Heavy Minerals in Alluvial Sediments of the Boca River (Nízke Tatry Mts., Slovakia)

ALEXANDER SMIRNOV* and MARTIN CHOVAN**

Department of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, 84215 Bratislava, Slovakia
**To whom correspondence should be addressed: Martin Chovan, phone: +421 (0)2 60296298, email: chovan@fns.uniba.sk
* Present address: Department of Geosciences, State University of New York, Stony Brook, NY 11794-2100, USA

Abstract. Mineralogical studies of pan-samples from the Boca River revealed a wide variety of heavy minerals. Anatase, apatite, arsenopyrite, barite, carbonates, cinnabar, epidote, garnets, gold, chlorites, ilmenite, magnetite, micas, monazite, quartz, pyrite, rutile, scheelite, titanite, xenotime, zircon as well as anthropogenic material were identified. With the exception of cinnabar and scheelite, provenance of all minerals can be assigned to one or more rock complexes and/or ore mineralizations present in the drainage area of the Boca River and its tributaries. Alluvial gold reaches considerable concentrations and was actively exploited in the past.

Keywords. heavy minerals, gold, alluvium, provenance, Nižná Boca

Introduction

The idea of studying heavy minerals in the Boca River alluvial sediments was originally spurred by our investigations of ore mineralizations in the area of the Nižná and Vyšná Boca Villages (Smirnov, 2000). The objective of this study is to: a) characterize heavy minerals in alluvial sediments in a qualitative and quantitative manner; b) attempt to resolve the provenance of heavy minerals; c) map the area with preserved man-made features of alluvial gold exploitation.

Area Description

The Boca River is located in the Bocianska dolina Valley (Fig. 1), south of Liptovský Hrádok. The valley stretches in a general N-S direction with an approximate length of 17 km. The Boca River originates on the northern slopes of the Ďumbierske Nízke Tatry Mountains, 400 m northeast of the Kumštové saddle. The longitudinal profile and stream gradient for each kilometer of the Boca River is shown in Fig. 2 and Fig. 3, respectively. The Boca River has a stream gradient of 260 m/km (14.6°) at its headwaters with a gradual decrease to 6 m/km (0.3°) towards the mouth. The slope of the river [°] was calculated as $tan^{-1}*(\Delta y/x)$, where Δy is the altitude difference per 1 km of river (x).

The Boca River's headwaters cut through rocks of the Tatric crystalline basement. Its middle and lower courses cut through the Late Paleozoic and Triassic rocks of the Hronicum tectonic unit (Fig. 1).

In the headwater area, the Tatric crystalline massif is represented mainly by biotite to two-mica paragneisses and by granitite rocks of two types: the Ďumbier and the Králička (Biely et al., 1992). Other types of metamorphic rocks, such as garnet–biotite gneisses, orthogneisses or metaquartzites, are present to a lesser extent. The Ďumbier-type granitoid is represented by biotite tonalities to granodiorites (metaaluminous I-type granitoid) (Petrík et al., 1993). Cambel et al., (1990) calculated a crystallization temperature of 670–700 °C and age of ~368±22 Ma. The Králička-type granitoid is less abundant and was classified by Petrík et al., (1993) as peraluminous S-type granitoid with a crystallization temperature of 670 – 690 °C and age of 365±17 Ma.

The Variscan Tatric basement is enveloped by Mesozoic sequences. Preserved remains of the sedimentary cover are made up of Lower Triassic quartzites and sandstones. The central part of the studied area is built of a megastructural, Alpine-formed, Hronicum unit, which consists of several nappes. Late Paleozoic volcano-sedimentary sequences (Upper Carboniferous - Permian in age) are represented by conglomerates, sandstones, siltstones, shales, tholeiite basalts and andesites, tuffites and tuffaceous sandstones. Basal complexes of the Hronic nappe are referred to as the Ipoltica Group and consist of the Nižná Boca and Malužiná Formations. Triassic sequences are represented by sandstones and quartzites (Scythian), shales and sandstones (Carnian), gray and white dolomites (Amnesia-Norian), hauptdolomites (Carnian-Norian) and Dachstein limestones (Norian) (Vozárová & Vozár, 1988; Biely & Bezák, 1997).

