thickness of electrum particles were measured by means of optical microscopy. The equivalent circular and spherical diameters, Corey's shape factor, flatness ratio and isometry were calculated, and particles' sphericity was determined. A comparison to morphometry of gold from the epithermal, high-sulfidation, acid-sulphate, volcanic-hosted Chelopech gold-copper deposit, Central Srednogorie Mountain, Central Bulgaria, was made.

Key words: electrum, morphometry, Khan Krum, Ada tepe, Bulgaria

Introduction. The shape and morphometric characteristics of gold and electrum represent important technological properties that determine the methods of their recovery during ore processing and the methods of gold and silver metals extraction. They also provide data on the geometry of deposition environment and deposit origin, usually showing considerable differences between different genetic types of deposits. These data are also useful during the prospecting for gold mineralizations in adjacent gold-bearing areas. This makes size determination and morphometric characteristics of electrum from Khan Krum deposit an important issue from technological, mineralogical and exploration point of view.

It was established that the electrum from Khan Krum deposit (known also as Ada tepe deposit) is micron-sized [1–6]. More detailed measurement of the electrum size on the basis of granulometry of 100 electrum particles was presented in [3]. The author pointed out that the size of electrum varies from 8 to 50 µm at the surface and from 1–4 to 25 µm in depth. According to Jelev [6], about 90% of electrum in Khan Krum deposit has a size from 3–12 to 65–75 µm, but particles between 50 and 180 µm were also observed, as well as individual crystals forming chains up to 650 µm. However, these data are not sufficient for a systematic characterization of electrum morphometry.

This paper is aimed at characterizing the morphometry of electrum from Khan Krum gold deposit by measuring a great number of electrum particles in three dimensions thus ensuring a statistical representativity of the study.

The Khan Krum gold deposit is located in Eastern Rhodope Mountain, SE Bulgaria, 4 km to the south of the town of Krumovgrad. The deposit is hosted within the northern periphery of Kessebir Gneiss Dome [8], covered from the north by colluvial-proluvial-alluvial, poorly consolidated and sorted out polymict breccias and breccia-conglomerates (Shavar Formation) of a Maastrichtian-Paleocene age [9]. The boundary between the underlying metamorphic rocks of the Dome and the covering sediments of Shavar Formation is traced by the regional, low-angle Tokachka Detachment Fault [10]. The gold mineralization is epithermal, low-sulfidation, adularia-sericite type, sediment-hosted [1], around 35 Ma of age [2], formed from low salinity solutions [11] at a temperature of about 180–210 °C [2, 11].

The style of mineralization includes two types of ore bodies entirely developed above Tokachka Detachment Fault within the clastic sediments of the Shavar Formation: a layer-like massive body and an open-space filling of E-W-trending high-angle listric faults [2, 6, 12]. The layer-like massive body is best outcropped at the surface in Stenata outcrop (The Wall). It is formed by intense pervasive silicification of gravel to coarse, clast-supported polymict breccias and breccia-conglomerates and is composed of massive microcrystalline quartz (98–99%), adularia and kaolinite (1–2%), dispersed micron-sized electrum, marcasite and goethite pseudomorphs after pyrite (below 1%) [4]. It is accompanied by quartz-adularia metasomatites (±sericite, ±kaolinite) [1]. Generally, electrum from the layer-like pervasive silicification in Stenata outcrop is observed as dispersed grains of oval, euhedral and subhedral shape and groups of grains in massive microcrystalline quartz, as well as aggregates in massive quartz interstices. Occasionally, it is also observed as intergrowths with pyrite and as filamentary crystals in small voids [4, 5]. Electrum also forms grains, aggregates and dendrites in cross-cutting quartz-adularia veinlets [2, 5, 6]. Electrum from Stenata outcrop, just above Tokachka Detachment Fault, has a fineness between 637 and 764 and mean Au:Ag ratio of approximately 2:1 [4]. The general Au:Ag ratio in Khan Krum deposit is around 3:1 [2].

The probable reserves (122 code) of Khan Krum deposit are 10892.6 kg gold at 7.3 g/t grade and 6440.6 kg silver at 4.3 g/t grade. The measured resources (331 code) are 17294 kg gold at 2.4 g/t grade and 7503 kg silver at 1 g/t grade [7].

Material. The studied electrum comes from layer-like pervasive silicification in Stenata outcrop, the sample covering a 3-metre range just above Tokachka Detachment Fault and being 6660 kg of weight.

