First results of systematic provenance analysis of the heavy mineral assemblages from the Albian to Cenomanian exotic flysch deposits of the Klape Unit, Tatricum, Fatricum and some adjacent units

Simona Bellová[1], Roman Aubrecht[1,2] & Tomáš Mikuš[3]

[1]Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, SK-842 15 Bratislava, Slovakia, e-mail: simona.bellova@gmail.com, roman.aubrecht@uniba.sk
[2]Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, SK-845 28 Bratislava, Slovakia
[3] Earth Science Institute, Slovak Academy of Sciences, Workplace Banská Bystrica, Ďumbierska 1, SK-974 01 Banská Bystrica, Slovakia, e-mail: mikus@savbb.sk

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Abstract: This paper brings results of the first systematic heavy-mineral analysis of the oldest exotics-bearing units in the Western Carpathians. Samples the Klape Unit, Poruba Formation (Tatric and Fatric units), Manín Unit and Orava Unit were analyzed. Most samples are dominated by chrome-spinels, zircon, tourmaline, apatite and rutile in various ratios. Garnet occurs in small amounts but there is considerable enrichment in a few samples. Titanite, kyanite, monazite and epidote occur only rarely; sillimanite and staurolite are very rare. There is also a local enrichment in blue amphiboles, pyroxenes, garnet and kyanite in some samples. The analyzed spinel grains predominantly match the harzburgite field, with some overlap to the fields of podiform chromitites and cumulates in the $Mg/(Mg + Fe^{2+})$ vs. $Cr/(Cr + Al)$ diagram. The TiO_2 vs. Al_2O_3 diagram indicates the predominant origin of spinels from the supra-subduction zone peridotites for most of the analyses, whereas the other, aluminium-depleted and higher-titanium grains best match the arc volcanic field. The analyzed blue amphiboles are glaucophanes to ferroglaucophanes and were most likely derived from HP/UHP metamorphosed basaltic rocks in a subduction zone. Pyroxenes are mostly represented by orthopyroxenes (enstatite) and less by clinopyroxenes (augite, diopside). Their common euhedral shape and fresh appearance indicate that they were probably not derived from the same ophiolitic source as the Cr-spinels and blue amphiboles, but rather from some adjacent and nearly coeval volcanics which might be of calc-alkaline provenance. Detrital tourmaline grains in the analyzed samples were mostly unzoned except of some grains; some even possessed a complex intergrowing pattern with a mosaic appearance. Most of the grains were derived from various sorts of metasediments. Almost all tourmaline grains from Havranský vrch Hill were likely derived from Li-poor granitoid rocks. The results indicate input of minerals of dominantly ophiolitic provenance, such as Cr-spinels, blue amphiboles, and eventually mosaic tourmaline. Zircon, rest of the tourmaline and rutile were likely derived from older sediments. Garnet, staurolite, kyanite, sillimanite occurring in relatively small amounts were mostly derived from metamorphic rocks of various degrees of metamorphism. No significant differences were observed among the individual units which most likely shared the same source.

Key words: heavy minerals, provenance, Cr-spinel, blue amphibole, tourmaline, Cretaceous, Western Carpathians.

1. INTRODUCTION

Albian was the time of large paleogeographic and paleotectonic changes all over the Tethyan realm. In the Western Carpathians one of the manifestations of these changes was onset of exotics-bearing flysch sedimentation that in some units lasted to Paleogene. As exotics detritic material of unknown provenance, either of psephitic or psammitic size is considered. Despite of long-time research, content of the exotics, together with unexpected transport directions and position of the exotic flysch deposits is still full of mysteries and their investigation represents large challenge up to now.

Main units consisting of exotics-bearing flysches are Klape Unit in the Pieniny Klippen Belt and Poruba Formation in the Central Western Carpathians (Tatric and Fatric units). These are also the units with the earliest, Albian onset of the exotic flysch deposition. Somewhat younger onset occurred in the Manín Unit in form of the Cenomanian Praznov Formation. Manín Unit, presently situated in the Pieniny Klippen Belt, is considered to be derived either from the Tatric, or Fatric domains of the Central Western Carpathians (Andrusov, 1938; Mahel', 1978; see also Rakús & Hók, 2005 and the references therein). In most of the Oravic units of the Pieniny Klippen Belt (PKB sensu stricto), the input of exotics started later, in the Coniacian, represented by the Sromowce Formation of the Kysuca Unit and some transitional Oravic units (Birkenmajer, 1977). Albian terrigenous psammitic to psephitic input in the Oravic units is rare. There is an occurrence of the Albian flysch of unknown attribution below the large klippe of the Orava Unit (Havranský Hill and Kozinský Hill) near Zázrivá village in Orava territory. It was first described by

