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Vertical mineralization interval and forecast of the position of an ore-body in the Alšar Sb–As–Tl deposit, FYR Macedonia

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Abstract. Establishing a vertical interval of mineralization is a complex geological task based on the knowledge of many parameters and quantities that describe the genesis of an ore deposit. It is particularly important to know the time and the primary depth of the formation of an ore-body and its recent position.

The establishment of the vertical mineralization interval is considered in this work on the example of the Alšar Sb–As–Tl mineral deposit. The research methods used were geomorphological analysis (the principal exploration method), measurement of cosmogenic radioactive (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides to determine the erosion velocity (control method) and comparison of the obtained results with the geological exploration data from operative mine workings. A detailed geological study of the formation of the Alšar deposit preceded the research.

The research data are the following: depth interval of the ore-body is 10–50 m below the present ground surface; average level of erosion in the Alšar deposit area is 20–80 m over a period of 10^6 years (Ma), or about 100–400 m from the beginning of the volcanic activity to the present day (≈5 Ma); thickness of the eroded rock complex over the ore bodies from the beginning of the hydrothermal alteration and the formation of ore bodies (4.31 Ma) to the present is ≥150 m (Crven dol), or ≥230 m (central deposit); the palaeointerval of the formation of the ore-body is 230 m (200–430 m); and, finally, the potentially mineralized interval is deep, from 10 m to 280 m below the surface.

Key words: vertical mineralization interval, geomorphology, cosmogenic nuclides, erosion rate, genesis, Alšar, Macedonia.

Апстракт. Одређивање вертикалног интервала распрострањења рудне минерализације је сложен геолошки задатак који подразумева познавање бројних параметара и величина које описују генезу лежишта. Од посебног значаја међу њима су познавање времена и примарне дубине стварања рудних тела, као и одређивање дубине њиховог данашњег положаја у простору.

Одређивање вертикалног интервала распрострањења рудне минерализације у овом раду, показано је на примеру Sb–As–Tl лежишта Алшар. Истраживања су извршена применом више метода: геоморфолошке анализе (основна метода истраживања), мерењем космогених радиоактивних (^{10}Be, ^{26}Al) и стабилних нуклида (^{3}He, ^{21}Ne) за одређивање брзине ерозије (контролна метода) и поређењем добијених резултата са подацима оперативних геолошких истраживања из рударских радова. Истраживањима су претходила детаљна студијска изучавања геолошке грађе и генезе лежишта Алшар.

Истраживањима су добијени следећи резултати: одређен је горњи интервал распрострањења рудних тела на дубини од 10–50 m од данашње површине терена; утврђен је просечни ниво ерозије терена за шире подручје лежишта Алшар у износу од 20–80 m за период од 10^6 година (Ma), односно ≈100–400 m за период од почетка вулканске активности на подручју лежишта до данас (≈5 Ma); утврђена је дебљина еродованог комплекса стена из повлатног дела рудних тела у периоду од почетка хидротермалне алтерације и стварања рудних тела (4,31 Ma) до данас, и износу ≥150 m (локалитет Црвен дол), односно ≥230 m (Централни део лежишта); утврђен је вертикални палеоинтервал стварања рудних тела у износу од 230 m (200–430 m) и, на крају, констатовано је да се потенцијално рудоносни хоризонт налази на дубини од 10–280 m од данашње површине терена.

Кључне речи: вертикални интервал минерализације, геоморфологија, космогени нуклиди, ниво ерозије, генеза лежишта, Алшар, Македонија.

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Introduction

Knowledge of the vertical mineralization interval is important for scientific research and for economic geology. Scientific research of an interval is necessary for the correct interpretation of the deposit formation, and economic geology for geological prediction of the spatial position of an ore body, rational design of exploratory work at the stage of detailed prospecting, possible delineation of ore bodies using a small volume of field work, high efficiency, and geological and cost-effective exploration.

How well a vertical mineralization interval is defined and the position of an ore-body is predicted depends on many geological attributes of the primary ore-body environment and the genetic model of its formation. Particularly important are the geology and structural geology of the region, the age of mineralization and the geological unit to which it is related in space and origin, the shapes of ore bodies and factors that controlled their spatial position, the mineral composition, the lateral and vertical zones of the distribution of the ore elements, the types of alteration, time and conditions of formation, *etc*.

Basically, the vertical interval of an ore body is established when its upper and lower boundaries are located in an explored mineral deposit, whereas its prediction requires knowledge of its formational palaeodepth, and velocity and level of erosion in the region. The prospecting activities include geological, geochemical, petrological and some other research, the commonest being the method of quantitative geomorphological analysis.

The primary depth of an ore-body formation and the depth of its recent interval are difficult to establish for hydrothermal mineral deposits that are spatially and genetically associated with the products of extensive and intensive volcanic processes in an environment heterogeneous in lithology and age. The Alšar Sb–As–Tl deposit in the FYR Macedonia is this type of mineral deposit.

The Alšar deposit was explored in detail from 1986 to 2011 under the LOREX Project (FREEDMAN *et al.* 1976; PAVIĆEVIĆ & AMTHAUER 1994; PAVIĆEVIĆ *et al.* 2004). A significant segment of exploration under the Project was the depth of thallium mineralization (primary lorandite) and its extraction from ore bodies in the Crven dol and Central part. The vertical interval of Sb–As–Tl mineralization in the Alšar deposit, the palaeodepths of the known ore bodies and potential environments of mineral ore localization were explored in 2011 under the LOREX Project, and under the Projects 176016 and 176019 financed by the Ministry of Education and Science of the Republic of Serbia. The basic search method used under the Projects was quantitative geomorphological analysis (GMA). For control and correction of the obtained results, the velocity and level of erosion were calculated through measurement of cosmogenic radioactive (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides.

