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Limitations in drainage area determination by analysis of chemical composition of heavy minerals in stream sediments: Provenance of sediments from the Bílý potok stream, Czech Republic

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Abstract

Analysis of the chemical composition of heavy minerals such as garnet, amphibole and tourmaline represents a very efficient tool for determination of the source area of clastic sediments. In small and geologically simple river basins containing contrast rocks, this method even allows to quantify to certain degree the share of the individual rock types on the modal composition of clastic sediments. There are, however, substantial limitations for the applications of this method. The chemical composition of heavy minerals present in the sediments of small streams is considerably influenced by the local geological setting of the particular sampling site and it is very often impossible to determine the exact proportion of the material coming from older sedimentary formations.

Key words: heavy minerals, chemical composition, provenance, stream sediments, Czech Republic

Introduction

The modern methods of sedimentary petrology strive to determine the provenance of the studied sediments by the chemical composition of heavy minerals (HMs). The petrologists compare the chemical composition of HMs with that of the minerals present in rocks, which are considered to be a potential source of the sedimentary material (Čopjaková et al., 2005; Li et al., 2005; Sabeen et al., 2002). Several mineral groups can be used for provenance studies, but, so far, amphiboles (Mange-Rajetzky and Oberhansli, 1982), tourmalines (Henry and Guidotti, 1985), and garnets (Morton, 1985) seem to be the best suitable groups for given applications. The contemporary methods allow estimating of the origin of detrital material in the studied samples but some unanswered questions still remain: Can we identify the redeposition of HMs from older sediments? Does the spectrum composition of HMs in the studied sediment really reflect the composition of the geological base in the source area? How distinctively react the composition of HMs fraction in the sediments on the change of geological structure of the stream bed? The only way to find answers to these questions is to test the behaviour of heavy minerals in a well-explored catchment area. We have chosen a small drainage basin of the Bílý potok stream, which is characterized by a relatively uncomplicated geological structure.

Methodology

10-liter samples of unsorted alluvial heavy mineral concentrates were taken on several carefully selected sites down to a depth of 30 to 40 cm from the stream bed. The sampled material was washed in water and sieved on a 2 mm grading screen. The coarse-grained fraction (>2 mm) was visually estimated (volume in %) and discarded. The fine fraction (<2 mm) was carefully rid of mud and clay and cradled until only a grey heavy mineral concentrate remained. The on-site documentation included the sample identification, type of the sampled material, percentual estimate of the coarse fraction volume and that of the clear fine fraction, the grade of mechanical anthropogenic contamination and the sampling date.

The samples were dried in a laboratory and sieved over a 0.15 mm grading screen. The coarser grains (0.15 to 2 mm) were separated into a ferromagnetic fraction (FMF, strongly magnetic minerals), a magnetic fraction (MF, paramagnetic minerals), and a non-magnetic fraction (NF, diamagnetic and non-magnetic minerals) using a permanent magnet. Light minerals in the NF were subsequently removed by a separation in a dense liquid (bromoform, $CHBr_3$, $\rho = 2.89$ g/cm^3) and barite colour tests were performed. All the obtained fractions were weighed on a 0.01 g precision balance.

The basic method of evaluation of heavy mineral concentrates (0.15–2 mm fraction) was a semiquantitative mineralogical analysis. This analysis aimed to determine all the mineral components present in the concentrate and to quantify their content in grams per 1 m^3 of the sampled material. Expressing the concentration of a given mineral and its classification into the appropriate content class is based on the volume of the analysed fraction, the quantity of the grains, the size and the shape of the grains, and the mass of the given component per 1 m^3 of the sample. The identification of the minerals and their quantification are performed using a binocular stereoscopic microscope. Minerals are determined according to their colour, transparency, luster, degree of erosion, residua of crystalline restrictions, secondary alterations, intergrowth with other minerals, hardness, frangibility, cleavage, type of fragmentation after mashing or scratching, etc. Scheelite is identified with an UV lamp. Because the identification of some minerals is very difficult, only the mineralogical groups are identified (garnets, tourmalines, pyroxenes, amphiboles, etc.). Mineralogical analyses of heavy mineral concentrates were performed by our external co-worker from the GEOMIN Group, Mrs. D. Fiřtová. Mineral analyses were carried out using the electron microprobe Cameca SX-100 at the Institute of Geological Sciences, Faculty of Science, Masaryk University in Brno. The measurement conditions were following: wave dispersion mode, 15 kV acceleration voltage, 5 μm diameter of the electron beam, 30 nA current, integration time 20 seconds, operator R. Čopjaková. K_α X-ray lines and standards of augite (Si, Mg), orthoclase (K), jadeite (Na), chromite (Cr), almandine (Al), andradite (Fe, Ca), rhodonite (Mn), TiO (Ti) were used. The crystallochemical formula of tourmalines was calculated to contain 31 anions (from the stoichiometry followed: B = 3, OH + F = 4), that of staurolites contained 46 O and that of garnets 12 O. Amphiboles were evaluated according to the valid classification by Leake et al. (1997) and Fe^{3+} was calculated using the 13eCNK method (Schumacher, 1996). The used mineral abbreviations are according to Kretz (1983). Percentual shares of sediment grains belonging to the areas corresponding to the individual rock types in the studied locality were determined by summing up the points in the given areas of the diagram.

Geological and mineralogical characterization of the source area

The basin of the Bílý potok stream comprises three relevant and lithologically well-defined geological units: sediments of the Bohemian Cretaceous Basin, the Svratka Crystalline Complex and the Polička Crystalline Complex (Fig. 1).

The Svratka Crystalline Complex is represented by a relatively small area by the NE-edge of the studied drainage basin (Buriánek et al., 2006). This area is formed by migmatites and mica schists with garnet and staurolite.