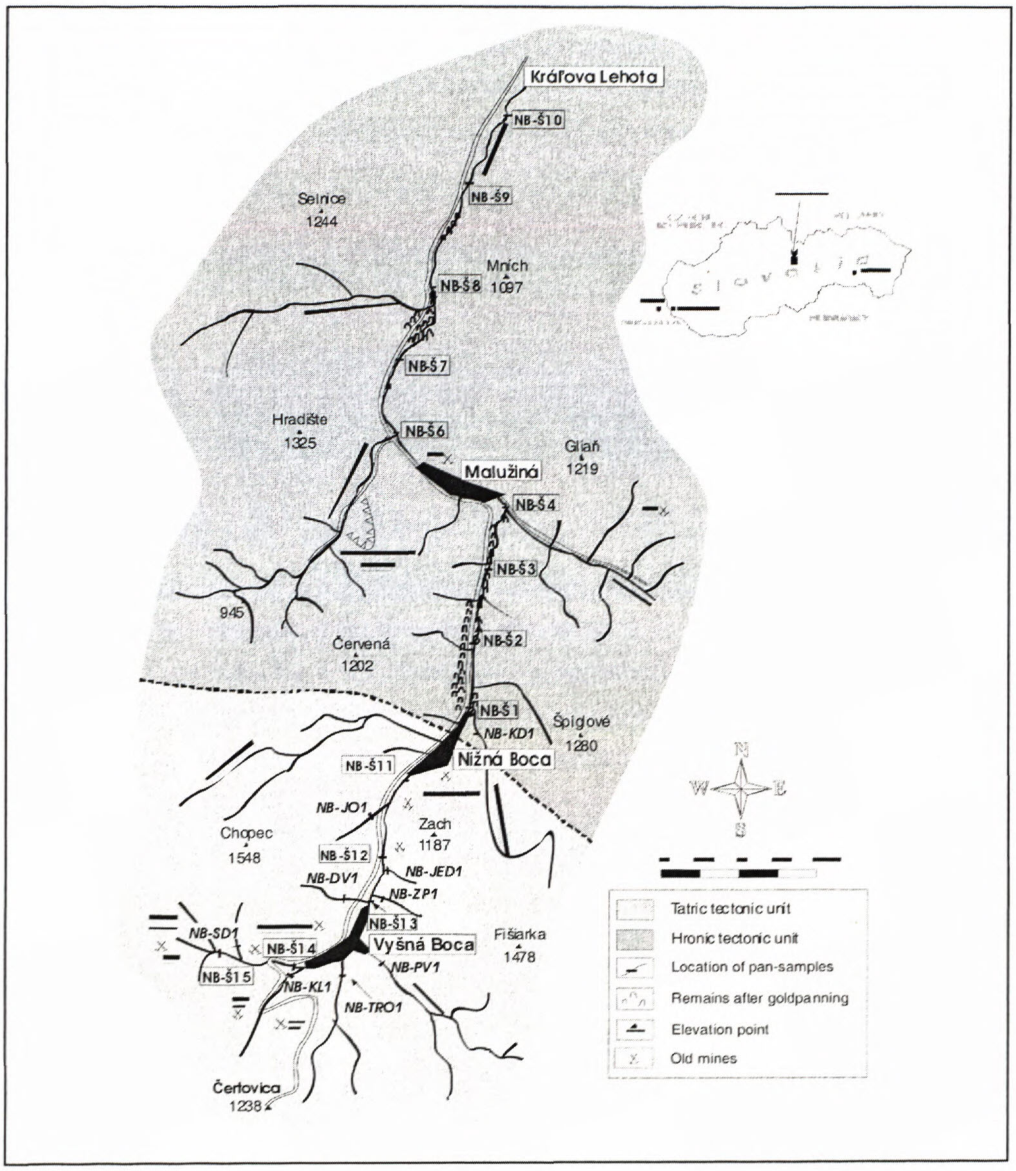

Fig. 1. Map of the Boca River drainage system.

The dominant types of ore mineralization in the area are the hydrothermal quartz – carbonate veins with Sb-Au mineralization, located in the Variscan Tatric basement, south of the Nižná Boca Village. Gold, and later stibnite, were the main objects of exploitation in the 16th century at the Zach locality (Fig. 1) where the terrain morphology is significantly affected by numerous remains after mining. Less intense gold exploitation took place at the Chopec mining field, west of the Vyšná Boca Village. The most abundant minerals of this mineralization are pyrite, arsenopyrite, chalcopyrite, gold, stibnite and Pb-Sb sulfosalts (Smirnov, 2000). The gold is weathered out of its host rock and becomes part of alluvial sediments and was exploited as early as the 13th century.

Siderite veins west and south of the Vyšná Boca Village (Stará Boca – Čertovica) were exploited in the 18th and 19th centuries. These veins stretch several kilometers to the north (localities Zach, Chopec) and occur together with Sb-Au mineralization in the rocks of the Tatric Basement. The dominant minerals of siderite mineralization are: siderite, barite, quartz, pyrite, tetrahedrite and chalcopyrite. Cu(Bi,Pb) sulfosalts are scarce (Ozdín & Chovan, 1999).

Base metal mineralization is located in carbonate sediments of the Hronic Nappe (Olovienka) north of the Malužiná Village. It comprises carbonate veinlets with galena and sphalerite.

Barite veins were exploited at the Doštianka Deposit, east of the Malužiná Village. Virtually monomineral barite veins are hosted by volcano-sedimentary rocks of the Hronic Nappe. Occurrences of barite and quartz-carbonate veins of lesser significance can be found in basalts of the Hronic Nappe at the Svidovo Quarry, west of the Malužiná Village.

Methods and Material Studied

To map the remains after gold panning, reconnaissance trips on both banks of the Boca River were conducted and the results were plotted into topographic maps

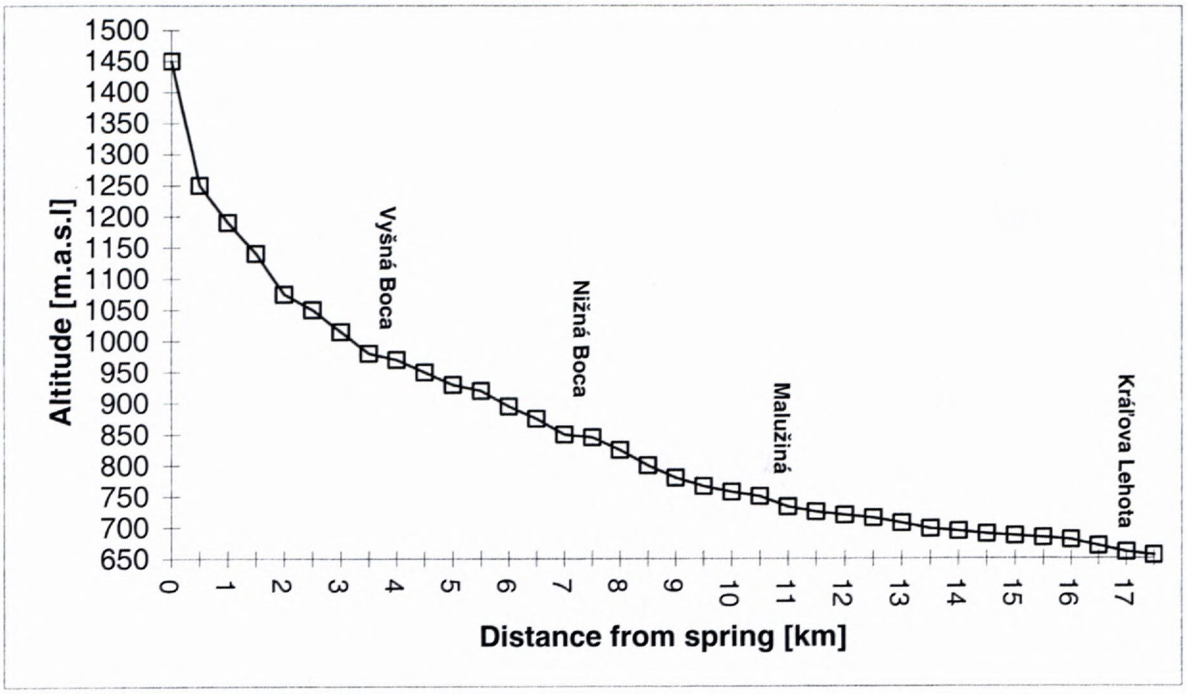

Fig. 2. Longitudinal profile of the Boca River.

of 1:10000 scale [36-22-12 (Nižná a Vyšná Boca), 36-22-07 (Malužiná), 36-22-17 (Čertovica) and 36-22-02 (Kráľova Lehota)].

Alluvial sediments of the Boca River were sampled for heavy minerals in the summer seasons of 1998 and 1999. Samples NB-Š1 to NB-Š15 were taken in approximately 1 km steps between the Starobocianska dolina Valley and the Kráľova Lehota Village. Tributaries of the Boca River that drain the rocks of the crystalline Tatric basement were sampled within 0.5 to 1 km distance from the confluence (to avoid contamination of the tributary sample with possible flash flood or storm sediments from the Boca River). These samples include: Kráľovská dolina (NB-KD1); Joachymstahlská dolina (NB-JO1); Jedlinská (NB-JED1); Za Pavčovým (NB-ZP1); Dievčia voda (NB-DV1); Podvrch (NB-PV1); Trojička (NB-TRO1); Kliesňová dolina (NB-KL1) and Sklepská dolina (NB-SD1).

The sampling depth varied between 40–80 cm and was generally limited by local bedrock and alluvium character. Preceding the standard panning procedure (Hvožďara, 1980, Matula & Hvožďara, 1985), the sample was sieved on a 2–3 mm mesh sieve to achieve a total of ~15 kg of alluvium material.