Methods. The size of 330 electrum grains was measured by optical microscopy. The major part of particles was obtained from pan-concentrated milled massive quartz. Another part was obtained after crushing in a ball mill down to +0.80 mm and a consequent dissolution of the concomitant quartz in hydrofluoric acid. The electrum particles were handpicked from the heavy mineral concentrate and put on a glass substrate and their dimensions were measured in reflected light using an Orthoplan Leitz optical microscope. For each electrum particle, the length L along its longest dimension, the width W perpendicular to the L direction and the thickness T, determined as the difference between the base and the highest point of the particle, were measured. L and W were measured using the microscope micrometer eyepiece grid, while T – by focusing the screw micrometer.

Additionally, the following morphometric characteristics were calculated: the equivalent circular diameter $\mathrm{ECD} = \sqrt{\mathrm{LW}}$, which characterizes the diameter of the L×W section [13]; the equivalent spherical diameter $\mathrm{ESD} = \sqrt[3]{\mathrm{LWT}}$ which represents the diameter of the particles considered as spheres [14, 15]; the Corey shape factor $\mathrm{CSF} = \mathrm{T}/\sqrt{\mathrm{LW}}$, which describes the particle flatness and varies from 0 to 1, the lower values indicating a high particle flatness and the higher ones indicating almost spherical particles [13]. The flatness ratio $(\mathrm{L}+\mathrm{W})/2\mathrm{T}$ [16] and the isometry $(\mathrm{L}+\mathrm{T})/2\mathrm{W}$ [17] were also calculated, both characteristics being equal to 1 for isometrical and spherical particles.

For determination of electrum particles sphericity on the W/L × T/W nomogram of KRUMBEIN [18] the W/L and T/W ratios were calculated. On the nomogram the sphericity varies from 0.3 to 0.9 being equal to 1.0 for spherical particles. The above mentioned ratios lay on the ground of the morphological groups in [19], that is why these groups are added with digits on the nomogram of Krumbein and their boundaries outlined with dashed lines.

For evaluation of the statistical representativity of measured dimensions of electrum, the enough number of measurements at desired accuracy was calculated by the formula $n = t^2\frac{pq}{\varepsilon^2}$, where n is the enough number of measurements, t is the value of Student's t-distribution with fixed probability P and degrees of freedom ($\nu = \infty$), p is the frequency of a given class of dimension, $q = 1 - p$, ε is the previously fixed error [20].

Results and discussion. The group of electrum particles obtained after milling was examined under scanning electron microscope for possible mechanical deformations from the milling. The observations showed that the morphometry of electrum is not influenced mechanically due to the small size of particles.

The enough number of measurements was calculated at $\varepsilon = 0.05$ and $P = 95\%$, and $\varepsilon = 0.10$ and $P = 90\%$. Satisfactory results were obtained at $\varepsilon = 0.10$ and $P = 90\%$ and they show that our population is statistically representative with a 90% confidence probability. The enough number of measurements for the length, which has biggest range among the three dimensions, has to be 824 with $\varepsilon = 0.05$ and $P = 95\%$ (Table 1).

Table 1

Size of 330 electrum particles from Stenata pervasive silicification, Khan Krum deposit, divided into classes with the respective frequency for each class and enough number of measurements at previously fixed error ε and probability P calculated after [20]

Length					Width					Thickness				
Class, μm	N	p, %	n_1	n_2	Class, μm	N	p, %	n_1	n_2	Class, μm	N	p, %	n_1	n_2
0–20	7	2.12	22	3	0–20	34	10.30	100	15	0–10	17	5.15	53	8
21–40	80	24.24	199	30	21–40	188	56.97	266	40	11-20	125	37.88	255	39
41–60	123	37.27	253	38	41–60	69	20.91	179	27	21–30	115	34.85	246	37
61–80	53	16.06	146	22	61–80	22	6.67	68	10	31–40	48	14.55	135	20
81–100	34	10.30	100	15	81–100	16	4.85	50	8	41-50	8	2.42	26	4
101–120	16	4.85	50	8	101–120	0	0	0	0	51–60	11	3.33	35	5
121–140	10	3.03	32	5	121–140	1	0.30	32	5	61–70	3	0.91	9	15
141–160	5	1.52	16	2						71–80	3	0.91	9	15
161–180	1	0.30	3	5										
181–200	0	0	0	0										
201–220	1	0.30	3	5										
Sum	330	99.99	824	133		330	100.00	695	105		330	100.00	768	143