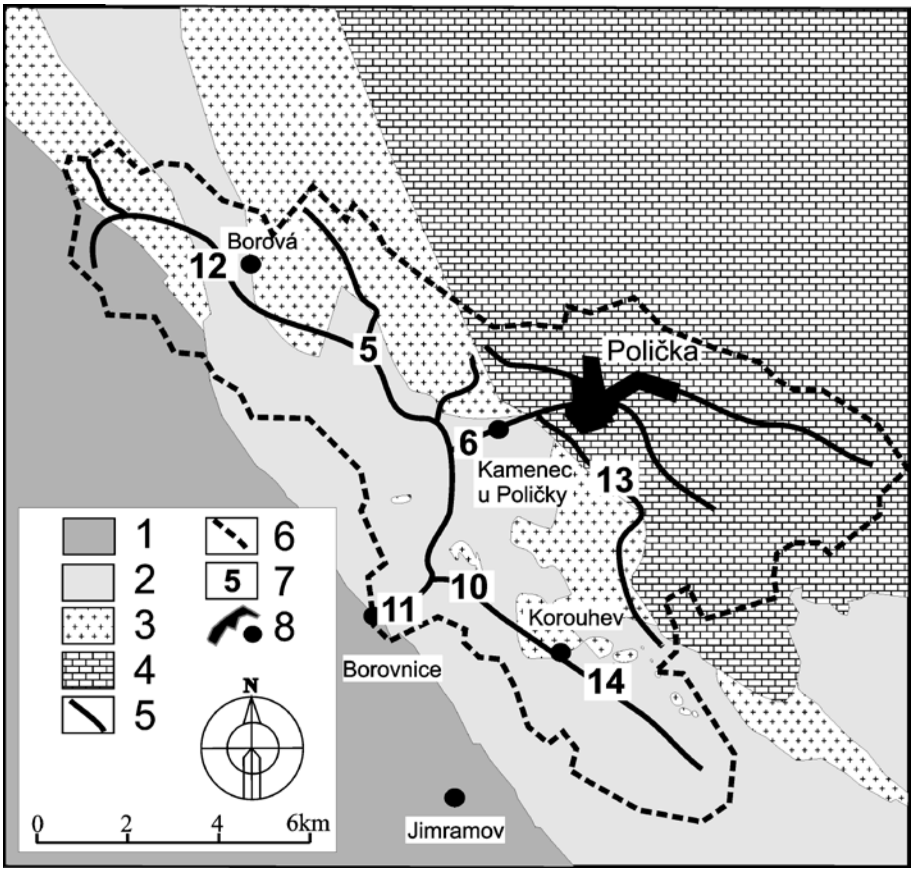

Fig. 1. Distribution of the studied samples and the range of the source area. Sketch of geological units (Buriánek et al., 2006 and Čech et al., 2005). 1 – Svratka Crystalline Complex, 2 – Polička Crystalline Complex, 3 – plutonic rocks of the Polička Crystalline Complex, 4 – sediments of the Czech Cretaceous Basin, 5 – main streams, 6 – source area, 7 – sample, 8 – town or village.

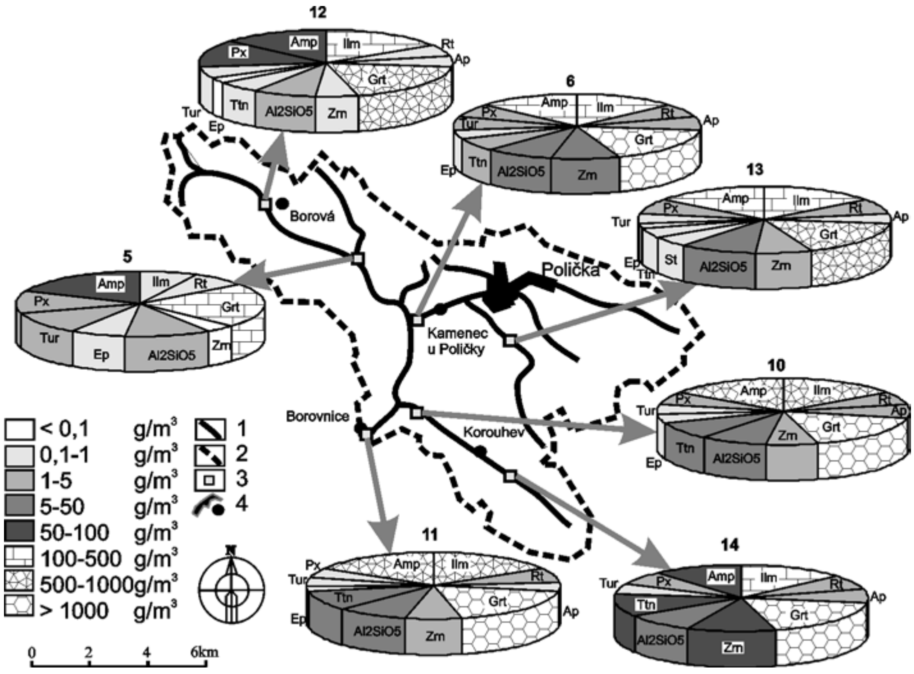

Fig. 2. Distribution of the studied samples and the range of the source area. Doughnut chart showing a proportion of main heavy minerals (without magnetite) in different parts of the studied area (in g per m^3 of sediments). 1 – main streams, 2 – border of source area, 3 – sample, 4 – town or village.