In the laboratory, each sample was closely studied for fluorescent minerals using an ultraviolet lamp (wavelength 254–366 nm) and the observations were compared with those compiled by Warren (1962) and Gleason (1972). After the permanently magnetic fraction was removed, the sample underwent a process of heavy liquid separation in tribromomethane ($CHBr_3$, density at 20°C = 2.894 g/cm^3). The resulting heavy fraction was electromagnetically separated (separator fi. Cook) into paramagnetic and diamagnetic fractions. Both para- and diamagnetic fractions were subsequently sieved into three size fractions (>0.5 mm; 0.5–0.2 mm; <0.2 mm). Only the 0.5–0.2 mm and <0.2 mm size fractions (in both para- and diamagnetic fractions) were optically studied using a binocular magnifying glass. Observations were compared to data summarized by Rost (1956). Each sample was quarted and the quantity of minerals was expressed as percents of a 200 grain count except for cinnabar, scheelite and gold (expressed in number of grains). Thus, each sample yielded data for four fractions (para- 0.5–0.2 mm; dia- 0.5–0.2 mm; para- <0.2 mm; dia-<0.2 mm) (Hvožďara, 1980).

SEM and BSE imaging techniques, as well as electron microprobe (WDS) analyses, were performed using JEOL JXA 840A microprobe analyzer (CLEOM, Comenius University). Analytic conditions for WDS analysis of gold were: 20 kV, 15 nA, ZAF and Phi-Rho-Z corrections, standards: Hg – HgS, pure metals Au, Ag, Cu, Sb, Bi, Te and Fe.

Results

Morphologically distinct, knoll-shaped remains after gold panning from past exploitation (Bergfest, 1952) (Fig. 4) were observed along the total 10 km distance between the Nižná Boca and Kráľova Lehota Villages (Fig. 1), with the highest concentration of knolls at the confluence of the Boca River and the Michalovský potok Brook. This is in good agreement with the morphology of the river valley (Figs. 2, 3). Decreasing stream gradient directly influences (lowers) stream velocity and overall energetics of the stream - allowing the stream to deposit its load (Abbot, 1999). In this area, alluvial sediments with sufficient gold content were subjected to intensive exploitation

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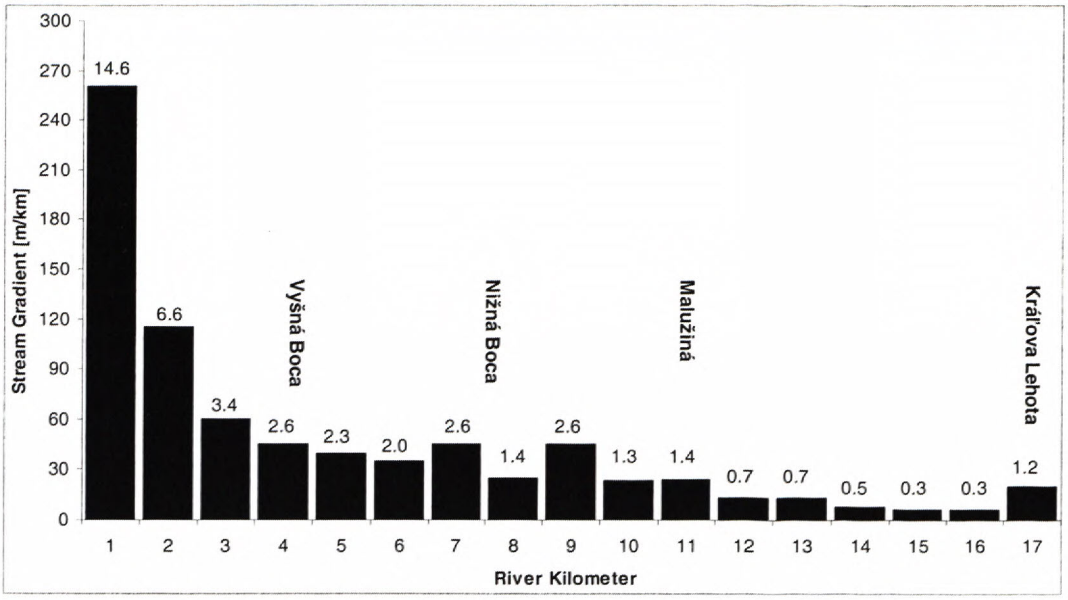

Fig. 3. Stream gradient values of the Boca River.

Fig. 4. Remains after gold panning located at the confluence of the Boca River and the Michalovský potok Brook.

by means of gold panning. The size of the knolls varies, but their height rarely exceeds 3 m and volume of few cubic meters

On the left bank of the Boca River, near the confluence with Kráľovská dolina Brook, numerous gold panning remains are visible on the ancient river terrace. They spread a distance of ~ 1 km towards the Malužiná Village.

Anatase

Anatase occurs rarely in the diamagnetic fraction. Only a few well-preserved euhedral crystals with tetragonal-dipyramidal habitus and striated faces were observed. Grain color varies from indigo-blue to dark blue with sub-metallic luster. Possible source rocks of anatase are igneous and/or metamorphic Tatric complexes (Biely & Bezák (eds.), 1997) and to a lesser extent sedimentary and/or volcano-sedimentary suites of the Hronicum unit (Vozárová & Vozár, 1988).

Anthropogenic Material

Admixtures of various anthropogenic materials are present in all samples, predominantly in the paramagnetic and permanently magnetic fraction. It's typically of black color, with varying shape and sub-metallic to metallic luster. Anthropogenic material is presumably introduced from municipal waste and/or road maintenance.

Apatite

Apatite is very abundant and occurs in the diamagnetic fraction of all samples. Euhedral crystals occur in two forms: short stubby and long slender. The latter usually forms prisms with simple pyramidal termination. Fragments of crystals are also frequently present, mostly of irregular shape. A considerable amount of grains exhibit rounding and scratched faces. Cleavage is poor. Bigger grains contain various inhomogeneities. Apatite is usually colorless, but white, bluish and grayish colors were also observed. Color variations are caused by admixtures of various chemical elements (Mange & Mauer, 1992). A maximum apatite content of 79% was found in sample NB-Š3 (the Boca River) (Fig. 5). The sample from the Sklepská dolina Valley (NB-SD1) contained 57% of apatite.

Potential source rocks of apatite are crystalline rocks of the Tatric unit in the headwater area (Biely & Bezák (eds.), 1997), and to a lesser extent Paleozoic sequences of the Hronic unit (Vozárová & Vozár, 1988).

Arsenopyrite

There is a scarce occurrence of arsenopyrite in the diamagnetic fraction. Arsenopyrite from the Boca River forms euhedral crystals of prismatic habitus sometimes with characteristic striation. It possesses typical tin-white to steel-gray color and high metallic luster. Arsenopyrite was found in hydrothermal siderite and Sb-Au mineralizations (Ozdín & Chovan, 2000; Smirnov, 2000).

Barite

Barite is abundant in the diamagnetic fraction of all samples (Fig.5).