Metallogenic position and basic geologic characteristics of the Alšar Sb–As–Tl deposit

The hydrothermal-volcanogenic Sb–As–Tl deposit Alšar is located on the NW slope of the Kožuf Mountain, FYR Macedonia, near the Greek border, which is a part of the Serbian–Macedonian metallogenic province, or the Kožuf ore assemblages (JANKOVIĆ & JELENKOVIĆ 1994; JANKOVIĆ *et al.* 1997; VOLKOV *et al*. 2006). The formation of the deposit is associated with the evolution of a complex intrusive volcanic structure of Pliocene age and the concomitant activity of hydrothermal ore-bearing systems.

The geology of the Alšar deposit has been studied in detail since 1960. The oldest lithologic members in the wider area of the deposit are dated Precambrian (albite gneiss, marble and mica schist) and the youngest geologic units are the Pliocene clastics, tufa, volcanic and pyroclastic rocks, and recent Quaternary deposits. Magmatism evolved in stages. Volcanism was central, developed over the intersection of regional-scale faults at the contact of Pelagonian Block and the Vardar Zone (BOEV 1988; KARAMATA *et al.* 1994; JANKOVIĆ *et al.* 1997; DUMURDZANOV *et al.* 2005; DIMANATOPULOS 2006; VOLKOV *et al.* 2006; BURCHFIEL *et al*. 2008).

The structural pattern of the Alšar deposit area is complex, composed of many ring structures and related fracture systems in different directions alongside regional faults of dominantly NW–SE to N–S (the Vardar direction) and E–W (Kožuf-Kukuš) trends.

Establishing the primary depth of the formation of the Sb–As–Tl ore bodies in the Alšar deposit was preceded by a study of its geology, identification of the primary and additional controls of the spatial position, shape, textural ore varieties, mineral composition and association of essential and minor elements of the ore-body. The age of volcanism, time of hydrothermal solution control, facies of hydrothermal alteration, time and order of their formation and dating the ore mineralization were given particular consideration. This was the basic information for establishing the primary formational depth of the ore bodies, which has been addressed since 1988.

The mentioned explorations determined Palaeozoic age of the schist, the oldest geologic unit in the Alšar deposit, and Triassic age of the silicified dolomite and marble. Geological and trial excavation prospecting in parts of the deposit revealed some sub-volcanic latite intrusions and sporadic presence of quartz latite, trachyte, andesite and dacite (Fig. 1). Most of the mentioned geologic units were covered by tuff and other pyroclastic materials in the closing phase of the geologic history (Ivanov 1965, 1986; Karamata *et al.* 1994; Percival & Radtke 1994; Janković & Jelenković 1994; Janković *et al.* 1997; Volkov *et al.* 2006).

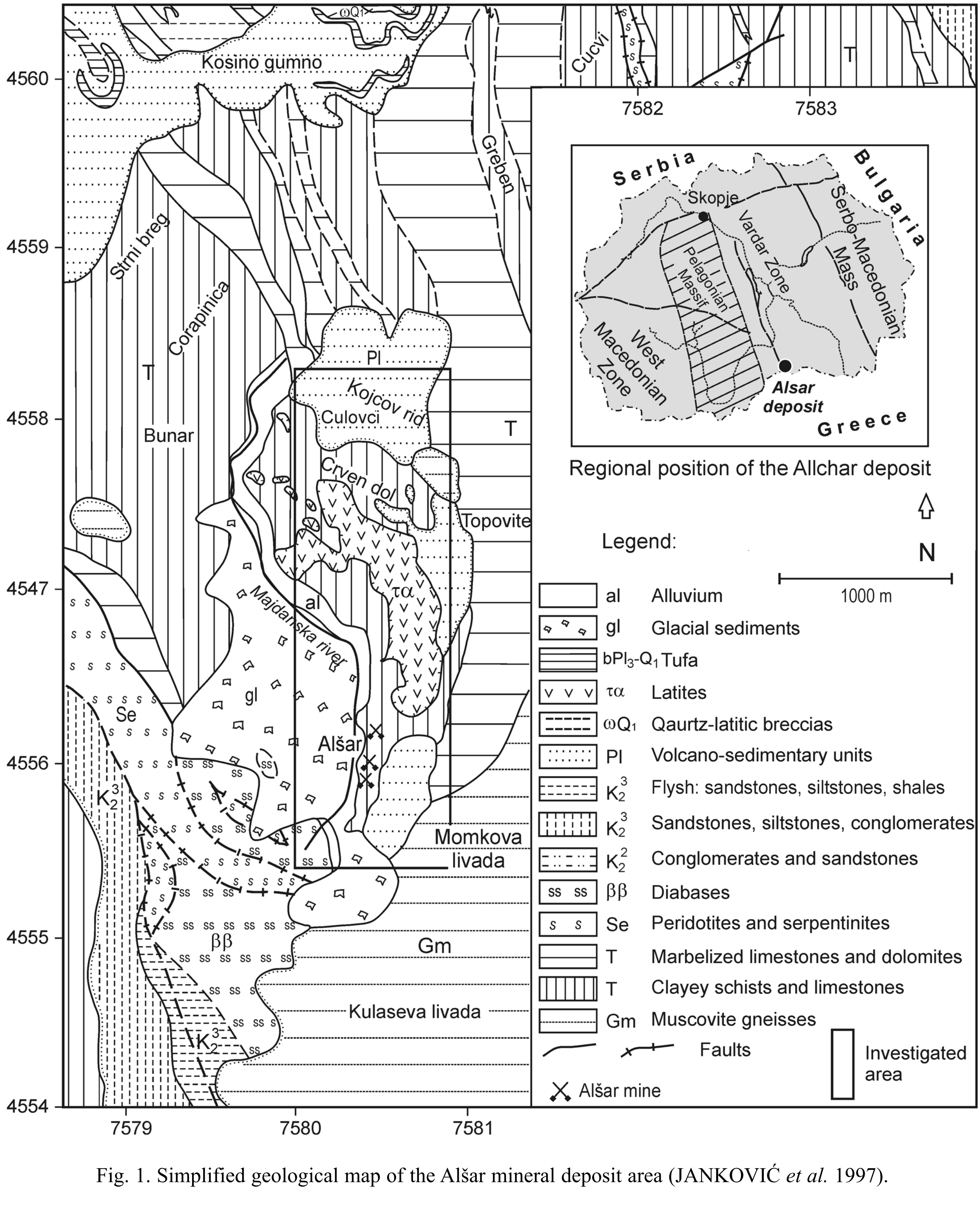

Fig. 1. Simplified geological map of the Alšar mineral deposit area (JANKOVIĆ *et al.* 1997).