Tab. 1
Volume of minerals in g/m^3 from heavy minerals concentrate in the Bílý potok stream sediments (localization same as in Fig. 1)

Sample Locality	5 Sádek	6 Kamenec	10 Korouhev	11 Maksičky	12 Borová	13 Polička	14 Korouhev
Y	620794	619066	619501	621223	623377	616108	616588
X	1098925	1101198	1104254	1104697	1096569	1102313	1106755
Cerussite	0	< 0.1	0	< 0.1	0	0	0.1–1
Barite	0	< 0.1	0	0	< 0.1	< 0.1	0.1–1
Pyrite	0	5–50	< 0.1	0	< 0.1	0.1–1	0
Spinel	0	0	0	0	0	0	0.1–1
Ilmenite	0.1–1	100–500	500–1000	500–1000	100–500	100–500	100–500
Rutile + Anatase	0.1–1	1–5	1–5	1–5	0.1–1	1–5	1–5
Limonite	0	0.1–1	0	0	0	0	0
Monazite + Xenotime	0.1–1	0.1–1	0.1–1	0	< 0.1	< 0.1	< 0.1
Apatite	0	1–5	1–5	0.1–1	0.1–1	0.1–1	1–5
Garnet	100–500	> 1000	> 1000	> 1000	500–1000	500–1000	> 1000
Zircon	< 0.1	5–50	1–5	1–5	0.1–1	1–5	50–100
Al_2SiO_5	1–5	5–50	5–50	5–50	1–5	5–50	5–50
Staurolite	0	0	0	0	0	0.1–1	0
Titanite	0	1–5	5–50	5–50	0.1–1	0.1–1	50–100
Epidote	0.1–1	0.1–1	0.1–1	< 0.1	< 0.1	< 0.1	0
Tourmaline	1–5	1–5	0.1–1	0.1–1	0.1–1	0.1–1	0.1–1
Pyroxene	1–5	1–5	1–5	0.1–1	50–100	1–5	1–5
Amphibole	50–100	100–500	500–1000	500–1000	50–100	100–500	5
Glauconite	0	0	0	0	0	1–5	0
Magenetite (wt.%)	0	5	0	1	0	0	80
FMF	0	0.41	0.23	0.06	0	0	0.33
MF	6.5	96.59	167.2	72.58	21.01	45.21	316.69
NF	0.17	0.66	1.03	0.42	0.1	0.57	1.55
PF	0.19	0.3	0.58	0.67	0.83	2.84	2.82
KTM	11.96	114.44	193.92	89.1	27.03	93.39	339.39

Explanation: FMF = ferromagnetic fraction, MF = paramagnetic minerals, NF = non-magnetic fraction, PF = undersize fraction, KTM = whole heavy minerals concentrate

Tourmaline is typical accessory mineral for this region. It can be found in migmatites, paragneisses and mica schists (it even forms small tourmalinite islets inside mica schists). Tourmaline in the Svratka Crystalline Complex can have quite a wide range of chemical composition (Fe/(Fe + Mg) = 0.24–0.96; Al_{tot} = 6.05–6.77 apfu) and usually corresponds to schorl-dravite or Al-rich schorl--dravite. Garnet is another very abundant mineral, which occurs mainly in mica schists, accompanied by staurolite, kyanite and sometimes sillimanite. Garnets from gneisses, staurolitic mica schists and tourmalinites in the northern part of the Svratka Crystalline Complex are of similar chemical composition ($Alm_{77-88}Sps_{1-13}Prp_{4-13}Grs_{0-12}Adr_{0-2}$). Staurolite and kyanite are the typical minerals of the northern part of the crystalline unit. Porphyroblasts of garnets in staurolitic mica schists very often demonstrate an increasing Mg/Ca ratio towards the edges (Buriánek and Čopjaková, 2008). There are two types of staurolites in the Svratka Crystalline Complex, which have a similar Fe/(Fe + Mg) ratio (0.79–0.88) but a different content of ZnO. Staurolites dispersed in mica schists contain 0.29 to 0.96 wt.% ZnO, whereas staurolites in quartz lentils contain between 3.14 and 3.41 wt.% ZnO. Most of the rocks in the crystalline unit contains the following accessory minerals: apatite, monazite, xenotime, zircon, ilmenite and rutile. One of the common rocks in the area is migmatite, which can locally contain garnet. The chemical composition of this garnet is rather variable ($Alm_{65-88}Sps_{5-23}Prp_{1-10}Grs_{0-12}Adr_{0-4}$).

The major part of the studied stream is carved in the rocks of the Polička Crystalline Complex, which also cover most of the source area of the stream (Buriánek et al., 2006; Čech et al., 2005). This crystalline unit contains a number of rock types but most of them are of a relatively small areal extent. The most plentiful rocks are biotitic to two-mica paragneisses of a varied degree of injection migmatitization with sillimanite, garnet and sometimes tourmaline. Pearl gneisses, amphibolites, marbles, metaconglomerates, qraphitic quartzites, garnetites and calc-silicate rocks are less abundant. These rocks emerge solely in a narrow belt strip along the border with the Svratka Crystalline Complex. Most of the amphiboles embodied in calc-silicate rocks and amphibolites can be classified as magnesiohornblendes. Marbles often contain tremolites. Diopsidic pyroxene commonly occurs in calc-silicate rocks, marbles and some amphibolites. Garnets from calc-silicate rocks are rich in the Grs component. Garnets in gneisses of the Polička Crystalline Complex ($Alm_{58-79}Sps_{1-26}Prp_{8-21}Grs_{0-5}Adr_{0-5}$) exhibit rather high average contents of Prp and Sps and lower contents of Grs in comparison with the garnets in mica schists and gneisses of the Svratka Crystalline Complex. Tourmalines in gneisses are similar in composition to those from the Svratka Crystalline Complex (Fe/(Fe + Mg) = 0.21–0.96; Al_{tot} = 5.57–6.82 apfu) and they can also be classified as schorl-dravites to Al-rich schorl-dravites.