The most habitus is irregular or rectangular (tabular). The latter is caused by excellent {001} cleavage. Barite grains have milky-white, yellowish-white, grayish-white or brownish-white color and vitreous (glassy) luster. Color variations can be caused by thin Fe-oxyhydroxides coatings. Fe-oxyhydroxides fill tiny cracks in barite grains as well. Frequently, barite is overgrown with quartz, pyrite and/or Fe-oxyhydroxides.

Barite content in samples from the Boca River varies from 2 to 93% (Fig. 5). Rost (1956) stressed that because of the excellent cleavage, barite is incapable of transport for very long distances. The barite content of the samples steadily increases, suggesting barite sources along the entire Boca River. Potential barite sources in the headwaters are siderite and, to a lesser extent, also Sb-Au mineralizations (Ozdín & Chovan, 2000; Smirnov, 2000). In the middle and lower course, the possible sources are numerous barite veins occurring in the Hronic unit (Ferenc & Rojkovič, 2001; Friedl, 1987; Turan, 1962).

Carbonates (undistinguished)

Carbonates are in both dia- and paramagnetic fractions. In the diamagnetic fraction, carbonate grains are usually irregularly angular, rectangular cleavage fragments or tabular. Euhedral rhombohedra were scarcely present. Perfect cleavage was observed in a majority of grains. Color varies from colorless to white, light-grayish and light-brownish to white with vitreous luster. Fe-oxyhydroxides coatings were rarely observed. The content of carbonates in the diamagnetic fraction does not exceed 3%. Because of their presence in this fraction, these carbonates are probably of calcite or dolomite composition.

In the paramagnetic fraction, the carbonate content does not exceed 5%. The grains are usually variously rounded rhombohedral crystals and fragments with grayish to yellow-brown color and glassy luster. The surface of the grains is frequently covered with thin Fe-oxyhydroxide coating owing to the higher Fe content of the carbonate.

The perfect cleavage and low hardness results in low resistance to river transport (Rost, 1956) and explains the low content of carbonates in the Boca River. The dominant sources of carbonates are the Mesozoic sequences in the middle and lower course of the Boca River. Ore mineralizations: siderite (Ozdín & Chovan, 2000); barite (Friedl, 1987; Turan; 1962); Sb-Au (Smirnov, 2000) can be considered a minor source of carbonates in the alluvium.

Chlorite group (undistinguished)

Minerals from the chlorite group are frequently present. The chlorite content in samples varies greatly, presumably due to the Fe content and/or separation methods (tribromomethane quality, electric current setting during electromagnetic separation).

Chlorites usually form thin flaky plates of round, oval or irregular shape; sometimes with curled margins. Pseudo-hexagonal euhedral crystals are scarce. Chlorites have excellent cleavage and their platy crystals are elastic. Typically greenish to gray- and brown-green in color with pearly luster. The samples usually contain up to 2% and 12% in dia- and paramagnetic fraction, respectively. Sources of chlorites can be some or all of the following: a) hydrothermally altered wall rocks of ore mineralizations (Ozdín & Chovan, 2000); b) primary minerals and/or weathering products of primary minerals in both Hronic and Tatric Units (Biely & Bezák (eds.) (1997), Friedl (1987), Vozárová & Vozár (1988); c) post-volcanic mineralization in the basaltic rocks of the Hronic Unit (Friedl, 1987).

Cinnabar

Usually forms irregular, variously rounded grains with no visible cleavage. It typically has typical cherry-red, brownish-red or light-red color with a highly glassy luster.

Cinnabar is a regular admixture in the diamagnetic fraction of samples, occurring in the Boca River in quantities varying from 3 to 35 grains. It is also present in samples from the Boca River's tributaries (X grains per sample) with the exception of the Kráľovská dolina Valley.

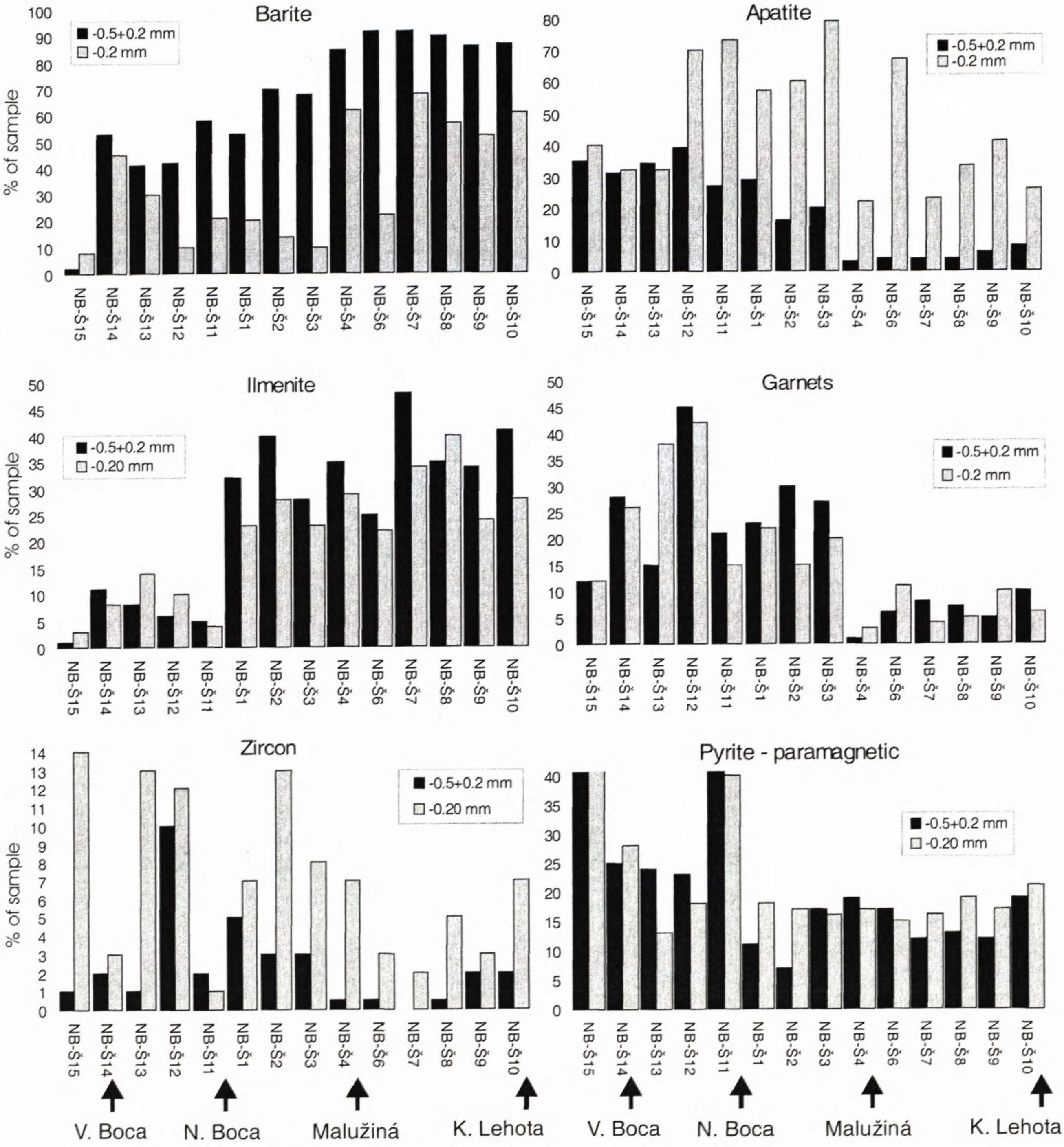

Fig. 5. Contents of selected minerals in pan-samples from the Boca River sediments (-0.5+0.2; -0.2 mm fractions).