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Haško (1977), who presented the contact with the main klippe as tectonic, because the unit is usually placed to the Oravic domain, lacking the Albian flysches. However, closer inspection of the occurrence near Zázrivá shows, that there is a gradual, continuous transition from the Barremian-Aptian marlstones to the Albian flysch and the contact seems to be stratigraphic rather than tectonic and the flysch can be most likely attributed to the Orava Unit. The opinion about attribution of the Orava Unit to Oravic units has been challenged by Mahel' (1986), who presumed that it may be eventually of Fatric provenance. There are also some occurrences of Albian flysch (Trawne Member) attributed to the Kysuca Unit (called Branisko Unit in Poland) as described by Birkenmajer (1987). The most surprising and unexpected was the fact that exotic ophiolitic psammitic material was registered in Upper Aptian-Albian sediments of the Czorsztyn Unit (Aubrecht et al., 2009), which was the shallowest of all the Oravic Units.

In the Central Western Carpathians, the exotics-bearing flysch deposition lasted until the Middle Turonian, when it ceased due to the main nappe thrusting during the Mediterranean Phase of the Alpine Orogeny. In the Klape and Oravic units, the exotics-bearing flysches sedimented until the end of Cretaceous. These were still the pure exotics, with no material derived from the neighbouring Oravic, or Central Carpathian Units. After the Maastrichtian Laramian collision between the internides and the Oravic block, exotic deposition continued in form of the Paleogene Jarmuta-Proč formations, but the detritic material displays strong admixture of new, non-exotic material from the adjacent, emerged units. Exotic sources influenced the deposition in these formations until the Eocene (Mišík et al., 1991).

We focused our research on the earliest, Albian-Cenomanian flysches in the Pieniny Klippen Belt and in the Central Western Carpathians, which mostly occur in the western and central Slovakia. These were subjects of thorough sedimentological and provenance research for several decades. Sedimentological analysis of the flysch deposits in the Klape Unit was done by Marschalko (1986). Poruba Formation in the Central Western Carpathians was defined and thoroughly sedimentologically analyzed by Jablonský (1978, 1986). In provenance analysis, the researchers were mostly attracted by psephitic material, which brings more complete information about the composition of the source areas. The exotic conglomerates of the Klape and Manín units were systematically analyzed mostly for their content of carbonatic pebbles (Mišík & Sýkora, 1981; Birkenmajer et al., 1990; Mišík & Marschalko, 1988), but some less systematic pebble analyses of crystalline metamorphic, magmatic, or siliciclastic rocks were presented, too (e.g. Krivý, 1969; Kamenický et al., 1974; Kamenický & Kráľ, 1979; Šímová, 1982, 1985[a,b,c]; Šímová & Šamajová, 1982; Ivan & Sýkora, 1993; Uher & Marschalko, 1993; Ivan et al., 2006; Zaťko & Sýkora, 2006). Similarly, systematic pebble analysis of carbonate components of the Poruba Formation was performed by Mišík et al. (1981).

Due to numerous data from pebble analyses, systematic analysis of psammitic fraction remained relatively neglected. Only the systematic analysis of the Poruba Formation for the first time included percentual ratios of the heavy minerals (Jablonský, 1986), but the results were published only partly (Jablonský et al., 2001). Provenance analyses of the individual minerals included only point locations (e.g. Sýkora et al., 1997; Straka, 2011), or were performed on selected minerals only, for instance on chrome-spinels (Jablonský et al., 2001).

This paper brings the first, preliminary data of systematic provenance research of heavy minerals in the Albian-Cenomanian exotics-bearing deposits in the Western Carpathians. The main final aim is the comparison with the data from adjacent areas (Eastern Alps, Transdanubian Central Range, Tiszia, Dinarides, etc.), where authors focused their research more to heavy minerals than to pebble analysis. The results presented in this paper are still preliminary because there is still a disproportion in the amount of samples from the individual units. Some units, such as Drietoma Unit in the Pieniny Klippen Belt were not sampled yet at all. The heavy-minerals data will be later complemented also by modal analysis of the examined sandstones.

2. STUDIED SITES AND METHODS USED

Samples from 28 localities were analyzed for heavy minerals: 10 from the Klape Unit (Uhry and Upohlav formations) and 16 from the Poruba Formation. From the latter, 12 localities of the Tatric units (Albian-Cenomanian) and 4 of the Fatric units (Albian - Turonian) were sampled (Fig. 1). So far limited number of Fatric samples will be later complemented by new samples from later field campaigns. For comparison, one sample from the Manín Unit and one from the Orava Unit were selected. Most of the samples were point samples from the scree, because the examined flysch units form outcrops only very rarely (only about 4 "fresh" outcrops were found).