N – number of measurements, p – frequency, n_1 – enough number of measurements at $\varepsilon = 0.05$ accuracy, n_2 – enough number of measurements at $\varepsilon = 0.10$ and $P = 90\%$

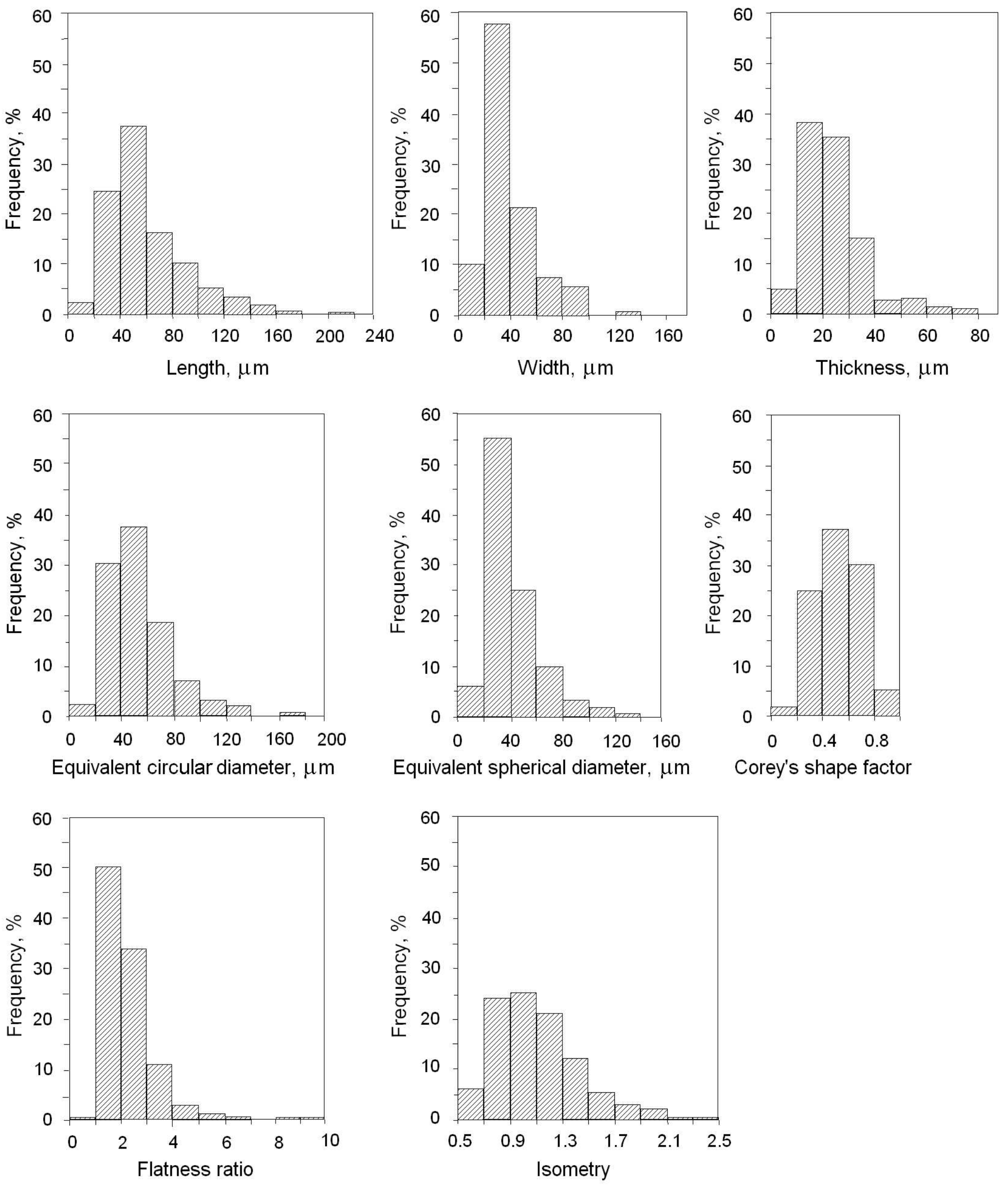

Fig. 1. Histograms of size and of morphometric characteristics of 330 electrum particles from Stenata pervasive silicification, Khan Krum deposit

The results from the electrum particles' size determination are presented in Fig. 1 and in Table 1 and Table 2. The length L of the electrum particles was found to vary from a few microns to 220 µm, the mean length being 67 ± 2 µm, and the distribution mode being 40–60 µm. 98% of the electrum from Stenata outcrop is below 140 µm in length. The width W varies from a few microns to 140 µm, being 44 ± 1 µm, on an average, and the mode peaks within the 20–40 µm range. 99.7% of the electrum particles is below 100 µm in width. The thickness T varies from a few microns to 80 µm, T a b l e 2