The volcanic rocks of the Alšar deposit were dated using various methods on different minerals. The K/Ar method applied on sanidine from andesite and tuff dated it from 6.5 ± 0.2 Ma to 1.8 ± 0.2 Ma (Boev 1988; Troesch & Frantz 1992). The ages of biotite and feldspar from tuff at Vitačevo and Rudina were determined by the same method to be 5.1±0.1 to 4.31 ± 0.2 Ma and those of biotite, feldspar and pyroxene from andesite at Crven dol to be 6.5 ± 4.3 Ma to 3.9 ± 0.2 Ma (Lippolt & Fuhrmann 1986). The Ar/Ar method determined the age of biotite (5.78 ± 0.12 Ma), amphibole (4.8 ± 0.2–3.3 Ma) and K-feldspar (3.3–4.0 ± 0.2 Ma) from latite at Kojčov Rid (northern part of the Alšar deposit). In addition, crystallization temperatures were established for amphibole (550–500°C), biotite (300°C) and K-feldspar (250–160°C) (NEUBAUER *et al.* 2009).

Hydrothermal alterations of the rocks surrounding the ore bodies in the Alšar deposit indicated two main places of hydrothermal activity, one at a temperature of ≈400°C that ankeritised dolomite, and the other at temperatures from 280–250°C to ≈120°C when neighbouring rocks were intensively silicified, argillitised, decalcified and dolomitised. Ore minerals were deposited in the latter phase of the hydrothermal activity, during the intensive rock alteration before 4.31 ± 0.02 Ma (Rudina location) (JANKOVIĆ *et al.* 1997; VOLKOV *et al.* 2006).

The primary source of ore elements building the Alšar deposit was the continental crust. Most of the mineral elements were primarily associated with calc-alkali magmatic rocks of Pliocene age. A far smaller proportion of ore elements originated from the surrounding geologic formations. Sulphur was derived from a heterogeneous source; in the Alšar sulphide minerals, it was mainly of volcanic origin, from some magma chamber. However, the values of $\delta^{34}S$ vary within a range from +2.03 ‰ to +3.93 ‰, mean +2.92, whereas the isotope $\delta^{18}O$ was between +14.92 ‰ and 28.72 ‰. The fluid salinity is fairly low (7.9–12.9 wt. % NaCl). Ore elements were transported in the form of complex ions (bisulphides) from the primary sources to the locations of deposition or of ore-body formation by acidic to mildly alkaline hydrothermal brines in an oxidizing environment, partly also as colloids in weakly reducing conditions. The temperature range for most ore minerals was 120–200°C (SERAFIMOVSKI 1990; BALIĆ-ŽUNIĆ *et al.* 1993; BERAN *et al.* 1994; JANKOVIĆ & JELENKOVIĆ 1994; JANKOVIĆ *et al.* 1997; VOLKOV *et al.* 2006).

The principal factors controlling the positions of the Alšar ore bodies were lithology and structure. The lithologic controlling factors includes heavily crushed and hydrothermally altered Triassic dolomites and marbles and contact zones of carbonate with volcanic rocks (andesite, latite, quartz latite) and the associated Pliocene volcanogenic–sedimentary products (tuffaceous dolomite). Faults and secondary fracture systems, bedding planes in carbonate rocks and their contacts with volcanic rocks were the structural controlling factors.

The varied and eventful geohistory of the Alšar deposit region and its complex geology controlled by polyphase magmatism and recurring pulsation of mineral-bearing fluids led to the formation of ore bodies different in morphology, texture and mineral composition.

Massive realgar bodies emplaced in dolomites, ore bodies of similar textural features in dolomite contact zones with sub-volcanic intrusions and zones of brecciation, and impregnations of Tl–As minerals localized in carbonate rocks, all complex in morphology, are prevailing in the northern part of the deposit (Crven dol).

Centrally located in the Alšar deposit are ore lenses in carbonate rocks and associated stockwork impregnations (dominantly ore of the realgar type), elongate-lenticular to vein-like pyrite/marcasite or bodies and antimonite-prevailing ore bodies, then complex, irregular lens-like and columnar antimonite ore bodies and accessory pyrite, marcasite and gold (at contacts of basal tuffaceous dolomite and tuff with carbonate rocks that include silicified and argillitised volcanic rocks), and pyrite–marcasite and stibnite bodies with accessory As–Tl sulphides localized in silicified dolomite.

The Alšar deposit has a complex mineral composition. Pyrite with marcasite formed in an early stage of the deposit; then followed hydrothermal activity that produced arsenopyrite, antimonite and sulphosalt Sb–Pb, and the process of mineral deposition ended with the formation of realgar, orpiment and Tl-sulphosalt (PAVIĆEVIĆ & El GORESY 1988; SERAFIMOVSKI *et al.* 1990; BALIĆ-ŽUNIĆ *et al.* 1993; JANKOVIĆ 1993; BERAN *et al.* 1994; FRANTZ 1994). The identified group of ore minerals was used to determine geochemical associations of elements in the Alšar deposit. The main ore elements were found to be Sb, As, Tl and Au, and minor elements were Hg and Ba. In addition, there are Pb, Zn and Cu in traces. The elevated Tl concentration is related to parts of the deposit where As, Sb and Hg are elevated (JANKOVIĆ 1960; PALME *et al.* 1988; JANKOVIĆ 1993; PAVIĆEVIĆ *et al.* 2010). All the aforementioned associations of ore elements characteristically have a lateral zonal distribution. Thus, As–Tl, less Sb, locally Hg and Au are prevalent in the north; Sb–Au, less As, Tl, locally Ba, Hg and Pb traces in the central, and Au and minor Sb are dominant in the southern parts of the deposit (IVANOV 1965; JANKOVIĆ *et al.* 1997).