The average weight of the samples was about 2 kg. Samples were crushed, washed in water and sieved to fraction of 0.08 - 1mm. Heavy fraction was separated by heavy liquids (bromoform, polytungstate, with densities of about 2.8). The fraction 0.08 to 0.25 mm was studied in transmitted light and percentual ratios of translucent heavy mineral assemblages were determined by ribbon point counting. Poorly translucent chrome-spinels were counted under the reflected light. Tourmalines, spinels, garnets, pyroxenes and blue amphiboles were hand-picked, embedded to epoxy resin and were subjected to various methods of provenance analysis.

Chemical compositions of the extracted grains were analyzed using a JEOL JXA-8530F electron microprobe at the Earth Science Institute of the Slovak Academy of Sciences in Banská Bystrica. The analytical conditions were 15 kV accelerating voltage and 20 nA beam current, with a peak counting time of 10 seconds for all standards, except of Ni and Zn (15 and 60 seconds, respectively), and a beam diameter of 2 to 10 μm. A beam diameter for spinel and garnet grains was 2 μm and 3 μm for tourmaline grains. Standards used: Si – orthoclase, Ti - TiO_2, Al - Al_2O_3, V – metallic V, Cr – metallic Cr, Fe – fayalite, Mn – rhodonite, Ni – metallic Ni, Zn – willemite, Mg – forsterite or MgO, Ca – wollastonite, Na – albite, K – orthoclase, F – LiF, and Cl – NaCl. Spectral line: Kα for all standards. Raw counts were corrected using a PAP routine.