Epidote group (undistinguished)

Minerals of this group (zoisite, epidote, pumpellyite) are usually colorless or of greenish to brownish color. They can occur in paramagnetic fraction as short stumpy prisms, needle-shaped crystals, tabular and platy fragments, but mostly as variously rounded and irregular fragments. Epidote content in the Boca River gradually increases towards its mouth, which implies an increasing abundance of its source rocks.

In the Boca River's upper course, the dominant sources are the rocks of the Tatric crystalline; while in the middle and lower course, epidote is an important constituent of post-volcanic mineralizations in basaltic rocks of the Hronic Unit (Friedl, 1987).

Garnet group (undistinguished)

Abundant in the paramagnetic fraction, usually occurs as isometric sub-rounded to rounded grains a nd irregular

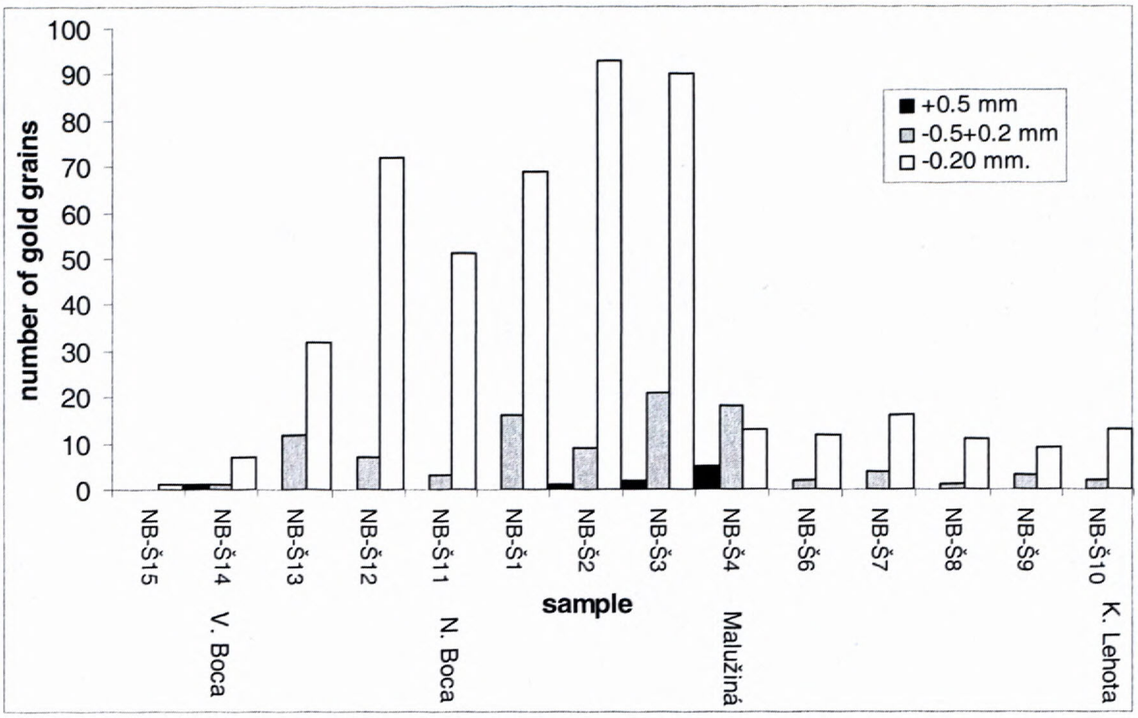

Fig. 6. Gold content in pan-samples from the Boca River sediments as a function of transport length.

sharp fragments with a typical glassy luster. Crystal faces are often scratched. Euhedral crystals are rare. Color varies from pink and red to brownish-red and yellowish-brown. Garnet content in the Boca River varies from 1 to 45%, while contents in its tributaries are between 7 and 89% (the Dievčia voda Valley). Garnet's source rocks are located mostly in the upper course of the Boca River (crystalline rocks of the Tatric Unit). This is in agreement with the decreasing garnet content in the river towards its mouth (Fig. 5). Garnet is also present in sedimentary and/or volcano-sedimentary rocks of the Hronic Unit (Vozárová & Vozár, 1988).

Gold

Gold is a regular constituent of most samples (Fig. 6). Gold from the Boca River has typical gold-yellow color; often varying to orange, mustard-yellow, reddish or yellowish white.

Its surface is occasionally coated with Fe-oxyhydroxides and often shows marks (scratches, prints, dents) indicating mechanical damage during the transport. The surfaces of all gold grains studied by SEM and BSE methods are porous. In 88-100% of gold grains, the pores were distributed evenly, while in some cases, elevated concentrations of pores were detected in vicinity the grain's rim. Most pores are of isometric shape and are a maximum 2 μm in size.

A majority of gold grains are rounded to a various degree (Fig. 7, 8, 9). There is no distinct correlation between the roundness of grains and the length of transport. Depending on the sample, approximately 30–70% of gold grains were overgrown with quartz (Fig. 10). The percentage of gold/quartz overgrowths does not decrease towards the mouth. Overgrowths with pyrite are rare.

The morphology of gold shows extensive variations. For the purpose of this study, all gold grains were assigned to one of three categories: flakes, nuggets or branching nuggets according to the ratio of the *a*, *b* or *c* dimensions. Flakes are the most frequent shape of gold particles (Fig. 11) and usually don't overgrow with quartz or pyrite. We didn't observe any distinct relationship between the gold particle shape and the distance of travel because the quantity of gold grains in samples from the headwaters (NB-Š14, 15) and from the mouth of the river (NB-Š6, 8, 9, 10) do not allow for a reliable statistical evaluation. However, a few trends can be established: a) the number of flake-shaped gold grains generally increases towards the mouth; and b) the number of nuggets and branching nuggets reaches its maximum in the middle course of the Boca River and then decreases gradually.

To assess features that indicate instability of Au-Ag alloys in an oxidizing aquatic environment, close attention was paid to compositionally different phases in the BSE images. The percentage of gold grains with "inclusions" (isolated, compositionally- different areas with higher/lower fineness) was observed to increase with the distance of travel. Gold-rich rims (Fig. 12) are abundant, generally 1 to 20 μm thick and may contain elevated concentration of pores or sponge-like structures. The percentages of gold-rich rims were also observed to increase with the travel distance, thus proving the time dependence of the Ag-leaching process.