Size and morphometric characteristics of 330 electrum particles from Stenata pervasive silicification, Khan Krum deposit

Size and morphometric characteristics	Minimum	Maximum	Mean value $\pm\Delta X$ at $P = 99\%$	Mode	Standard deviation	Relative standard devi., %
Length, µm	10	220	67±2	40−60	30	45
Width, µm	10	140	44±1	20−40	20	45
Thickness, µm	4	80	26±1	10−30	12	46
Equivalent circular diameter, µm	10	176	54±1	40−60	25	46
Equivalent spherical diameter, µm	5	135	43±1	20−40	19	44
Corey's shape factor	0.1	1.0	0.5±0.01	0.4−0.6	0.2	40
Flatness ratio	1.0	9.5	2.3±0.06	1−2	1.1	48
Isometry	0.6	2.5	1.1±0.02	0.7−1.1	0.3	27

being 26 ± 1 µm, on an average, and the mode peaks within the range of 10–30 µm. 98% of the electrum studied has a thickness below 60 µm. The measured size of the electrum under study is of the same order of magnitude as the size of the concomitant massive quartz [21]. The three histograms show a left-shift in comparison with the normal Gaussian distribution due to the reduced number of particles smaller than 20 µm around in size (Fig. 1). The reduction in the real number of particles sized below around 20 µm stems from the rinsing of the sample during pan-concentrating when the lightest particles were washed out by water as well as from the difficulty of handling so small particles.

The measured dimensions of electrum particles presented, herein, make the available data on the electrum size [3, 6] more precise showing that 98% of the electrum from Khan Krum deposit just above Tokachka Detachment Fault, which is the bottom of the electrum mineralization, is smaller than 140 µm. At the same time they could not confirm the data presented in [3] about the electrum size from 1–4 to 25 µm in depth.

The junction points of W/L and T/W-values of each electrum particle were plotted on the Krumbein nomogram for a detailed characterization of electrum sphericity (Fig. 2). Both ratios have many repeated values, so the figurative points in Fig. 2 are only some tens instead of 330. Figure 2 shows that the majority of electrum particles has a sphericity between 0.6 and 0.7, i.e. their sphericity is moderately high. The mean values of W/L = 0.66 and T/W = 0.59 determine a mean sphericity equal to 0.65, which is also moderately high. The studied electrum falls exclusively into the following morphological groups of Payene [19]: II (flat-spheroidal), III (spherical), V (flat-elongated-spheroidal) and VI (elongated-spheroidal particles).

The equivalent circular diameter varies from 10 to 176 µm, being 54 ± 1 µm, on an average, and the mode peaks within the range of 40–60 µm, i.e. the distribution of ECD is almost a normal Gaussian. The equivalent spherical diameter is of the same order of magnitude but smaller, namely it varies between 5 and 135 µm, being 43 ± 1 µm, on an average, the mode being 20–40 µm (Fig. 1, Table 2). The comparison of both characteristics shows that, in general, the electrum particles are moderately flattened.