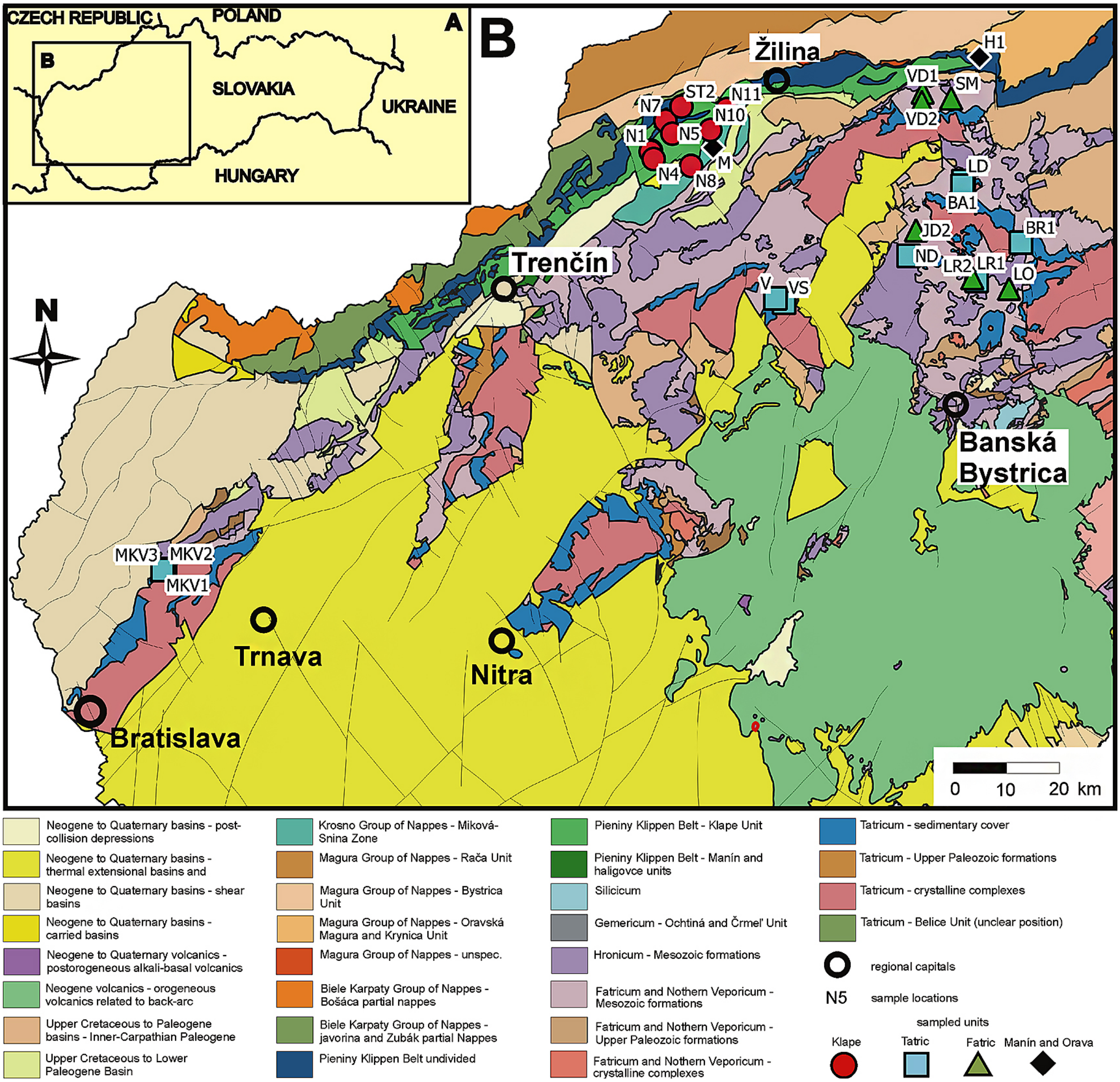

Fig. 1. **Position of the sampled localities in Slovakia and its geological units. Abbreviations of the localities names are explained in Tab. 1.**

A small amount of samples was also analyzed using a CAMECA SX-100 electron microprobe at the State Geological Institute of Dionýz Štúr in Bratislava under similar conditions.

3. RESULTS

3.1. Heavy mineral contents in the sandstones

Comparison of the heavy minerals assemblages (Fig. 2, Tab. 1) showed that most samples are dominated by chrome-spinels, zircon, tourmaline, apatite and rutile in various ratios. Garnet appears in small amounts (less than 11 %) in many samples. However, in the samples from Ľubochnianska dolina Valley (Tatricum) and Medziholie Saddleback (Fatricum), its ratio increases up to 78% and 76.5 %, respectively. Content of apatite increased in the sample from Záskalie to 58.6%. Titanite, kyanite, monazite and epidote occur only in some samples in relatively small amounts. At Havranský vrch Hill, the kyanite amount increased to 13.1 %. Very rare are sillimanite and staurolite. Blue amphiboles and pyroxenes are significant components in some samples from several occurrences. At Predmier (Klape Unit), blue amphiboles form more than 20 %. Pyroxenes occur at Balcová (Tatricum) and Liptovská Osada (Fatricum) localities (more than 45 %), as well as at Malé Karpaty Mts. – Vývrat locality (Tatricum, more than 10 %). Presence of chloritoid micas in some samples (e.g. Uhry) is worth mentioning as they were also reported from the exotic flysches in the Eastern Alps (Woletz, 1963; Von Eynatten & Gaupp, 1999). They were not included herein in the heavy mineral percentages because density of micas