The vertical interval of the mineral ore in the Alšar deposit is widely variable. It is comparatively short in the reactive environment of dolomite and its contact zone with volcanic rocks. In a weakly reactive geological environment, however, such as silicified dolomite, tuffaceous dolomite, felsitic tuff and argillitisation zones, the interval is ≈150–200 m. The determined vertical ore body interval is ≈50–100 m (depth ≈840–760 m) in the north and ≈75 m (depth ≈850–775 m) in the central Alšar (IVANOV 1965; JANKOVIĆ *et al.* 1997).

Determination methods of the vertical mineralization interval

The vertical interval of the Alšar Sb–As–Tl mineralization was determined through three steps. The first two steps were establishing the base level of erosion, first by geomorphological analysis (GMA) and second by cosmogenic radiation (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides. In the last step, the obtained results were correlated and refined with the ore-body depth data from underground mining. The internal activity of data interpretation and drawing was performed alongside extramural explorations.

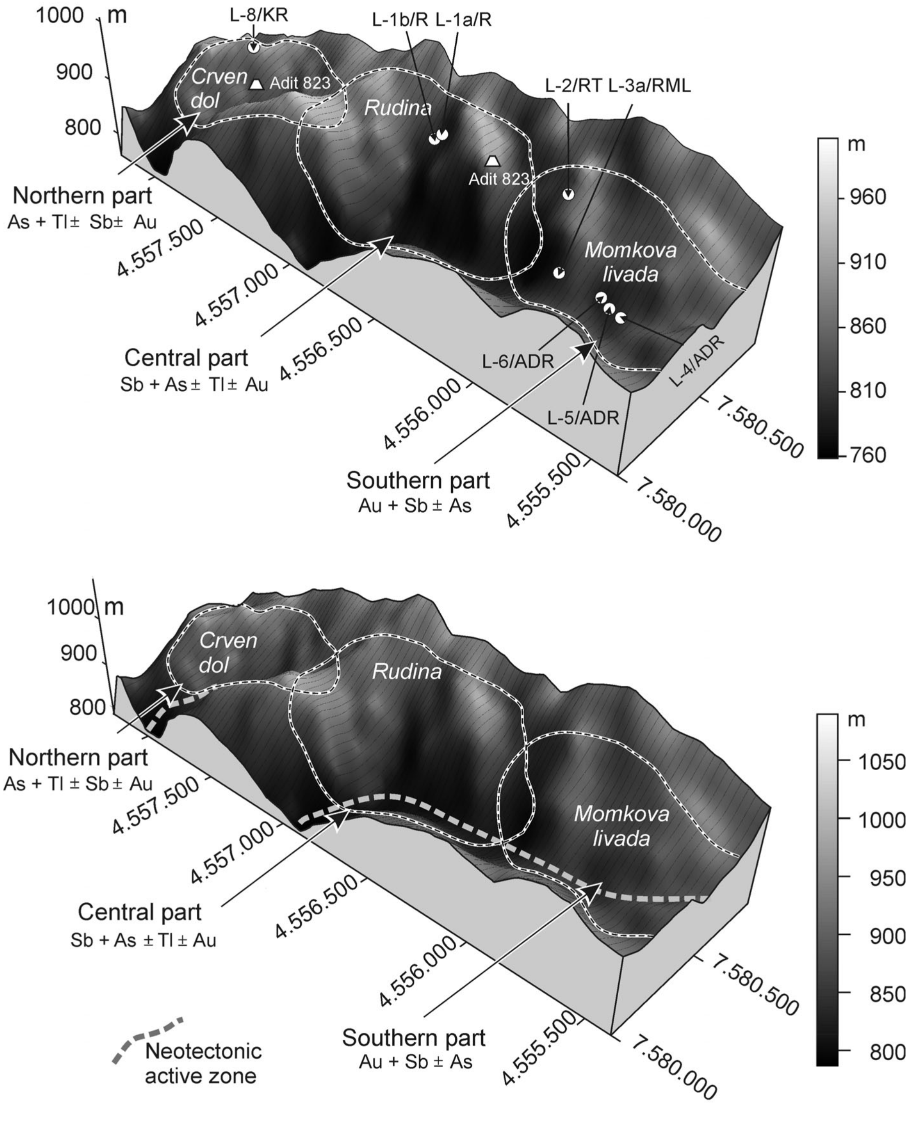

Fig. 2. Upper: 3D representation of the Alšar deposit area proper with delineated northern, central and southern parts, ore element associations, locations of Crven dol and Central part, sampling places and sample symbols for 2nd stage of the exploration. Lower: 3D palaeorelief of the Alšar deposit proper.

The first step methods and results

Several methods of qualitative and quantitative geomorphological analysis were employed in the first stage of determining the vertical interval of ore mineralization in the Alšar mineral deposit.

A qualitative geomorphological analysis of the Alšar region included interpretation of topographical and geological maps at the scales 1:100,000 and 1:25,000. The quantitative geomorphological analysis embraced treatments of the following: potential relief intensity, land slopes, comparison of the actual state of relief to the theoretical model, theoretical analogue of longitudinal stream sections, theoretical model of relief change in time and analysis of the erosion integral. The two substage research was realised in an area of 6 km^2.