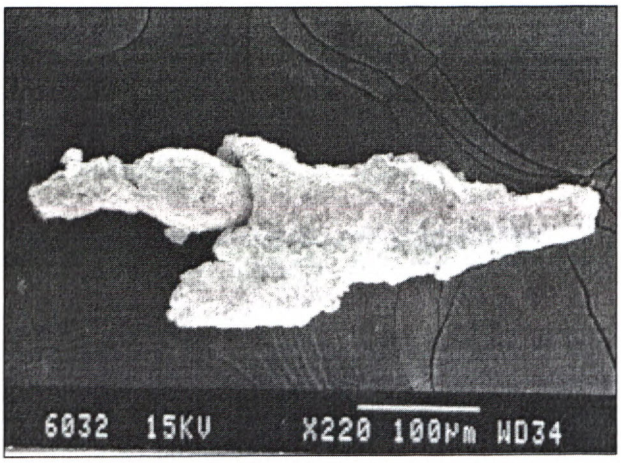

Fig. 7. Highly deformed (formerly flake-shaped) gold particle (NB-Š8).

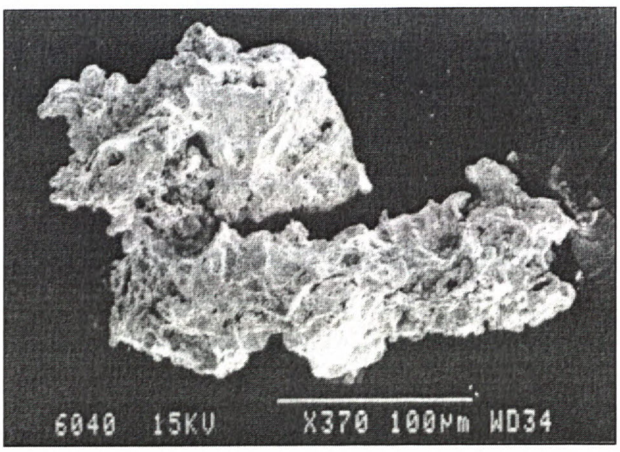

Fig. 8. Well-preserved gold particle, minimally rounded by the river transport (NB-Š2).

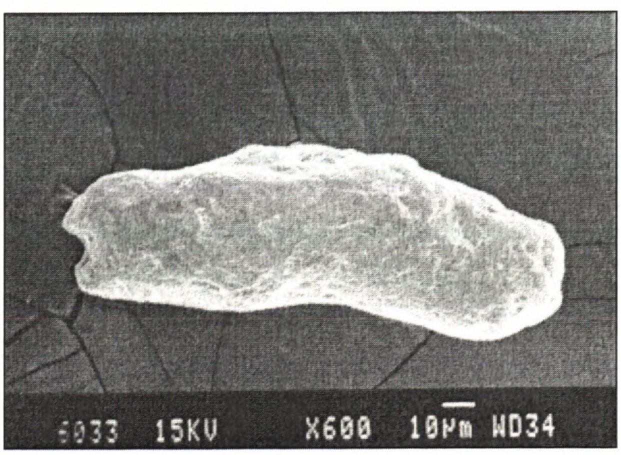

Fig. 9. Completely rounded wire-shaped gold grain (NB-Š7).

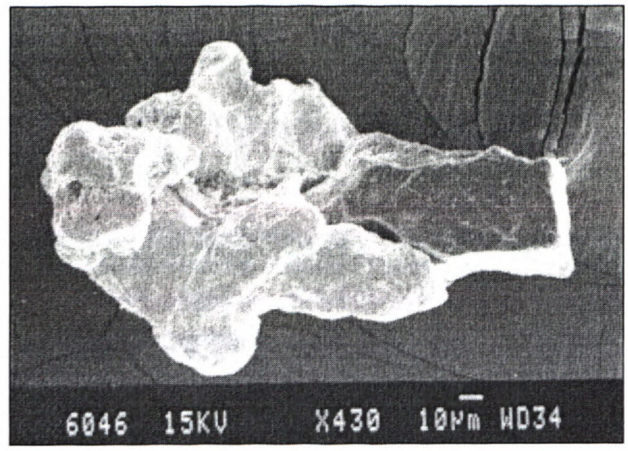

Fig. 10. Rounded gold grain overgrown with quartz. (NB-Š4).

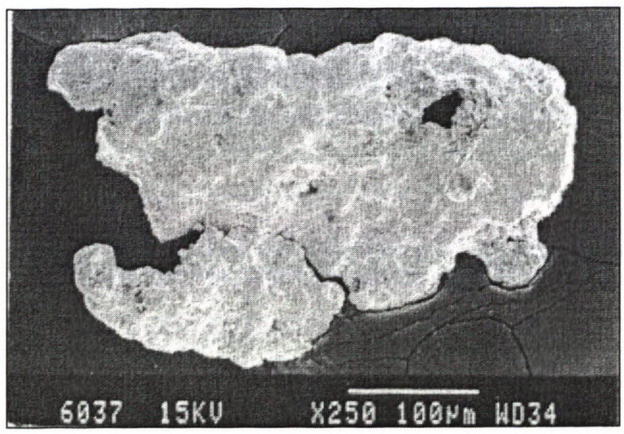

Fig. 11. Well-rounded, flake-shaped gold grain (NB-Š2).

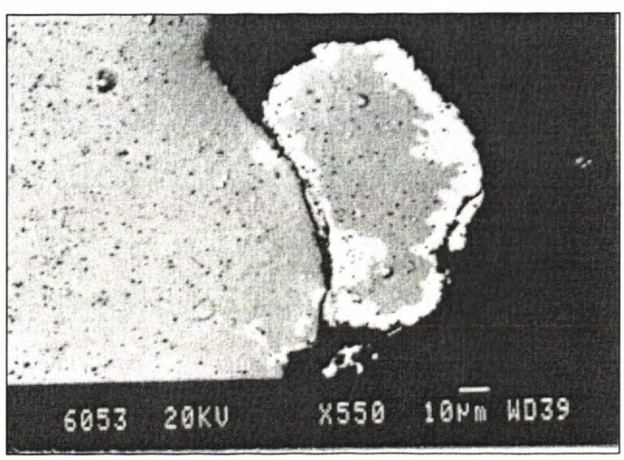

Fig. 12. Example of well-developed gold-rich rim on alluvial gold grain (NB-Š3).

Au:Ag ratio of gold grains varies between 2.1 (65.8:30.5 wt.%) and 70.6 (94.6:1.34 wt.%). The true fineness (F_T) values range between 683 and 986. As a consequence of similar lattice constants of gold and silver, a strong correlation exists between Au and Ag content. Hg content is slightly elevated (up to ~2.2 wt.%) with the exception of one gold grain containing 22.83 wt.% of Hg. This anomalously high Hg concentration is a result of amalgamation process. The concentration of other analyzed elements (Fe, Sb, Bi, Te, Cu) does not exceed 0.95 wt.%. Representative WDS analyses of gold are in Tab. 1.