The metamorphosed rocks of Polička Crystalline Complex are intruded by plutonic rocks. Basic and ultrabasic rocks form numerous bodies of a small areal extent (tens to hundreds m in diameter), which are dispersed virtually all over the crystalline complex. Amphiboles in the ultrabasic rocks correspond to tremolite or, rarely, to

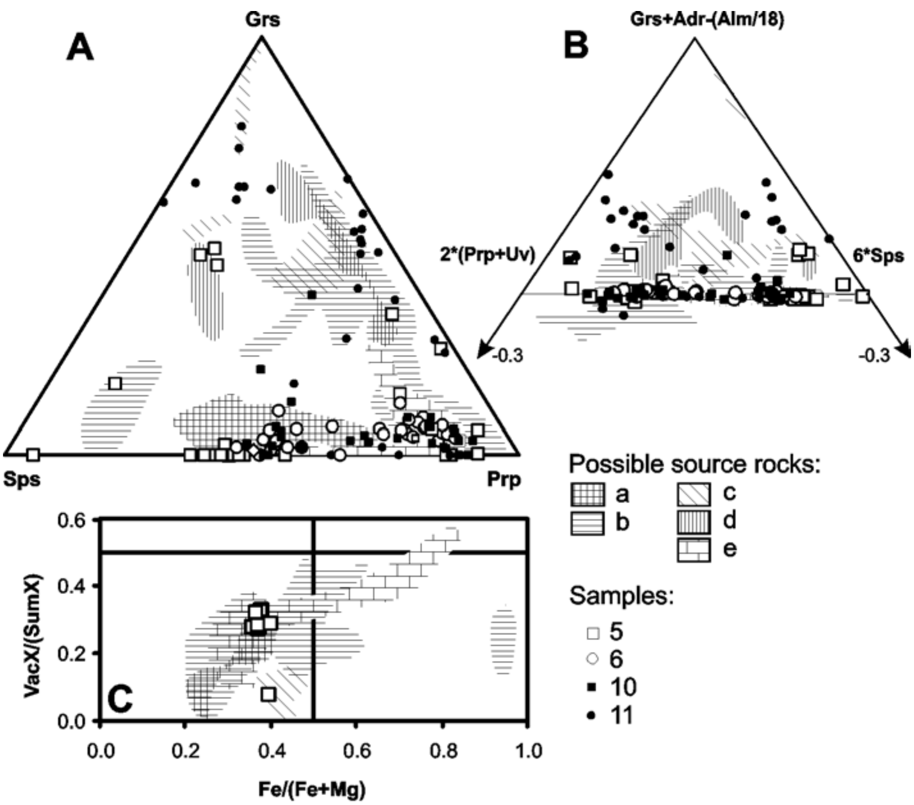

Fig. 3. Plots Sps – Grs – Prp (A), 2*(Prp + Uv) – Grs + Adr-(Alm/18) – 6*Sps (B) for garnets and the plot Fe/(FeO + MgO) – Vac X/(SumX) for tourmaline (C). a – gneisses from the Polička Crystalline Complex, b – mica schists and gneisses from the Svratka Crystalline Complex, c – calc-silicate rocks and garnet--rich rocks from the Polička Crystalline Complex, d – quartz diorite and granodiorite from the Polička Crystalline Complex, e – sediments from Bílá Hora and the Peruc--Korycany Formation (sediments of the Czech Cretaceous Basin). Chemical composition of garnets from the source rocks according to Buriánek et al. (2006), Čech et al. (2005) and Buriánek et al. (in prep.).

magnesiohornblende. Amphibole-pyroxenic to amphibole-biotitic gabbros contain mostly magnesiohornblende with a Mg/(Mg + Fe) ratio ranging from 0.62 to 0.92. Amphibole-biotitic tonalites to granodiorites (sometimes containing pyroxene and garnet) are of a large areal extent in the locality of interest. They contain amphiboles corresponding to magnesiohornblende, tschermakite or actinolite and show slightly lower Mg/(Mg + Fe) ratios than gabbros, i.e. 0.49 to 0.85. Garnets occurring in the igneous rocks demonstrate somewhat higher contents of the Grs component than garnets in gneisses and mica schists ($Alm_{62-80}Sps_{2-15}Prp_{4-14}Grs_{7-16}Adr_{0-4}$). There are also veins and bodies of biotitic to muscovite-biotitic granites, pegmatites and aplites emerging in the locality. The most abundant accessory minerals in the Polička Crystalline Complex are apatite, monazite, xenotime, zircon, ilmenite, rutile and titanite.

Cretaceous sediments contain HMs coming from the surrounding crystalline units (Buriánek et al., in prep.). We have studied samples from the Korycany Formation and from the Bílá Hora Formation, which contain a similar spectrum of HMs. Amphibole and garnet prevail in all samples and minerals typical for amphibolite facies rocks (e.g. staurolite, kyanite and sillimanite) are also always present. In general, the content of the HM fraction corresponds well to the expected spectrum of heavy minerals, which can be derived from the weathered rocks of the Polička and Svratka crystalline complexes. Both samples show a similar range of chemical composition of garnet, tourmaline, staurolite and amphibole. The occurrence, as well as chemical composition of HMs in various stratigraphic horizons by the southern edge of the Vysoké Mýto Syncline, is very constant. We therefore expect the source of the clastic material for these Cenomanian to Lower/Middle Turonian sediments to be rather homogeneous and constant in time. The sedimentary material was transported here from the distances ranging from a few kilometers to several tens of kilometers. Cretaceous sediments can thus be identified only partially in the spectrum of HMs.