In view of the previously determined age of volcanic activity in the Alšar region, the onset of the hydrothermal activity and the age of ore mineralization, the level of erosion was established for a period of 5 Ma. The unit field area, from which topographical and geological information was collected and further prospected, was 1 km^2. A detailed quantitative geomorphological analysis was made for the northern (Crven dol) and central (Central part) parts of the Alšar deposit, the locations in which Sb–As–Tl ore bodies were explored earlier in boreholes and adit excavations under the LOREX project. Since the morphology of the ore bodies, the recent interval of the ore bodies and controlling factors of their spatial position were determined in the two locations, they were used in the third step as gauges for amendment of geomorphological data. The level of erosion was established for the mentioned locations for the periods of five and one million years. The unit area for the calculation was 0.25 km^2 for the latter period (JELENKOVIĆ & PAVIĆEVIĆ 1994). Upon thorough consideration of all data, or geological and geostatistical processing, and reference to the elevation differences of the land surface, further analysis in either case used the potential energy of relief, the first trend of the height and slope variation.

A potential energy relief map was constructed and, using the method of current mean values, translated into a map of the first trend vertical breakdown of the relief. Based on this map, areas of positive and negative elevations, or parts of the considered space in which ground is slowly rising or sinking, were denoted on a topographical map. Comparison of the topographical and geological maps revealed that the sinking parts of the terrain were bounded by large faults, or were the geomorphologic features suitable for accumulation of waste materials, located in the catchment of the Majdanska River and its major tributaries.

The rising part of the terrain WSW and ESE in the research area is interpreted as landforms of intensive erosion, and the land between the rising and the features of waste accumulation are interpreted as active neotectonic structures. A map of the surface slope angles was prepared to determine the potential erosion. The level of erosion was established by deducting the recent land surface area from the palaeorelief applying the software package Surfer 9. The resulting surface is graphically represented in Fig. 2.

The mean level of erosion, indicated by the data obtained for the greater Alšar deposit for a period of five million years is ≈250 m, or within the interval from ≈100 m to 400 m, locally higher. Mean velocities of erosion were 37 m/Ma and 54 m/Ma at Crven Dol (northern part of the deposit) where the As–Tl ore bodies were well explored and in the old mine workings over the Sb–As–Tl ore bodies, respectively.

Second stage - methods and results

The levels of erosion were determined in the second stage of this research by application of cosmogenic radioactive (^{10}Be, ^{26}Al) and stable (^{3}He, ^{21}Ne) nuclides. Two methods of research were employed: first, AMS or accelerated mass spectrometry of the long-life radioactive cosmogenic nuclides ^{10}Be and ^{26}Al (PRIME Lab – Purdue Rare Isotope Measurement Laboratory, Purdue University) and second, MS or mass spectrometry of the noble gases or stable cosmogenic nuclides ^{3}He and ^{21}Ne (Geoforschungs Zentrum, Potsdam). The laboratory measurements were preceded by field sampling of silicified rocks (enriched by hydrothermal metasomatic quartz) from several places in the Alšar deposit and of sanidine and diopside, and their detailed petrological and mineralogical examinations by optical microscopy, X-ray diffraction and SEM–EDX. The methods for producing pure stoichiometric quartz were described by PAVIĆEVIĆ *et al.* (2006), whereas analytical MS treatments and methods for the isotopes ^{3}He and ^{21}Ne were described by NIEDERMANN *et al.* (1997) and NIEDERMANN (2002). The results of the AMS and MS measurements were further mathematically treated to estimate the erosion velocity or its level for a period of 10^6 years, and the conclusions are summarized in Table 1.

The isotope ^{10}Be and the ratio ^{10}Be/Be in BeO (1σ = 3–5 %) were determined in sixteen samples by AMS. The spectroscopy results were used to calculate the velocity and thickness of the eroded overburden, which varied within the range from 3.4 ± 0.5 m/Ma to 14.7 ± 1.8 m/Ma and were lower than the corresponding values determined by other methods.

The isotope ^{26}Al and the ratio ^{26}Al/^{27}Al in Al_2O_3 (1σ = 26–87 %) were determined in 21 samples. The erosion level of the rock complex overlying the Sb–As–Tl ore bodies was estimated to vary from a minimum of 67 ± 24 m/Ma to a maximum of 640 ± 150 m/Ma. These values are higher in relation to the erosion intensity obtained from the quantitative geomorphological analysis and from other analytical treatments in the study of cosmogenic radioactive and stable nuclides.

The isotopes ^{21}Ne and ^{3}He were measured in quartz by the NG MS method (samples from three different locations), in sanidine (one location) and in diopside (two locations). The results were similar, in some instances two-times higher than those resulting from the quantitative geomorphological analysis, For example, the erosion velocity determined by quartz sample analysis was ≥22–51 m/Ma, for ^{21}Ne in sanidine ≥69 (1σ = 10 % – 60 %), and ≥15 m/Ma for ^{3}He in diopside.

Discussion

The conclusions based on an analysis of the information presented above are the following:

1. The level and velocity of soil erosion in the greater Alšar deposit, in the past 5 Ma, the period from the onset of the volcanic activity and hydrothermal-mineralization activity to the present, were not uniform over the study area. The qualitative and quantitative geomorphological analyses revealed that the eroded overlying rocks were ≈100–400 m thick in the northern and central Alšar deposit containing economic ore bodies, and that average erosion velocity range was 20–80 m/Ma.
2. A study of the cosmogenic radioactive and stable nuclides indicated some similarities between them, but also certain dissimilarities. A high agreement was noted in of the data produced by the quantitative geomorphological analysis and the study of the isotopes ^{10}Be, ^{3}He and ^{21}Ne. The isotope ^{26}Al, however, demonstrated significant difference from the results obtained by other employed methods.
3. Further interpretation and metallogenetic analyses gave different GMA and AMS data that resulted from the following factors: (1) the high ^{27}Al concentration in hydrothermal quartz, associated with the formational conditions, type of volcanism and hydrothermal activity; (2) limitations of the applied analytical method, or the high threshold of its sensitivity (1×10^{-15}), and (3) different lengths of time for which the level of erosion was calculated (≈40,000 years) in re-

Table 1. Signs, locations and types of materials sampled for the study of cosmogenic nuclides and the determined erosion velocities (sample position denoted in Fig. 2). Abbreviations: al - albite; ap - orpiment; ba - barite; D - hydrothermally altered dolomite; di - diopside; Feh - Fe-hydroxide; ja - jarosite; M - hydrothermally altered and mineralized rocks without visible relics of their primary texture; mr - marcasite; py - pyrite; q - hydrothermal quartz; re - realgar; sa - sanidine; sc - scorodite; se - sericite; st - stishovite; V - hydrothermally altered and mineralized volcanoclastics; GMA - geomorphological analysis; S-1, S-2, S-3 - sample numbers; na - not analysed.