The Corey shape factor varies from 0.1 up to 1.0 being 0.5 ± 0.01, on an aver-

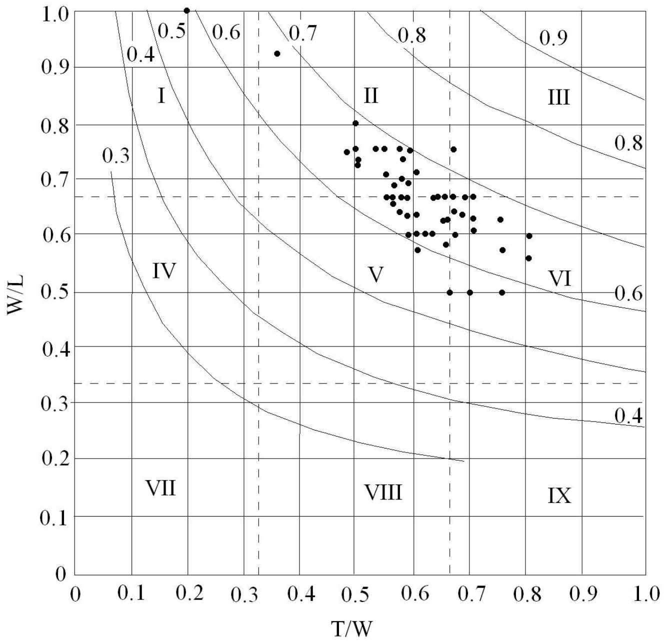

Fig. 2. A nomogram for determination of particle sphericity [18]. The sphericity varies from 0.3 to 0.9. Dashed lines link the points where W/L and T/W ratios are equal to 1/3 and to 2/3, which are boundaries of morphological groups of Payene [19], indicated by figures as follows: I – disc-like, II – flat-spheroidal, III – spherical, IV – flatly elongated disc, V – flat-elongated-spheroidal, VI – elongated-spheroidal, VII - flatly elongated, VIII – elongated rods, IX – various particles

age, the mode peaks within the 0.4–0.6 range. The majority of values (around 92%) is grouped between 0.2 and 0.8, thus indicating a presence of flattened, moderately flattened particles and ones close to a spherical shape (Fig. 1, Table 2). The highly flattened particles (CSF < 0.2) and the almost spherical ones (CSF > 0.8) are presented in quantities below 8% of the electrum population. The mean value of 0.5 shows that the mean thickness is half the mean value of $\sqrt{\mathrm{LW}}$.

The calculated flatness ratio showed a similar result – it varies from 1.0 to 9.50, being 2.30±0.06, on an average, the mode peaks within the 1–2 range (Table 2), i.e. close to that of gold from hard-rock deposits, where according to [22] gold is represented by weakly-to-moderately flattened particles. About 85% of the electrum particles under study are weakly to moderately flattened and the remaining 15% of the particles – highly flattened (Fig. 1).

The calculated isometry varies from 0.6 to 2.5, the average value being 1.12 ± 0.02 and the mode being within the range of 0.7–1.1. Isometrical and close to isometrical particles are predominant. Anisometric particles of an isometry both below 0.7 and above 1.5 are sporadic (Fig. 1, Table 2).

The characteristics discussed above show similar relative standard deviations that have medium values. This is not valid for the isometry which shows a low relative standard deviation (Table 2).

The predominant moderately low flatness of the electrum particles, their moderately high sphericity, the predominant shape which is close to an isometrical and spherical, and the close values of sizes of electrum and embracing massive quartz, allow us to conclude that the major part (around 80%) of the electrum from the pervasive silicification in Stenata outcrop, just above Tokachka Detachment Fault, is deposited together with quartz during the silicification of clastic sediments of Shavar Formation as well as in small voids in the pervasive silicification. The highly flattened electrum particles can be related to hair-like joints, which are abundant in the pervasive silicification, while the highly elongated ones – to filamentary electrum from small voids and to dendrites from colloform banded quartz-adularia veinlets described in [2, 5].

It is interesting to compare electrum from Khan Krum deposit to electrum/gold of different genetic type deposits. Chelopech deposit provides such opportunity because similar morphometric data were presented on gold from it [15]. The Chelopech deposit is one of the biggest and economically important gold-copper deposits in Bulgaria, of epithermal, high-sulfidation, acid-sulphate, volcanic-hosted type. The gold from Chelopech deposit is of high fineness (around 950) and its main morphological types include flattened, irregular, elongated and branched crystals which have nucleated in thin cracks, cleavages and intergranular fractures [15]. In comparison to gold from Chelopech deposit, electrum from the layer-like, pervasive silicification in Stenata outcrop, Khan Krum deposit, shows significant differences both in size and morphometric characteristics (Table 3): electrum is smaller in size, less flattened and more isometrical

Table 3

Comparison of gold from Chelopech deposit [15] and electrum from Stenata pervasive silicification, Khan Krum deposit, by size and morphometric characteristics

Size and morphometric characteristics	Mean value $\pm\Delta X$	
	Chelopech deposit	Khan Krum deposit
Length, µm	160±6	67±2
Width, µm	106±4	44±1
Thickness, µm	18.4±0.7	26.5±0.7
Equivalent circular diameter, µm	130±4	54±1
Equivalent spherical diameter, µm	67±2	43±1
Corey's shape factor	0.14	0.5±0.01

and spherical. This is due to the different geometry of the deposition medium in both deposits. Unlike Chelopech deposit, the major part of the electrum in Stenata outcrop (around 80%) is deposited together with quartz in the more isometrical medium of porous gravel and coarse polymict breccias and breccia-conglomerates and in small voids in the pervasive silicification. Much smaller part of it (around 20%) is deposited in highly anisometric medium analogous to the gold in Chelopech deposit.