Tab. 2
Chemical composition of garnets

Sample	5	5	6	6	10	10	11	11	11	11
SiO_2	37.01	38.29	37.26	36.72	37.19	36.30	36.47	38.66	36.46	37.78
TiO_2	0.02	0.27	0.02	0.02	0.13	0.01	0.10	0.08	0.03	0.11
Al_2O_3	20.50	21.90	21.16	21.10	21.04	20.94	20.51	21.80	20.50	21.25
Cr_2O_3	0.00	0.02	0.06	0.03	0.11	0.01	0.00	0.00	0.00	0.01
Fe_2O_3	1.13	0.82	0.94	1.03	0.97	0.99	1.28	0.89	1.16	1.05
FeO	25.04	25.91	31.45	32.46	33.01	32.24	28.33	23.96	36.18	26.91
MnO	6.27	0.95	1.47	2.68	1.10	5.80	2.62	0.54	1.77	0.53
MgO	1.68	10.07	5.99	4.58	5.79	3.46	0.76	8.66	2.88	4.89
Na_2O	0.00	0.00	0.02	0.02	0.00	0.00	0.02	0.00	0.01	0.00
P_2O_5	0.00	0.02	0.00	0.04	0.04	0.07	0.02	0.02	0.04	0.02
Y_2O_3	0.14	0.01	0.00	0.17	0.01	0.00	0.00	0.04	0.00	0.02
CaO	8.26	1.84	1.76	1.57	1.00	0.59	9.91	5.66	1.34	7.92
Total	100.07	100.10	100.12	100.41	100.39	100.40	100.01	100.31	100.37	100.51
Si^{4+}	2.974	2.943	2.952	2.935	2.949	2.932	2.947	2.964	2.954	2.957
P^{5+}	0.000	0.001	0.000	0.003	0.003	0.005	0.001	0.002	0.002	0.001
Ti^{4+}	0.001	0.016	0.001	0.001	0.008	0.000	0.006	0.004	0.002	0.006
T–site	2.976	2.960	2.953	2.939	2.959	2.937	2.954	2.970	2.958	2.965
Al^{3+}	1.942	1.983	1.976	1.988	1.966	1.993	1.953	1.970	1.958	1.961
Cr^{3+}	0.000	0.001	0.004	0.002	0.007	0.001	0.000	0.000	0.000	0.001
Fe^{3+}	0.068	0.048	0.056	0.062	0.058	0.060	0.078	0.052	0.071	0.062
Ti^{4+}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Y^{3+}	0.006	0.000	0.000	0.007	0.001	0.000	0.000	0.002	0.000	0.001
B–site	2.017	2.032	2.036	2.059	2.032	2.055	2.031	2.023	2.029	2.024
Fe^{2+}	1.683	1.665	2.083	2.170	2.189	2.178	1.914	1.536	2.452	1.761
Mn^{2+}	0.427	0.062	0.099	0.182	0.074	0.396	0.179	0.035	0.121	0.035
Mg^{2+}	0.201	1.153	0.707	0.545	0.684	0.416	0.091	0.990	0.348	0.571
Ca^{2+}	0.711	0.152	0.149	0.134	0.085	0.051	0.858	0.465	0.116	0.665
Na^{+}	0.001	0.000	0.005	0.004	0.001	0.000	0.005	0.000	0.002	0.001
A–site	3.024	3.032	3.044	3.035	3.032	3.041	3.048	3.026	3.039	3.033
Alm	55	54	68	71	71	71	62	50	80	57
Andr	3	2	3	3	3	2	4	3	4	3
Grs	20	3	2	1	0	0	25	13	0	19
Prp	7	39	24	19	23	14	3	33	12	19
Sps	14	2	3	6	3	14	6	1	4	1
Uv	0	0	0	0	0	0	0	0	0	0

Results of the study of the heavy-mineral (HM) fraction

All studied samples have similar contents of the HM fraction (Tab. 1). The locality of the Bílý potok stream was represented by four samples (two samples from the upper stream course and two from the lower course). Sediments of the given catchment area typically contain the following mineral association: garnets + amphiboles + pyroxenes + ilmenite + apatites + tourmalines + Al_2SiO_5 minerals. Monazite in low concentrations is also common.

The HM fraction in the sample No. 14 (stream heavy mineral concentrate from the vicinity of Korouhev) is interestingly and unusually large – the recalculated mass of the HM fraction amounts to 339 g of HMs per 1 m^3 of the sample, the prevalent fraction being the magnetic one. In addition to common minerals, it also contains high concentrations of titanite (class 5) and zircon. Magnetite, spinel, barite and cerrusite are also present.

Garnet prevails in all samples and its abundance increases along the flow direction. In the upper course, the contents range from 100 to 1000 g per 1 m^3 of sediment, whereas in the lower course the contents exceed 1000 g/m^3 (Tab. 1). Amphibole is the second most abundant mineral and its contents follow a similar pattern as those of garnet (i.e. they increase in the direction of the stream flow, see Fig. 2). Concentrations of amphibole range from 50 to 100 g/m^3 in the upper course and from 100 to 1000 g/m^3 in the lower course. Contents of another frequent mineral in the area, ilmenite, grow from 0.1–500 g/m^3 in the upper course to 100–1000 g/m^3 in the lower course. Concentrations of zircon and TiO_2 minerals (rutile, anatase) grow in the same manner, namely from <0.1–1 g/m^3 to 1–50 g/m^3, and the contents of Al_2SiO_5 minerals (kyanite, sillimanite) increase from 1–5 g/m^3 to 5–50 g/m^3. Contrary to all mentioned minerals, the contents of pyroxene decrease from 1–100 g/m^3 in the upper course to 0.1–5 g/m^3 in the lower course. Contents of other present minerals, namely of tourmaline (0.1–5 g/m^3), epidote minerals and phosphates (apatite, monazite, xenotime), are relatively stable.

Chemical composition of the sediment minerals from the Bílý potok stream

The chemical composition was studied in four samples, which were taken in different parts of the watercourse so that the whole source area down to the confluence of the Bílý potok stream with the river Svratka was covered. The predominant mineral in majority of the samples is garnet with prevailing Alm component (Fig. 3), accompanied by higher contents of Prp and Sps components (Alm_{79-54} $Sps_{2-34}Prp_{2-39}Grs_{0-4}Adr_{2-4}$). Less than 10 % of grains contain more than 5 % of the Grs component. Only the sample from the confluence with the Svratka river by Lačnov contains about 60 % of grains having more than 5 % of the Grs component and a variable content of the Prp component ($Alm_{48-75}Sps_{0-18}Prp_{0-34}Grs_{8-28}Adr_{2-5}$). The chemical composition of amphibole is very similar for all studied samples (Tab. 3). Magnesiohornblendes are absolutely prevailing (Fig. 4) and amphiboles correspon-ding to ferrohornblende, ferroactinolite, tschermakite and ferrotschermakite (Mg/(Mg + Fe) = 0.23–0.94, Si 6.05–7.97 apfu) are very rare (classification according to Leake et al., 1997). Tourmaline was thoroughly studied only in one sample, where it corresponded to aluminium-rich schorl--dravites (Fe/(Mg + Fe) = 0.52–0.57, Al = 6.40–6.57 apfu,