Location	Sampled materials	Thickness of the eroded rocks + / – error of determination (m/Ma)				
		^{10}Be	^{26}Al	^{21}Ne	^{3}He	GMA
L-1a/R	S-1: D, q, py, mr, sa, Feh. S-2: V, q, ja, mr.	na	na	= 69 +145/28	na	50 ± 10
L-1ba/R	q	14.7 ± 1.8	400 +120	51 +99/21	na	50 ± 10
L-2/RT	S-1: M, q, sc, re, ba, Feh. S-2: V, q, re, ap, sc, se, Feh. S-3: q.	5.4 ± 0.6	na	41 +24/14	na	46 ± 9
L3a/RML	V, q, se, ja, Feh.	5.1 ± 0.7	67 ± 24	39.4 +16/9	na	28 ± 6
L-4/ADR	S-1: V, q, se, mr, ba, ja, Feh. S-2: q.	4.2 ± 0.5	94 ± 19	40.8 +22/11	na	27 ± 5
L-5/ADR	V, q, se, mr, ba, Feh.	5.6 ± 0.7	345 ± 100	22 +2.6/2.1	na	30 ± 6
L-6/ADR	V, q, se, mr, ja, sc, Feh.	3.4 ± 0.5	640 ± 150	na	na	27 ± 5
L-8/KR	V, al, di, st.	na	na	na	≥15	40 ± 8

lation to the method of geomorphological analysis (5 Ma and 1 Ma).

4. The differences in the ^{26}Al/^{10}Be value as a function of ^{10}Be may be explained as being the consequence of any of the following: (1) linear erosion (steady-state irradiation history); (2) the presence of overlying rocks above the productive mineral-bearing interval with hydrothermal quartz that shielded it from radiation for a period of time (shielding from radiation); and (3) the complex history of the erosion processes (complex irradiation history). In view of the complexity of geohistory and metallogenic evolution, or the complexity of geology and evolution of the given region, case (3) seems to be the most likely event. Although the cosmogenic radionuclides ^{26}Al and ^{10}Be are the interaction products between cosmic radiation and hydrothermal quartz, their relationship (^{26}Al/^{10}Be) changed over time. Besides the dependence expressed by their different half-life (0.71 Ma for ^{26}Al and 1.36 Ma for ^{10}Be), this is also a consequence of the facts that sampling places from the time of hydrothermal quartz formation (4.31 Ma) to the present were repeatedly covered with pyroclastic materials, erosion rock debris from higher elevations and, later, with ice. When the ice melted, probably some 12,000 years ago, the sampled rocks were exposed to cosmogenic radionuclides and to intensive erosion which was determined using ^{26}Al and ^{10}Be. Different reference data and moraines in the immediate proximity of the Alšar deposit suggest that the rocks above an elevation of 1800 m were ice-covered. In view of the level of erosion determined by the quantitative geomorphological analysis for a period of 5 Ma, and of the calculated exposure period of the sample rocks to cosmic radiation of 10,000–85,000 years and the ≥2 Ma ground coverage with pyroclastic materials, the error of most the erosion level values is of the order of that for the quantitative geomorphological analysis (25 %).