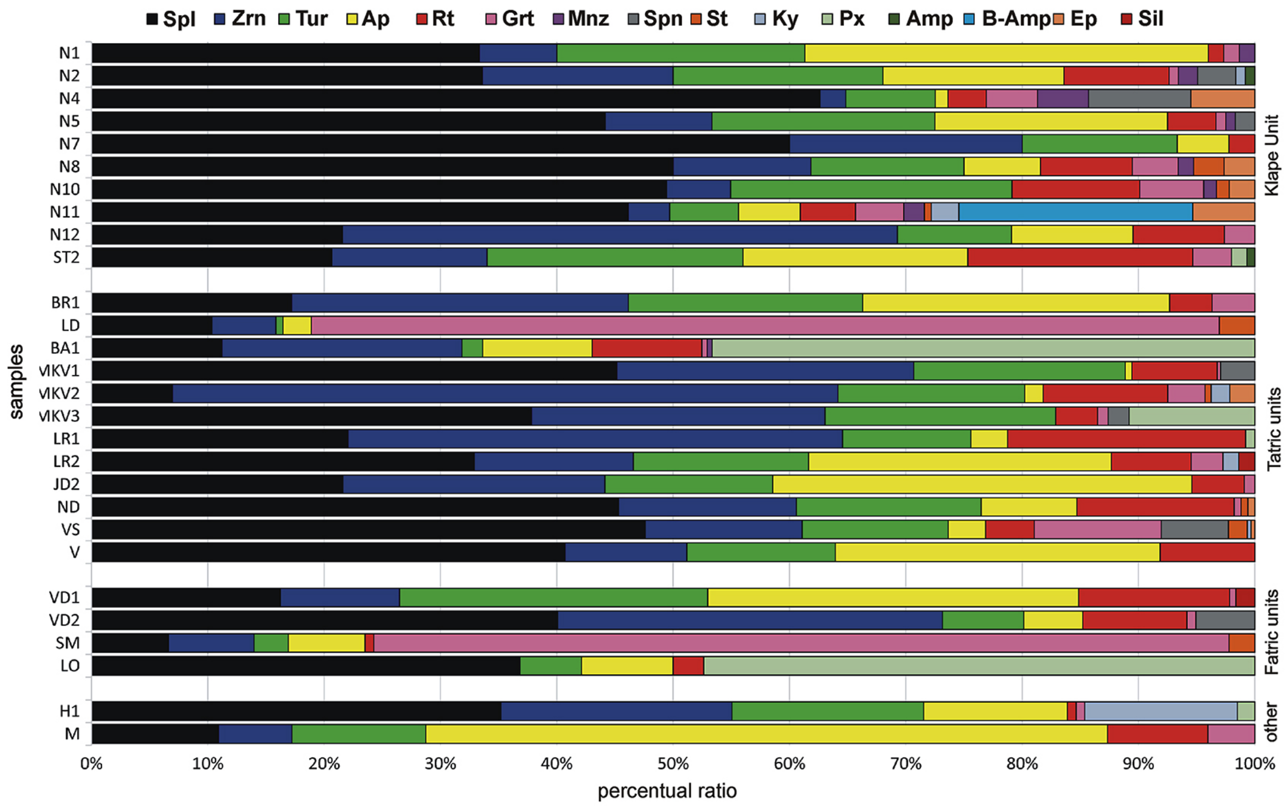

Fig. 2. Percentual ratios of the heavy minerals in the analyzed samples. Mineral abbreviations (after Whitney & Evans, 2010): Spl – spinel, Zrn – zircon, Tur – tourmaline, Ap – apatite, Rt – rutile, Grt – garnet, Mnz – monazite, Spn – titanite, St – staurolite, Ky – kyanite, Px – pyroxene, Amp – amphibole, B-Amp – blue amphibole, Ep – epidote, Sil - sillimanite.

is not always higher than the density of heavy liquid used for separation and the number of their grains in heavy fraction is incomplete. Baryte grains at some localities occurred in considerable amounts, e.g. at Uhry, Balcová, Stupné, Havranský vrch Hill and Jasenská dolina Valley. However, this mineral is most likely of authigenic origin and cannot be involved among the clastic admixture analyzed for provenance purpose. No significant differences between the percentual ratios of heavy minerals were observed among the individual units, except of slightly increased content of chrome-spinel in the Klape Unit versus slightly higher ratio of zircon in the Poruba Formation.

Assessed ZTR index (proportion of ultrastable zircon-tourmaline-rutile trinity – Hubert, 1962) is relatively moderate. However, when chrome-spinels ratio is added to this index, it is evident that most of the samples are vastly and systematically dominated by ultrastable and resistant minerals (spinels also belong to very resistant minerals). The ratio is lower only in the samples with exceptionally higher content of garnet, pyroxene or apatite.

3.2. Chemical analyses of selected heavy minerals

For provenance analysis, microanalyses of the most common heavy minerals, such as chrome-spinels and tourmaline were performed. Along with them, minerals which are important from the provenance and petrogenetic points of view were analyzed, such as blue amphiboles, pyroxenes and garnets.

3.2.1. Chrome-spinels

The analyzed spinel fragments are relatively homogeneous, without visible zonation. Only in one grain from Uhry locality, there was an alteration rim visible (Fig. 3B). Many spinel grains show porosity caused by dissolution of the pyroxene and olivine inclusions during weathering (Fig. 3A). No measurable inclusions were preserved. The spinel primary provenance may be assessed by chemical variability in the main elements which are diagnostic of their provenance, such as Mg, Fe, Cr, Al, and Ti (Tab. 2). Two types of diagrams are used for the provenance estimation: (1) $Mg/(Mg + Fe^{2+})$ vs. $Cr/(Cr + Al)$, and (2) Al_2O_3 vs. TiO_2. The first one was introduced by Dick & Bullen (1984), who distinguished three fields in their diagram: (1) Type I ophiolites which correspond to peridotite for which $Cr/(Cr + Al)$ in spinel does not exceed 0.60. These peridotites evolved in mid-oceanic ridge settings; 2) Type III ophiolites representing peridotites bearing spinel with $Cr/(Cr + Al)$ above 0.60, which are related to the early stages of arc formation on oceanic crust; and 3) Type II ophiolites bearing spinels with a wide range of $Cr/(Cr + Al)$, representing transitional phases. Based on these classifications, Pober & Faupl (1988) discriminated spinels derived from harzburgite and lherzolite rocks.

To distinguish the spinels derived from peridotites and volcanics, a diagram of TiO_2 vs. Al_2O_3 was developed by Lenaz et al. (2000) and Kamenetsky et al. (2001). The boundary between peridotitic and volcanic spinels was set at a TiO_2 value of 0.2 wt% (for overview see Lenaz et al. 2009).

Tab. 1. Percentual ratios of heavy minerals in the analyzed samples. Abbreviations of mineral names – see Fig. 2. ZTR = sum of the percentages of the ultrastable trinity zircon-rutile-tourmaline (ZTR index).