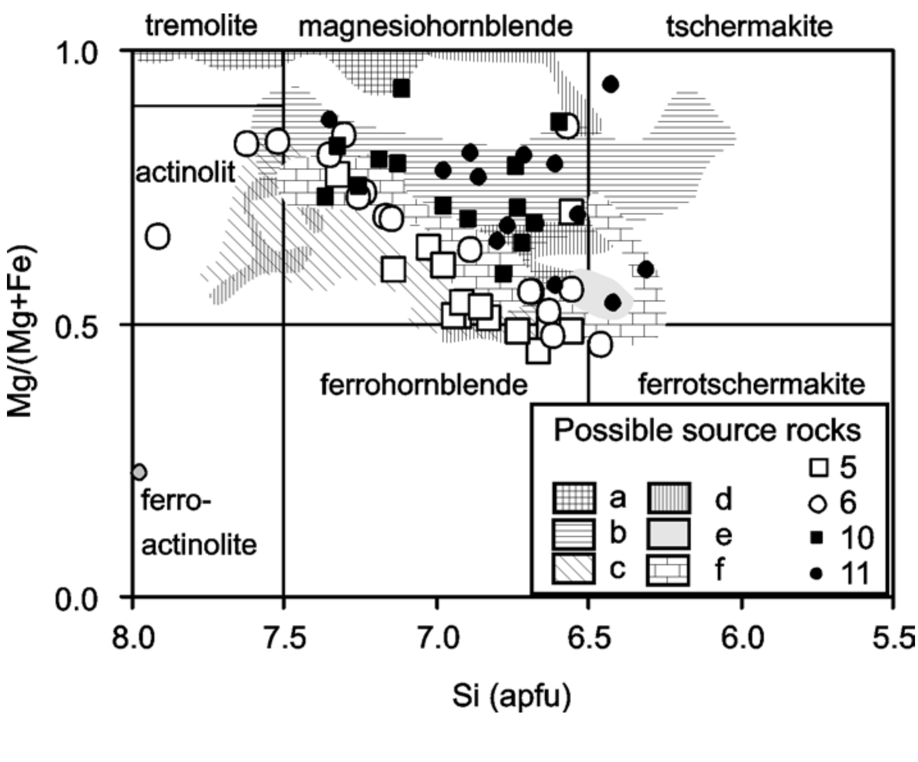

Fig. 4. Classification diagram Si – Mg/(Mg + Fe) (Leake et al., 1997) for the study of amphiboles. a – marbles and ultrabasic rocks from the Polička Crystalline Complex, b – gabbros from the Polička Crystalline Complex, c – tonalites from the Polička Crystalline Complex, d – amphibolites and calc-silicate rocks from the Polička Crystalline Complex, e – amphibolites and calc-silicate rocks from the Svratka Crystalline Complex, f – sediments from Bílá Hora and the Peruc--Korycany Formation (sediments of the Czech Cretaceous Basin). Chemical composition of amphibole from the source rocks according to Buriánek et al. (2006), Čech et al. (2005) and Buriánek et al. (in prep.).

Ca = 0.08–0.15 apfu; Fig. 3). Such chemical composition is typical of metapelites (Henry and Guidotti,1985). Only one grain differed from the others in its chemical composition (Fe/(Mg + Fe) = 0.46, Al = 5.60 apfu, Ca = 0.40 apfu).

Interpretation of chemical composition of selected minerals in the HM sediment fraction

Content of most minerals increases along the stream flow. Based on the comparison of the chemical composition of minerals from the source rocks with that of minerals from sediments, we have estimated the occurrence of heavy minerals from particular rock types in given sediments (since some of the areas in the classification diagrams overlap, the estimation is only approximate).

Stream sediments from upper part of Bílý potok stream (mixture of two sources HM from similar crystalline units)

The first sample from the vicinity of the village of Sádek (sample 5) represents the source area formed from 10 % by the rocks of the Svratka Crystalline Complex and from 90 % by the rocks of the Polička Crystalline Complex.

The contents of heavy minerals in the sediments of this part of the stream (samples 5 and 12) can be slightly variable. Garnet (500–1000 g/m^3) and amphibole (50–100 g/m^3) prevail in both studied samples.

The chemical analysis of the sample 5 revealed that circa 70 % of garnets are derived from the Polička Crystalline Complex and 20 % from the Svratka Crystalline Complex. The source of the remaining 10 % could not be determined. According to the classification diagram (Fig. 3), the vast majority of garnets come from gneisses and mica schists. Only one grain could have been derived from migmatites of the Svratka Crystalline Complex, several other grains come most probably from migmatites of the Polička Crystalline Complex (tonalites and quartz diorites).

The chemical analysis of amphiboles confirmed that more than 90 % of the studied grains can be attributed to the plutonic rocks from the Polička Crystalline Complex (20 % of which are corresponding to amphiboles from gabbros and 80 % to amphiboles from tonalites).