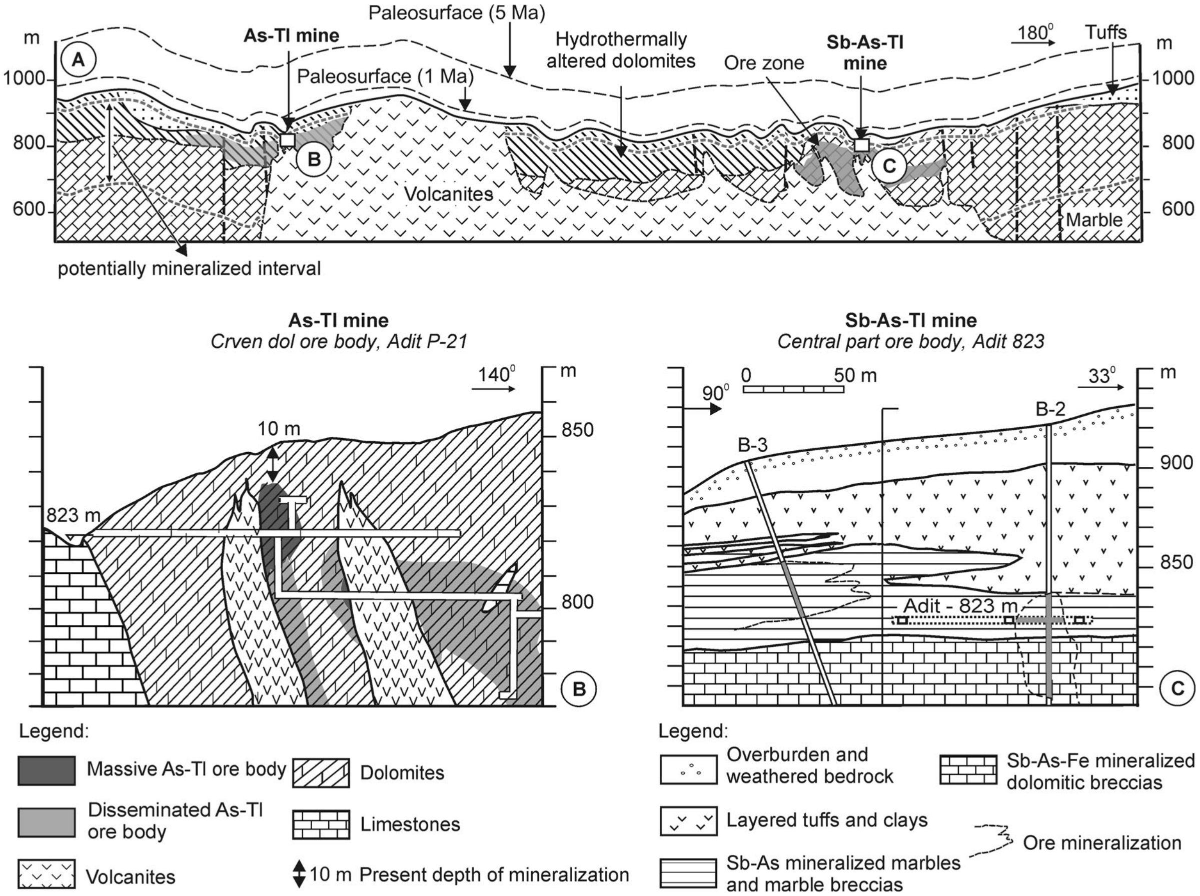

Fig. 3. A: Simplified geologic cross-section of the Alšar Sb–As–Tl deposit showing palaeosurfaces for different periods (5 Ma and 1 Ma), positions of the ore bodies and potentially mineralized rocks in the As–Tl mine (Crven dol) and the Sb–As–Tl mine (Central) locations. B: Characteristic geological cross-section at Crven dol (adit 823 m) and C: Characteristic geological cross-section at the Central part (adit 823 m) showing the positions of the identified ore bodies and the vertical intervals of ore mineralization verified in underground workings.

5. The average depth of erosion over the As–Tl ore bodies (Crven Dol) in the northern Alšar deposit was calculated to be 36 m for a period of million years (Fig. 3). The average depth of erosion in the Central area of the Sb–As–Tl ore bodies, where the old mine workings are located, was 54 m. Since the deposition of the minerals is associated with a period 4.31 ± 0.02 Ma and was concomitant with the onset of intensive hydrothermal alteration of the rocks surrounding the ore bodies, the average thickness of the eroded overlying rock complex should be ≈150–230 m.
6. The upper contour of the ore bodies in Crven dol, northern Alšar, is ≈10 m below the land surface. The mean depth of the ore bodies in the Central area is ≈50 m at present. In view of the abovementioned thickness of the overlying eroded rocks, the palaeodepth of the Sb–As–Tl ore-body formation in the Alšar deposit varied from 165 m to 380 m.
7. Vertical interval of the Alšar ore minerals was found by geological prospecting and excavations to be ≈80 m thick (depth interval 760–840 m) in Crven dol and ≈75 m (depth interval 775–850 m) in the Central area. The palaeointerval of their formation varied from 200 m to 430 m, or was ≈230 m. This value agrees with the vertical mineralization interval of most of the low- to medium-temperature hydrothermal mineral deposits, the duration of which is associated with young volcanogenic-intrusive complexes of calc-alkali magma (interval 200–300 m in length).
8. The position of a potentially mineral-bearing interval to be searched geologically is located at depths from 10 m to 280 m from the ground surface (Fig. 3).

Conclusions

The presented data may lead to the conclusion that the method of quantitative geomorphological analysis gives reliable information on the level and velocity of erosion used in preliminary and detailed prospecting for mineral resources, and for their geological exploration. Compared to the methods of the erosion level and velocity study by measurement of stable and radioactive cosmogenic nuclides, GMA has many advantages, such as comparatively simple application, fast operation and low cost.

The limitations of quantitative geomorphological analysis are many compared to other methods for the determination of the velocity and level of land erosion. Unlike other methods that give fairly reliable information on the erosion levels for geographically well-defined sampling microlocations, the GMA data are approximations, interpretations of the statistically processed information drawn on corresponding maps. For this reason, the level of erosion determined by GMA for accurately defined geographical locations mainly differs from the actual erosion values. Another group of limitations is related to the personal attitude of the researcher using GMA, or the subjective approach to the interpretation of the geologic evolution of the region. Additional factors affecting the accuracy of the calculation the level and velocity of erosion by GMA are: the scales of the geological and topographical maps used, the surface areas of the individual blocks from which data were collected for calculation of the erosion level and the calculation time interval. The quantity of the calculation error increases with increasing scale of the maps employed and the period for which the erosion is determined. For the scales of the maps used and the time interval for which the erosion level was determined, the mean calculation error empirically determined for the Alšar deposit area was ±25 %. The palaeodepth of the ore body formation was accordingly defined as an interval ≈120–350 m below the ground surface.

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Резиме

Вертикални интервал минерализације и прогноза положаја рудоносног нивоа у Sb–As–Tl лежишту Алшар (БЈР Македонија)

Одређивање вертикалног интервала распрострањења рудне минерализације је везано са бројним питањима генезе лежишта, и посебно, одредбом времена и палеодубине стварања рудних тела. У овом раду, извршено је на примеру Sb–As–Tl лежишта Алшар применом комплекса метода геоморфолошке анализе као основних метода истраживања, изучавањем радиоактивних (^{10}Be, ^{26}Al) и стабилних (^{3}He, ^{21}Ne) космогених нуклида (контролна метода) и поређењем добијених резултата са подацима оперативних геолошких истраживања из рударских радова. Истраживањима су претходила детаљна студијска изучавања геолошке грађе и генезе лежишта Алшар на основи којих је оно сврстано у класу сложених хидротермално-вулканогених лежишта плиоценске старости изграђених од више морфоструктурних типова рудних тела, комплексног минералног састава. Утврђена је старост вулканске активности, старост доминантних фација хидротермалних алтерација и рудне минерализације.