Conclusions. 1) Electrum from layer-like pervasive silicification in Stenata outcrop, Khan Krum gold deposit, just above Tokachka Detachment Fault, is micron-sized, with mean values of 67 ± 2 µm in length, 44 ± 1 µm in width and 26 ± 1 µm in thickness. The size of electrum particles is comparable to that of the embracing quartz. 2) The electrum particles have mean values of: 0.65 for the sphericity, 0.5 ± 0.01 for the Corey shape factor, 2.3 ± 0.06 for the flatness ratio and 1.12 ± 0.02 for the isometry which points out that moderately flattened and almost isometrical and spherical particles are predominant. Highly flattened and highly elongated particles are rarely presented in the electrum population. 3) According to W/L and T/W ratios, the electrum particles belong to the following morphological groups of Payene: flat-spheroidal, flat-elongated-spheroidal, elongated-spheroidal and spherical particles. 4) The data obtained point to a joint nucleation of the major part of electrum and quartz of the pervasive silicification in the comparatively isometric medium of porous breccias and breccia-conglomerates of Shavar Formation. The highly flattened electrum particles are nucleated in hair-like joints, the highly elongated ones being filamentary electrum from small voids and dendrites from cross-cutting colloform banded quartz-adularia veinlets.

Acknowledgements. Thanks are due to the Balkan Mineral and Mining Co. for the permission to sample the Khan Krum deposit. The author is grateful to T. Kerestedjian for the critical remarks.

REFERENCES

[1] Kunov A., V. Stamatova, P. Petrova. Mining and Geology, 2001, No 4, 16–20 (in Bulgarian).
[2] Marchev P., B. Singer, D. Jelev, S. Hasson, R. Moritz, N. Bonev. Schweiz. Mineral. und Petrogr. Mitt., 2005, No 84, 59–78.
[3] Ilieva A. Master Thesis, Sofia, 2004 (in Bulgarian).
[4] Marinova I. Proc. of the Jubilee Inter. Confer, Sofia, 2005, 168–170.
[5] Marinova I. Proc. of the Nat. Confer. with Inter. Participation Geosciences 2006, Sofia, 2006, 113–116.
[6] Jelev D. Mining and Geology, 2006, No 7–8, 27–33 (in Bulgarian).
[7] Jelev D. Mining and Geology, 2006, No 9, 27–32 (in Bulgarian).
[8] Bonev N. Abstract of PhD Thesis summary, 2002, 42 p. (in Bulgarian).
[9] Goranov A., G. Atanasov. Geol. Balc., **22**, 1992, No 3, 71–82.
[10] Bonev N. Ann. Universite Sofia, **89**, 1996, No 1, 97–106.
[11] Marton I., R. Moritz, P. Marchev, T. Vennemann, J. Spangenberg. In: Au-Ag-Te-Se deposits, Izmir, Dokuz Eylul University, 2006, 116-123.
[12] Jelev D., S. Hasson. Review Bulgarian Geol. Soc., 2002, 58–59.
[13] Giusti L. Can. J. Earth Sci., **23**, 1986, 1662–1672.
[14] Wentworth C. J. Hob. geol., **27**, 1919, 507–521.
[15] Bonev I., T. Kerestedjian, R. Atanassova, C. Andrew. Mineralium Deposita, **37**, 2002, No 6–7, 614–629.
[16] Wentworth C. U.S. Geol. Survey Bull., 1922, 91–102.
[17] Sarkisian S., L. Klimova. Orientation of pebbles and methods of palaeogeographic reconstructions. USSR Acad. Sci., 165 p. (in Russian).
[18] Krumbein W. C. J. Sed. Petrology, **II**, 1941, No 2, 64–72.
[19] Payene T. Bull. American Ass. of Petrolium Geologists, **26**, 1942, No 11.
[20] Vuchev V. Bull. Geol. Institute – ser. Stratigraphy and Lithology, **XVIII**, 1969, 223–230 (in Russian).
[21] Marinova I. Compt. rend. Acad. bulg. Sci., **59**, 2006, No 9, 945–948.
[22] Tishchenko E., M. Tishchenko. Prospecting and preservation of Earth's womb, 1974, No 3, 52–54 (in Russian).

Academician Ivan Kostov Central Laboratory of Mineralogy and Crystallography
Bulgarian Academy of Sciences
Acad. G. Bonchev Str., Bl. 107
1113 Sofia, Bulgaria
e-mail: marinova@clmc.bas.bg