Tourmalines could only be analysed in this sample. Their chemical composition is very homogeneous and similar to that of tourmalines from the Polička Crystalline

Tab. 3
Chemical composition of amphiboles

Sample	5	5	6	6	7	7	8	10	10	11
SiO_2	43.99	48.56	54.06	50.38	48.10	43.00	42.23	44.15	49.97	48.87
TiO_2	0.98	0.61	0.16	0.49	0.62	0.60	0.86	1.31	0.42	0.22
Al_2O_3	9.80	6.90	3.11	6.18	8.63	15.09	11.91	10.84	7.35	8.65
Cr_2O_3	0.04	0.05	0.21	0.22	0.02	0.05	0.00	0.13	0.03	0.02
FeO	18.00	14.34	6.97	9.77	12.46	11.65	16.32	11.65	7.23	6.09
Fe_2O_3	2.51	1.79	1.08	1.52	1.71	4.58	3.05	1.99	4.06	11.39
MgO	8.21	11.94	18.46	15.43	12.59	9.83	8.34	12.52	15.34	12.08
CaO	11.81	12.08	13.01	12.53	11.99	11.04	12.06	12.44	12.33	9.88
MnO	0.79	0.54	0.18	0.32	0.44	0.39	0.39	0.33	0.28	0.17
Na_2O	1.01	0.70	0.29	0.64	0.85	1.25	0.85	1.28	0.60	0.92
K_2O	1.13	0.55	0.15	0.52	0.53	0.29	1.38	1.19	0.30	0.23
Cl	0.05	0.03	0.01	0.02	0.04	0.05	0.15	0.05	0.05	0.01
H_2O^*	2.00	2.06	2.14	2.10	2.07	2.06	1.99	2.05	2.12	2.12
O = Cl	-0.01	-0.01	0.00	0.00	-0.01	-0.01	-0.03	-0.01	-0.01	0.00
Total	100.28	100.14	99.82	100.12	100.04	99.87	99.48	99.91	100.06	100.64
T: Si^{4+}	6.659	7.135	7.622	7.232	7.006	6.309	6.421	6.516	7.125	6.977
Al^{3+}	1.341	0.865	0.378	0.768	0.994	1.691	1.579	1.484	0.875	1.023
C: Al^{3+}	0.407	0.330	0.138	0.278	0.488	0.919	0.554	0.401	0.359	0.432
Ti^{4+}	0.111	0.067	0.016	0.053	0.067	0.066	0.098	0.145	0.045	0.024
Fe^{3+}	0.285	0.198	0.115	0.164	0.188	0.505	0.349	0.221	0.436	1.224
Cr^{3+}	0.004	0.006	0.024	0.025	0.003	0.005	0.000	0.015	0.003	0.002
Mg^{2+}	1.853	2.615	3.880	3.302	2.733	2.150	1.890	2.754	3.261	2.571
Fe^{2+}	2.278	1.762	0.822	1.172	1.518	1.354	2.075	1.438	0.862	0.727
Mn^{2+}	0.061	0.021	0.006	0.005	0.003	0.000	0.033	0.026	0.034	0.020
B: Mg^{2+}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.000	0.000	0.000	0.000	0.000	0.076	0.000	0.000	0.000	0.000
Mn^{2+}	0.040	0.046	0.016	0.034	0.051	0.048	0.016	0.015	0.000	0.000
Ca^{2+}	1.914	1.901	1.965	1.927	1.870	1.736	1.965	1.968	1.884	1.511
Na^{+}	0.046	0.053	0.018	0.039	0.079	0.140	0.019	0.017	0.116	0.254
A: Na^{+}	0.250	0.146	0.059	0.139	0.160	0.214	0.230	0.349	0.050	0.000
K^{+}	0.218	0.103	0.028	0.094	0.099	0.055	0.268	0.223	0.054	0.042
Cl^{-}	0.014	0.006	0.003	0.004	0.010	0.013	0.037	0.014	0.013	0.001
Sum	15.482	15.255	15.090	15.237	15.270	15.282	15.536	15.586	15.116	14.808

Complex, which is, however, overlapping with the field of tourmalines from mica schists of the Svratka Crystalline Complex. Nevertheless, the homogeneous composition of these tourmalines indicates that they most probably come from the Polička Crystalline Complex. One grain most probably comes from calc-silicate rocks of the Polička Crystalline Complex. This sample shows a good overall consistency with the expected petrographic composition in the source area.

Stream sediments from left affluent of the Bílý potok – predominantly Janský potok (Cretaceous sediments as the main sources of HM)

The second sample was taken from a left affluent of the Bílý potok stream in the vicinity of Kamenec u Poličky (sample 6). This tributary drains an area formed predominantly by Cretaceous sediments.

The content of heavy minerals in the sediments of this affluent (sample 6 and 13) can be highly variable, but amphibole (100–500 g/m^3), garnet (500 – greater than 1000 g/m^3) and ilmenite (100–500 g/m^3) prevail in both studied samples. Concentrations of pyroxene and tourmaline are relatively stable (0.1–5 g/m^3).

The relative proportion of individual minerals in stream sediments which originated by weathering of Cretaceous rocks is very similar to that of sediments originated by weathering of the rocks in the crystalline complex. The sample from the locality Kamenec u Poličky represents a source area, which is formed from Cretaceous rocks and from the rocks of the Polička Crystalline Complex. There are two maxima in the chemical composition of garnet. The first corresponds to gneisses of the Polička Crystalline Complex (35 %) and the second to Cretaceous sediments (60 %). The origin of a small amount of grains (5 %) could not be determined. 80 % of amphibole grains can be attributed to gabbros and 15 % to tonalites of the Polička Crystalline Complex. Again, the origin of 5 % of grains could not be determined. This is in good agreement with the fact that one of the affluxes (Janský potok) drains an area, the subsoil of which is formed by a large body of gabbros. The proportion of minerals from the Cretaceous sediments could not be determined unequivocally because the chemical composition of Cretaceous amphiboles coincides to a large extent with that of gabbros and tonalites from the Polička Crystalline Complex. The maximum proportion of this material did not exceed 60 %. We can again observe quite a good congruence between the occurrence of a given group of rocks in the source area and the presence of heavy minerals, which are most probably derived from these rocks, in the stream sediment.

Stream sediments from Korouhevský potok stream (Polička Crystalline Complex as the main sources of HM)

For the HM-studies, two samples 10 and 14 were taken in the drainage area of the Korouhevský potok stream, which is entirely situated within the Polička Crystalline Complex. The compositions of the heavy-mineral associates are in good agreement with the petrographic composition of the source area.