Квантитативна геоморфолошка анализа ширег простора лежишта Алшар обухватила је примену више поступака: поступак анализе енергије рељефа терена, анализу нагиба падина терена, поступак поређења реалног стања рељефа са теоријским моделом, поступак теоријског аналогона уздужног профила водотока, теоријски модел развоја рељефа у времену и анализу ерозионог интеграла. Истраживања су спроведена у две подфазе, на површини од 56 km^2, на ширем простору лежишта и на површини од 6 km^2 (ужи простор лежишта).

Ниво ерозије је одређен за период од 5 милиона година. Површина јединичног прорачунског поља износила је 1 km^2 и 0,25 km^2. Детаљна квантитативна геоморфолошка анализа је спроведена у локалитетима Црвен дол и Централни део у којима су претходних година истражним бушењем и рударским истражним радовима вршена детаљна геолошка истраживања Sb–As–Tl рудних тела. Будући да су у поменутим локалитетима детаљно утврђене морфолошке карактеристике рудних тела, вертикални интервал распрострањења рудне минерализације и контролни фактори њиховог положаја у простору, она су у трећој фази рада коришћена као

еталони за корекцију података геоморфолошке анализе. После детаљног сагледавања, геолошке и геостатистичке обраде улазних података праћене анализом вертикалне расчлањености рељефа, даља анализа терена у оба случаја извршена је применом поступака енергије рељефа терена, првог тренда енергије рељефа терена и нагиба падина терена.

У даљем току рада, конструисана карта енергије рељефа је методом текућих средњих вредности преведена у карту првог тренда вертикалне расчлањености рељефа. На основу ње су затим, на топографској основи издвојени простори са позитивним и негативним вредностима изолинија, односно делови анализираног простора у којима је вршено лагано издизање или спуштање терена. Зоне издизања терена су интерпретиране као простори интезивније ерозије, док су делови терена који се налазе између зона издизања и зона акумулације еродованог материјала, интерпретирани као неотектонски активне структуре. Одређивање нивоа ерозије терена извршено је одузимањем површи савременог рељефа од површи палеорељефа терена применом софтверског пакета Surfer 9.

Друга фаза рада је подразумевала одређивање нивоа ерозије применом космогених радиоактивних (^{10}Be, ^{26}Al) и стабилних (^{3}He, ^{21}Ne) нуклида применом метода акцелераторске масене спектрометрије дугоживећих радиоактивних космогених нуклида ^{10}Be и ^{26}Al и масене спектрометрије племенитих гасова или стабилних космогених нуклида ^{3}He и ^{21}Ne. Лабораторијским испитивањима су претходила теренска узорковања хидротермалног кварца са више локалитета лежишта Алшар, њихова детаљна петролошка и минералошка испитивања применом метода оптичке микроскопије, X-ray дифракције и SEM-EDX.

Изучавање изотопа ^{10}Be и односа ^{10}Be/^{9}Be у BeO (1σ = 3–5%), извршено је на 16 узорака применом AMS методе. На основи добијених података, срачунати су брзина и дебљина еродованог повлатног комплекса стена рудних тела у износу од 11–31 m/Ma. Изучавање изотопа ^{26}Al и односа ^{26}Al/^{27}Al у Al_2O_3 (1σ = 26–87%), извршено је на 21 узорку. Процењен је ниво ерозије у износу од минимум 67 ± 24 m/Ma до максимум 640 ± 150 m/Ma, што је знатно више у односу на вредности које су добијене применом квантитативне геоморфолошке анализе. Мерења изотопа ^{21}Ne и ^{3}He извршена су у хидротермалном кварцу применом MS методе (пробе са три различита локалитета), у санидину (једна локација) и у диопсиду (две локације). Добијени резултати се крећу у распону ≥22–51 m/Ma за ^{21}Ne у кварцу, ≥69 за ^{21}Ne у санидину (1σ = 10–60%), и ≥15 m/Ma за ^{3}He у диопсиду.

На основу претходно изложених података закључено је да су ниво и брзина ерозије терена на ширем подручју лежишта Алшар, у протеклих 5 Ma у периоду од почетка вулканске и хидротермалноминерализационе активности до данас, били су различити у различитим деловима анализираног простора. У северном и централном делу Sb–As–Tl лежишта Алшар у коме се налазе економски најзначајнија рудна тела са повишеним концентрацијама талијума, применом метода квалитативне и квантитативне геоморфолошке анализе утврђено је да дебљина еродованог комплекса повлатних стена износи ≈100–400 m. Просечна брзина ерозије терена кретала се од 20–80 m/Ma.

Поређењем добијених података са резултатима изучавања космогених радиоактивних и стабилних нуклида, уочене су одређене сличности али и разлике. Висок степен подударности података уочен је између резултата који су добијени применом методе квантитативне геоморфолошке анализе и резултата изучавања изотопа ^{10}Be, ^{3}He и ^{21}Ne. У случају изотопа ^{26}Al, међутим, одступања од резултата других метода су значајна.

Коначни закључци примењених истраживања су следећи: *а*- горњи интервал распрострањења рудних тела налази се на дубини од 10–50 m од савремене површине терена, *б*- просечни ниво ерозије терена на ширем подручју лежишта Алшар износи 20–80 m за период од 1 Ma, односно ≈100–400 m за период од времена почетка вулканске активности до данас (≈5 Ma); *в*- дебљина еродованог комплекса стена из повлатног дела рудних тела у периоду од почетка хидротермалне алтерације и стварања рудних тела (4,31 Ma) до данас износи ≥150 m за локалитет Црвен дол, односно 230 m за централни део лежишта; *г*- вертикални палеоинтервал стварања рудних тела износи ≈230 m (200–430 m) и *д*- потенцијално рудоносни хоризонт налази се на дубини од ≈10–280 m од савремене површине терена.