Sample	Localization	Unit	N-latitude	E-longitude	Spl	Zrn	Tur	Ap	Rt	Grt	Mnz	Spn	St	Ky	Px	Amp	B-Amp	Ep	Sil	ZTR	ZTR+Spl
N1	Nosice - railway	Klape	49°7′31.45″	18°21′51.60″	33.3	6.7	21.3	34.7	1.3	1.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.3	62.7
N2	Nosice - valley above the railway	Klape	49°7′24.85″	18°21′48.31″	33.6	16.4	18.0	15.6	9.0	0.8	1.6	3.3	0.0	0.8	0.0	0.8	0.0	0.0	0.0	43.4	77.0
N4	Nosice - ridge	Klape	49°6′42.66″	18°22′17.82″	62.6	2.2	7.7	1.1	3.3	4.4	4.4	8.8	0.0	0.0	0.0	0.0	0.0	5.5	0.0	13.2	75.8
N5	Uhry - abandoned quarry	Klape	49°9.252′	18°24.961′	44.2	9.2	19.2	20.0	4.2	0.8	0.8	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.5	76.7
N7	Udiča - conglomerate outcrop at the road	Klape	49°10′29.35″	18°23′51.00″	60.0	20.0	13.3	4.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.6	95.6
N8	Považská Bystrica - outcrop at Tesco	Klape	49° 6′9.90″	18°27′53.56″	50.0	11.8	13.2	6.6	7.9	3.9	1.3	0.0	2.6	0.0	0.0	0.0	0.0	2.6	0.0	32.9	82.9
N10	Plevník - abandoned quarry	Klape	49°9′44.35″	18°30′35.68″	49.5	5.5	24.2	0.0	11.0	5.5	1.1	0.0	1.1	0.0	0.0	0.0	0.0	2.2	0.0	40.7	90.1
N11	Predmier - roadcut	Klape	49°11′49.87″	18°32′56.95″	46.2	3.6	5.9	5.3	4.7	4.1	1.8	0.0	0.6	2.4	0.0	0.0	20.1	5.3	0.0	14.2	60.4
N12	Stupné - conglomerate outctop at the river	Klape	49°11′56.34″	18°26′9.98″	21.6	47.7	9.8	10.5	7.8	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.4	86.9
ST2	Stupné 2 - conglomerate outctop at the river	Klape	49°11′56.34″	18°26′9.98″	20.7	13.3	22.0	19.3	19.3	3.3	0.0	0.0	0.0	0.0	1.3	0.7	0.0	0.0	0.0	54.7	75.3
BR1	Valley towards Brankovo Waterfall	Tatric	49°59′33.3	19°17′20.2″	17.2	28.9	20.1	26.4	3.7	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.7	70.0
LD	Ľubochnianska dolina Valley - slope	Tatric	49°5′27.5″	19°8′33.0″	10.4	5.5	0.6	2.4	0.0	78.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1	16.5
BA1	Balcová - forrest road - below the Krížna Nappe	Tatric	49°5′0.0″	19°8′25.7″	11.2	20.6	1.8	9.4	9.4	0.4	0.4	0.0	0.0	0.0	46.6	0.0	0.0	0.0	0.0	31.8	43.0
MKV1	Malé Karpaty Mts. - Vývrat - forrest road-cut	Tatric	48°24′29.1″	17°12′05.6″	45.2	25.5	18.2	0.6	7.3	0.3	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	51.0	96.2
MKV2	Malé Karpaty Mts. - Vývrat - forrest road curve	Tatric	48°24′37.4″	17°12′36.1″	7.0	57.2	16.0	1.6	10.7	3.2	0.0	0.0	0.5	1.6	0.0	0.0	0.0	2.1	0.0	84.0	90.9
MKV3	Malé Karpaty Mts. - Vývrat - scree at the forrest road	Tatric	48°24′30.6″	17°12′13.4″	37.8	25.2	19.8	0.0	3.6	0.9	0.0	1.8	0.0	0.0	10.8	0.0	0.0	0.0	0.0	48.6	86.5
LR1	W of Liptovské Revúce - sandstone in the Turecký potok creek	Tatric	48°55′58.5″	19°10′14.0″	22.0	42.5	11.0	3.1	20.5	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	74.0	96.1
LR2	W of Liptovské Revúce - field road-cut	Tatric	48°55′42.3″	19°10′52.6″	32.9	13.7	15.1	26.0	6.8	2.7	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	1.4	35.6	68.5
JD2	Jasenská dolina Valley - road-cut below the ski downhill course	Tatric	49°0′31.3″	19°1′40.4″	21.6	22.5	14.4	36.0	4.5	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	41.4	63.1
ND	Necpalská dolina Valley - at the necpaly Creek	Tatric	48°57′59.6″	19°0′40.6″	45.3	15.3	15.9	8.2	13.5	0.6	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.6	0.0	44.7	90.0
VS	Vyšehradné Pass - scree at the road	Tatric	48°53′4.1″	18°42′23.2″	47.6	13.5	12.5	3.2	4.2	10.9	0.0	5.8	1.6	0.3	0.0	0.0	0.0	0.3	0.0	30.2	77.8
V	Vyšehradné - roadcut above the village	Tatric	48°53′28.1″	18°41′4.4″	40.7	10.5	12.8	27.9	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.4	72.1
VD1	Vrátna dolina Valley - at the turning to Štefanová	Fatric	49°14′1.2″	19°2′8.7″	16.2	10.3	26.5	31.9	13.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	49.7	65.9
VD2	Vrátna dolina Valley - Pod Sokolím Hotel - roadcut	Fatric	49°13′5.3″	19°2′2.9″	40.1	33.1	7.0	5.1	8.9	0.8	0.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49.0	89.1
SM	Medziholie Saddleback	Fatric	49°13′31.02″	19°6′25.11″	6.6	7.4	2.9	6.6	0.7	73.5	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	11.0	17.6
LO	Liptovská osada - south of the village at the main road	Fatric	48°55′0.8″	19°15′43.3″	36.8	0.0	5.3	7.9	2.6	0.0	0.0	0.0	0.0	0.0	47.4	0.0	0.0	0.0	0.0	7.9	44.7
H1	Havranský vrch Hill - creek-cut	Orava	49°17′36.9″	19°10′31.0″	35.2	19.9	16.5	12.4	0.7	0.7	0.0	0.0	0.0	13.1	1.5	0.0	0.0	0.0	0.0	37.1	72.3
M	Záskalie	Manín	49°08′1.34″	18°31′6.56″	10.9	6.3	11.5	58.6	8.6	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.4	37.4