There was an unusually high content of magnetite (80 wt.%) in the sample from the locality of Korouhev (sample 14). This is very likely related to the presence of ultrabasic rocks, which are situated near the sampling site (magnetite is an abundant mineral in these rocks). This anomaly is no longer present in the second sample 10 from the same drainage area, which indicates that the local geological anomalies can substantially influence the spectrum of the present heavy minerals. The prevailing minerals in the spectrum of HMs in this drainage area are garnet and amphibole (50 – greater than 1000 g/m^3), somewhat lower contents of ilmenite and zircon fluctuate between 1 and 1000 g/m^3. Higher contents of amphibole and ilmenite are accompanied by a decrease in the content of titanite and zircon. Contents of tourmaline and pyroxene almost unchanged. These changes are probably related to a higher sediment input from gabbros and tonalites and a lower input from amphibolites and gneisses.

The interpretation of the chemical composition of the sample 10 from the drainage area of the Korouhevský potok stream is not so unambiguous. Only 40 % of garnets correspond to the garnets from gneisses of the Polička Crystalline Complex. The rest of the grains could either not be attributed to any source or they correspond to garnets from Cretaceous sediments (around 50 %), however, there are no Cretaceous sediments in the drainage area of this stream. This peculiarity could perhaps be explained by a presence of residues remaining after the weathering of Cretaceous sediments, which could have been preserved in the bowls on the crystalline bedrock. Neither can we exclude a possible redeposition of the material from old stream sediments. Nevertheless, there is not enough evidence for any of these two theories for the time being.

The chemical composition of amphiboles in sediments nicely reflects the geological situation in the drainage area. Most of the grains have a composition corresponding to that of amphiboles from gabbros of the Polička Crystalline Complex; some grains could have come from ultrabasic rocks, amphibolites and calc-silicate rocks of the same crystalline unit.

Stream sediments from locality near the confluence of the Bílý potok stream and the Svratka river (mixture of various sources of HM)

The fourth sample was taken near the confluence of the Bílý potok stream and the Svratka river at the village of Lačnov, situated on the border of the Svratka and the Polička Crystalline Complex.

The studied HMs could have come from all three aforementioned source areas. The proportion of rocks from the Svratka Crystalline Complex is negligible and it can thus be stated that about 30 % of the drainage area is formed by Cretaceous sediments and about 70 % by the Polička Crystalline Complex.

A closer look at the chemical composition of garnet reveals that there is no direct proportionality between the occurrence of the rocks in the drainage area and the presence of accessory minerals of these rocks in the studied sediment. Unlike the previous samples, this sample contained no material typical for the gneisses of the Polička Crystalline Complex. Most of the grains do not correspond to any of the reference groups (high contents of Grs component). Part of these grains could have come from the Cretaceous sediments. The rest could be derived from various types of calc-silicate rocks, garnetites (Buriánek and Otava, 2007) and quartz diorites of the Polička Crystalline Complex, which have not yet been studied sufficiently. Similar rocks are plentiful only in a narrow belt along the border to the Svratka Crystalline Complex. If this is really the case, the sediments of the Bílý potok stream would preferentially reflect the local geological changes. The Bílý potok stream carves into similar rocks exactly in the section between Lačnov and Sádek. The composition of amphiboles is close to that of amphiboles from the basic rocks of the Polička Crystalline Complex.

Discussion

Supposing the relatively simple geological structure of the rock base, we can determine the extent of the source area based on the chemical composition of HMs. To a certain degree, we can even quantify the volume of the individual rock types, from which the sediments were derived. This is, however, only a rough estimate, which depends on many factors (modal proportion of the studied mineral in the individual source rocks, the intensity and the type of weathering processes, etc.).

If the drainage area gets larger and the geological structure of the rock base gets more complex, the determination of the source rocks becomes also much more complicated. The main problem is usually posed by a high overlap of the chemical composition of minerals coming from different geological units. Another complicating factor can be the presence of rocks with a high content of one of the studied HMs, which are of a small areal extent (e.g. garnetites; Buriánek and Otava, 2007). Such garnets can occur locally in high concentrations, even though there is no corresponding mother rock described in the source area (because it forms only a minuscule body, which can easily be overlooked).

Conclusions

The studied drainage area is formed mainly by volcano-sedimentary rock complex metamorphosed under amphibolite facies and basic to acidic plutonic rocks. Considering the geochemical and mineralogical situation, the studied area includes a variety of rock types, which participate on the formation of clasts of sedimentary rocks. Owing to the similar degree of metamorphism of both main units (the Svratka and the Polička Crystalline Complex), the chemical composition of rock forming minerals from these units overlap in the classification diagrams. There are, nonetheless, rocks containing minerals with a chemical composition specific for only one of the units. Some grains do not correspond to any of the reference groups and could have come from the rests of the older sediments (e.g. Cretaceous sediments).

In the case of small drainage areas with a simple geological structure, the chemical composition of garnet reflects very well the relative proportion of rock types in the given area. For example we are able well define contribution from metasediments, plutonic rocks and calc-silicate rocks. If the drainage area gets bigger and/or if it contains a number of similar geological units, the determination of the source becomes highly problematic. There are often minerals in the HM spectrum, the composition of which does not correspond to any rock type known in the source area. The main reason is probably in the fact that there are often small relicts of older weathered rocks and sediments on the crystalline bedrock (e.g. river terraces), that can contain exotic material.

Another reason can be the presence of small rock bodies, which have not yet been discovered in the area, but which contain high amounts of the studied HM (e.g. garnetites). We very often cannot determine the exact proportion of the material from older sedimentary formations. This is also given by the fact that the source area of the older sediments was similar to that of the studied sediments.

The chemical composition of HMs in the studied locality reveals a substantial impact of the local geological structure. The change of geological structure influences the composition of garnet already within a few first kilometers of the stream. The combination of chemical analyses of garnet, amphibole and tourmaline proved to be a very efficient tool for the determination of the source areas of clastic sediments.

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