*Tab. 1. Representative WDS analyses of gold from the Boca River. Analysis (1) represents gold grain with anomalous Hg content. Analyses (2a) and (2b) represent homogenous gold grain and analyses (3a) and (3b) gold grain with gold-rich rim sample No. NB-Š-3??? (note the differences in F_T). * - because of the high Hg content, F_T calculated as Au/(Au+Ag+Hg) x 1000.*

Analysis Location	(1) rim	(2a) core	(2b) rim	(3a) core	(3b) rim
Fe	0.48	0.22	0.23	0.30	0.03
Te	0.25	0.01	0.01	0.15	0.07
Sb	0	0.14	0.16	0.17	0.10
Ag	6.93	2.67	3.09	28.29	1.34
Hg	22.83	2.13	2.22	0.95	1.04
Au	66.18	93.74	94.73	69.06	94.64
Cu	0.13	0.10	0.11	0.11	0.11
Bi	0.55	0.51	0.57	0	0.40
Σ	97.35	99.50	100.77	99.02	97.73
F_T	690*	952*	947*	709	986
Formula	$Au_{0.51}Ag_{0.32}Hg_{0.17}$	$Au_{0.93}Ag_{0.05}Hg_{0.02}$	$Au_{0.92}Ag_{0.06}Hg_{0.02}$	$Au_{0.57}Ag_{0.43}$	$Au_{0.97}Ag_{0.03}$

The gold distribution in the Boca River is uneven, primarily governed by the location and availability of primary sources. The second important influence is the morphology and profile of the Boca Valley (Fig. 2, 3). Low gold content in headwater samples is primary caused by a limited (or none) number of primary occurrences, as well as by unsuitable depositional conditions (high stream velocity, a narrow valley). The gold content in samples then generally increases from sample NB-Š13 to sample NB-Š3. This feature correlates well with valley morphology (the valley broadens and stream velocity decreases), as well as with more abundant primary sources: mine fields Chopec (SE of V. Boca) and Zach (E-NE of N. Boca) had both been exploited for gold (Bergfest, 1952) and recent studies confirm the presence of gold at these localities (Ozdín & Chovan, 2000; Smirnov, 2000). Low gold content in samples from the Boca River's lower course (NB-Š4 – 10) can be explained by a large distance from the gold's primary sources, even though the morphology would favor a sedimentation process. The gold content in the Boca River's tributaries is generally low, varying from 1 gold grain/sample (NB-KD1, NB-JO1, NB-JE1) up to 12 gold grains/sample (NB-SD1).

Ilmenite

Ilmenite is present in the paramagnetic fraction of all samples in the form of anhedral grains and fragments, usually with sharp edges. Euhedral tabular crystals are rare. Ilmenite possesses a characteristic black color with bluish tint and high metallic luster. The surface is often coated with the weathering product of ilmenite, leucoxene, which is of white to grayish color. The ilmenite content in the Boca River samples varies from 1% to 48% and gradually increases towards the mouth (Fig. 5). The latter indicates the presence of the source rocks all along the Boca River. The paramagnetic fraction of the Kráľovská dolina Valley sample contains 78% of ilmenite. Ilmenite was found as an accessory mineral in both Králička- and Ďumbier-type granitoids (Biely & Bezák (eds.), 1997). It is fairly abundant in sedimentary and/or volcanic rocks of the Hronic Unit (Vozárová & Vozár, 1988).

Magnetite

Magnetite is present in the ferro-magnetic fraction of every sample. It usually occurs as sub-rounded to rounded grains and rarely as euhedra l cubic crystals. The Boca River's magnetite possesses a typical black color and high metallic luster. The surface is often covered with weathering products - Fe oxyhydroxides ("limonite") that can also fill the fissures and cracks on the magnetite surface. It occurs in the ferro-magnetic fraction along with magnetic anthropogenic material and it is distinguishable only with difficulty. Due to the negligible significance of magnetite, its content in samples wasn't evaluated.

Micas (undistinguished)

Micas are a very common admixture of both para- and diamagnetic fractions of all samples. Due to the Fe content and/or separation methods (tribromomethane quality, electric current setting during electromagnetic separation), mica content in samples varies greatly. Micas occur invariably as {001} basal plates (very good cleavage), usually with a round, rarely irregular or pseudo-hexagonal outline. They usually have white, gray or silver-white color with a green or brown tint (presumably due to the elevated Fe content) and vitreous to glassy luster. Overgrowths with quartz and chlorites are common. Maximal mica content of samples from the Boca River is 38% in the diamagnetic fraction and 12% in the paramagnetic fraction (sample NB-Š15). Generally all rock types (with the exception of sedimentary carbonates) in the drainage area of the Boca River can be considered source rocks of micas (Biely & Bezák (eds), 1997). Muscovite was also described from wall-rock hydrothermal alteration zones of siderite mineralization in the Vyšná Boca area (Ozdín & Chovan, 2000).

Monazite

Monazite is an accessory admixture of most samples. It's yellowish to yellow-brown (honey-like) grains are usually well rounded, egg-shaped or spherical. Anhedral to subhedral crystals are rare. Its identification is somewhat problematic, because its rounded grains can be mistaken for titanite. Broska & Siman (1998) and Biely & Bezák (eds.) (1997) described accessory monazite from granitoid and metamorphic rocks of the Tatric Unit. Monazite, probably hydrothermal in origin, was described from veporic tectonic unit (Hvožďara, 1980, 1999). The Hronic Unit (Vozárová & Vozár, 1988) can be considered a minor source of monazite.

Pyrite

Pyrite is a very common admixture of all samples. In diamagnetic fractions, pyrite usually forms euhedral to subhedral hexahedrons, pyritohedrons (a dodecahedron with pentagonal faces) and various crystals with combinations of these forms. Well-rounded grains and crystal fragments are also common. Cubic faces often show striation parallel with the edges. The surface of pyrite crystals is often affected by oxidation in aquatic environments - typically pale to dark brassy-yellow color is changed to a red, red-brownish color. Thin coatings of oxyhydroxides ("limonite") were often observed on the surface of the grains. It readily dissolves in hydrochloric and nitric acid. In paramagnetic fractions, pyrite forms predominantly anhedral, rounded grains, partly or entirely changed into "limonite".

Pyrite distribution in both fractions is generally equable. Both fractions show an elevated pyrite content in the headwaters of the Boca River. This correlates with numerous outcrops of ore veins (Sb-Au, siderite) and their wall-rock alteration zones in the area (Ozdín & Chovan, 2000, Smirnov, 2000), which are also predominant donors of pyrite. Other possible donors include: accessory pyrite in crystalline rocks of the Tatric unit and volcanic rocks of the Hronic unit (Biely & Bezák, 1997); barite mineralization (the Svídovo Quarry, Malužinská dolina Valley); and Pb-mineralization (Malužiná-Olovienka).

The Boca River's tributaries contain 3-30% of pyrite in both para- (Fig. 5) and diamagnetic fractions (samples from Dievčia voda Valley (NB-DV1) and Joachymstáhlska dolina Valley (NB-JO1), respectively).