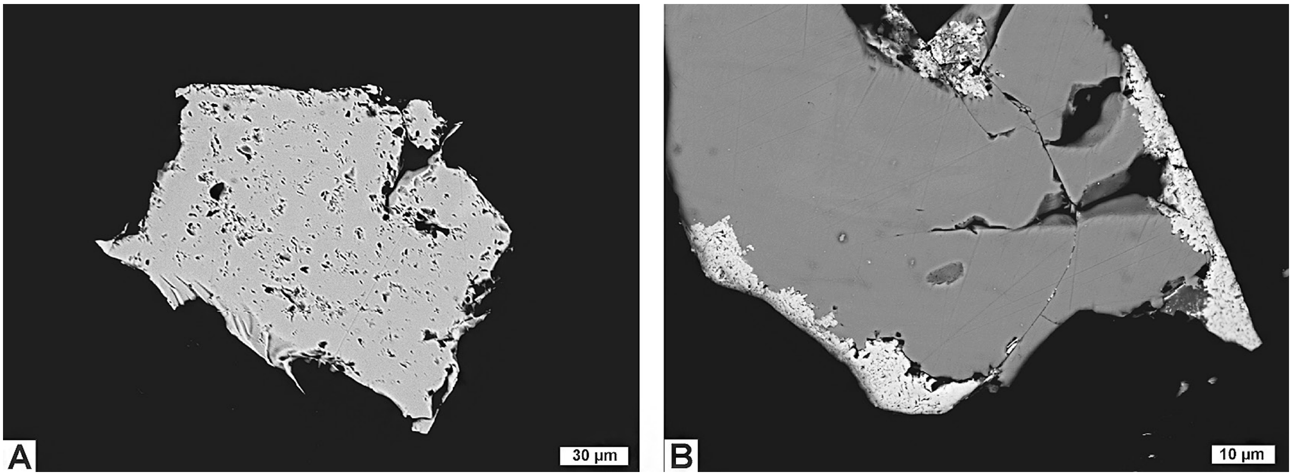

Fig. 3. BSE images of some analyzed spinels. A – Porous, weathered grain with leached inclusions, Vyšehradné Pass. B – Spinel grain (darker) with altered rim (lighter), Uhry.

In the Mg/(Mg + Fe^{2+}) vs. Cr/(Cr + Al) diagram (Fig. 4), the analyzed grains match harzburgites, with some overlap to the fields of podiform chromitites and cumulates (Pober & Faupl, 1988). Some spinels plotted outside the distinguished fields, having higher amounts of Cr and Fe, were most likely affected by alteration or metamorphism. Only 3 grains displayed

Tab. 2. Representative analyses of the spinel grains.