Quartz

Quartz is a regular constituent of every sample. Euhedral crystals are scarce. It usually forms anhedral grains and variously rounded fragments of milky-white to grayish color. Fe-oxyhydroxide coatings on the surface may influence its color. Overgrowths with chlorites, micas, pyrite or gold are common. Quartz content in samples varies due to the separation methods – especially tribromomethane quality. Fe-oxyhydroxide coatings are also of considerable importance during the electromagnetic separation.

Rutile

Rutile is a regular accessory mineral in all samples. It occurs mostly as variously rounded grains and fragments; non-rounded grains are usually euhedral crystals with well-developed pyramidal terminations or slender prisms. "Knee shaped" twins (Fig. 13) were rarely encountered. Its color varies from deep-blood red and brownish-red to brownish-black and black. Adamantine to sub-metallic luster is typical.

The distribution of rutile in the Boca River is generally even. Samples from the Za Pavčovým Valley (NB-ZP1) and Sklepská dolina Valley (NB-SD1) contain 10% and 8% of rutile, respectively. Major donor rocks of rutile are igneous and/or metamorphic rocks of the Tatric crystalline basement.

Scheelite

Scheelite is very rare in the Boca River and occurs irregularly in quantities as low as a few grains per sample. No scheelite we were found in the Boca River's tributaries. Its grains are well rounded; possess milky-white color and an adamantine to greasy luster. Characteristic blue fluorescence in UV light (Warren, 1969; Gleason, 1972) was observed.

Titanite

Titanite is an accessory mineral in most of samples. It forms irregular grains of yellow-brown to brown color, sometimes with observable cleavage. Color and luster of its rounded grains can be mistakenly identified as monazite or xenotime. The major sources of titanite are crystalline rocks of the Tatric Unit (Biely & Bezák (eds.), 1997).

Xenotime

Xenotime is very scarce, with only a few well-preserved euhedral crystals with tetragonal-dipyramidal habitus found. Its color is yellowish with vitreous to resinous luster. Its content in samples is presumably higher, since it can be mistakenly identified as monazite, or even zircon and titanite (Mange and Mauer, 1992). Accessory xenotime was described from granitoid and metamorphic rocks of the Tatric Unit (Biely & Bezák (eds.), 1997).

Zircon

Zircon is present in diamagnetic fraction of all samples. It typically occurs in a vast variety of well-defined, euhedral prismatic crystals with pyramidal termination (Fig. 14), owing to its hardness and high chemical stability (Nickel (ed.), 1973). The length of crystals (along *c*-axis) varies from <0.05 to ~1.5 mm. Fragments of euhedral crystals and sub- to well-rounded grains are rare. Generally, rounding is more advanced on larger grains. The color varies from deep red and pinkish to orange and even colorless varieties. Luster is adamantine. No luminescence in UV light was observed.

The zircon content in the Boca River varies between 1 to 14% and it gradually decreases towards the mouth (Fig. 5). Samples from some Boca River's tributaries, such as the Dievčia voda (NB-DV1) and Sklepská dolina (NB-SD1) Valleys contain 36% and 28% of zircon, respectively. Zircon is a common accessory mineral in granitoid and metamorphic rocks of the Tatric Unit (Broska & Uher, 1991). Vozárová & Vozár (1988) described accessory zircon from Late Paleozoic Hronic complexes present in middle and lower course of the Boca River.

Discussion and conclusions

Mineralogical research of heavy minerals in the Boca River showed the presence of 21 minerals and mineral groups. Cinnabar in a primary hydrothermal mineralization has never been described neither in the studied area nor in any other primary occurrence in the Nízke Tatry Mountains. However, it was described by Chovan et al., (1995) in alluvial sediments in the Magurka Deposit area with highest concentrations in the Rišianka Valley. Its primary occurrences can be presumably assigned to circulation of low-temperature fluids in areas of relatively young tectonic activity.

Scheelite, though never described in its host rock in the Boca River's drainage area, has been found at numerous localities in the Tatric and Veporic units (Hvožďara, 1985). Scheelite impregnations in paleobasalts and amphibolites and in quartz veins are present at W-Au deposit Jasenie – Kyslá (Pulec et al., 1983). Quartz-scheelite veins in metamorphic rocks of the Tatric unit are present at the Sb-Au Dúbrava Deposit (Čillík et al., 1979, Chovan et al., (ed.) 1994). Analogical source rocks are presumed in the studied area.

The find of cassiterite, identified by spectral and XRD analyses by Linkešová & Čillík (1979), remains speculative. Content of cassiterite in pan-samples varies between x and xx grains. Its possible source is unknown, nevertheless Linkešová & Čillík (1979) suspect its linkage to bodies of porphyric granites.

Content of micas and chlorites (a.k.a. layered silicates) is only orientational, because during the sample preparation, these tend to disintegrate into several daughter flakes (Dill, 1998) that introduce errors in the statistical evaluation.

We observed no carbonate and/or sulfide anomalies in our samples. This implies that siderite- and base metal mineralizations have virtually no effect on the mineral content of the alluvium compared to the influence of surrounding Mesozoic carbonate complexes.

Gold was actively mined in the Nižná and Vyšná Boca surroundings and also gleaned from the Boca River (Bergfest, 1952). Morphological evidence of mining of alluvial gold in the Boca Valley was found and documented. It was found that the highest concentration of remains after gold panning is at the confluence of the Boca River and the Michalovský potok Brook, between the villages of Malužiná and Kráľova Lehota. However, the highest gold counts were obtained from samples between Nižná Boca and Malužiná (samples NB-Š2, NB-Š3). These results are in very good agreement with morphology of the Boca Valley. Gold grains from the Boca River exhibit signs of mechanical damage (scratches, deformations, indentations) and rounding processes. However, we observed neither distinct correlation between the roundness of gold grains and distance of transport, nor decreasing number of overgrown gold grains (quartz) with increasing transport distance. These correlations were observed at numerous localities (e.g., Groen et al., 1990; Bakos & Chovan, 1999, Knight et al., 1999, Bahna et al. 2001). Flakes (not overgrown with quartz or pyrite) were found to be the most frequent particle shape. Our results suggest that the percentage of flake-shaped gold grains increases and the percentage of nuggets and branching nuggets decreases with increasing distance of transport. It is important to point out that our results can be biased because of small quantities of gold grains in several samples from the Boca River (NB-Š15, 14, 6, 8, 9, 10).

Gold-rich rim formation was observed on gold grains from the Boca River and the number of gold grain with this feature was found to increase with transport distance. Models summarized by Groen et al., (1990) suggest the formation of gold-rich rims by hydrometallurgical, self-electrorefining processes driven by electromotive force (EMF) between two different metals in a solution whose Eh is higher than that in which the alloy is stable.

Elevated Hg content in some alluvial gold grains (up to ~2.2 wt.%) and one grain with 22.83 wt.% of Hg confirm historic reports (Bergfest, 1952) that mention the use of amalgamation process to extract gold from the ore.

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