Sample/analysis	Uh-18	Uh-20	Uh-16	N-R-6	N-R-10	Pl-26	Pl-27	VP-1	VP-8	Pr-1	Pr-2
FeO	17.65	21.43	19.48	22.49	14.94	19.65	19.75	25.85	16.62	17.01	16.52
Al_2O_3	22.59	12.11	18.99	11.71	31.39	19.14	20.93	22.21	28.50	29.78	29.06
Cr_2O_3	46.07	56.76	48.75	56.07	37.66	48.30	46.04	41.49	40.54	38.79	39.62
MgO	12.43	8.66	11.56	8.63	14.76	11.04	11.14	9.81	13.95	14.23	14.19
TiO_2	0.09	0.13	0.13	0.12	0.14	0.04	0.04	0.42	0.09	0.07	0.05
MnO	0.27	0.45	0.27	0.43	0.15	0.31	0.27	0.35	0.27	0.34	0.25
TOTAL	99.10	99.53	99.19	99.45	99.03	98.48	98.17	100.13	99.98	100.21	99.69
Formulae based on 3 cations, 4 O anions and iron valence calculation											
Fe^{2+}	0.42	0.56	0.45	0.56	0.35	0.47	0.47	0.53	0.37	0.36	0.36
Fe^{3+}	0.04	0.04	0.07	0.06	0.02	0.06	0.06	0.14	0.04	0.06	0.05
Mg	0.58	0.43	0.55	0.43	0.65	0.53	0.53	0.46	0.62	0.63	0.63
Al	0.83	0.47	0.71	0.46	1.09	0.72	0.78	0.82	1.00	1.04	1.02
Cr	1.13	1.49	1.22	1.47	0.88	1.22	1.16	1.03	0.96	0.91	0.93
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Mn	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Sum A	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sum B	1.96	1.96	1.93	1.94	1.98	1.94	1.94	1.86	1.96	1.94	1.95
Mg/(Mg+Fe^{2+})	0.58	0.43	0.55	0.43	0.65	0.53	0.53	0.46	0.62	0.63	0.63
Cr/(Cr+Al)	0.58	0.76	0.63	0.76	0.45	0.63	0.60	0.56	0.49	0.47	0.48
End members (mol %)											
Galaxite	1	1	1	1	0	1	1	1	1	1	1
Ulvöspinel	0	0	0	0	0	0	0	1	0	0	0
Spinel	24	10	19	10	36	19	21	19	31	32	32
Hercynite	17	13	16	13	19	17	18	22	19	19	19
Magnesioferrite	1	1	2	1	1	2	2	3	1	2	1
Magnetite	1	1	2	2	0	1	1	4	1	1	1
Magnesiochromite	33	32	33	31	29	32	31	23	30	28	29
Chromite	24	41	27	41	15	28	27	27	18	17	17

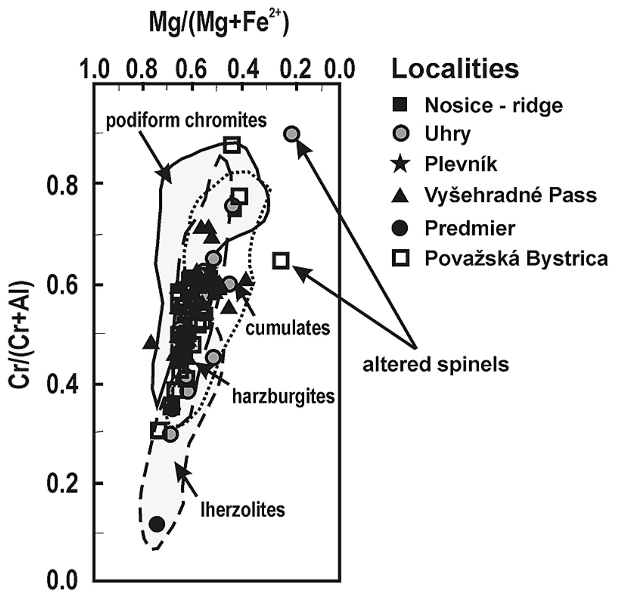

Fig. 4. Analyzed spinels plotted in the Mg/Mg + Fe^{2+} vs. Cr/Cr + Al diagram with fields distinguished by Pober & Faupl (1988).

chemical composition plotted to the non-overlapping part of the lherzolite field. The TiO_2 vs. Al_2O_3 diagram (Lenaz et al. 2000, 2009; Kamenetsky et al. 2001) indicates the origin of spinels in the supra-subduction zone peridotites for most of the analyses, whereas the other, aluminium-depleted and higher-titanium grains best match the arc volcanic field. Three grains that were plotted to pure lherzolite field in the previous diagram are plotted to the non-overlapping part of the MORB peridotites field (Fig. 5). The altered spinels display low aluminium content and some of them plot outside of any pre-defined fields of the fresh magmatic spinels.

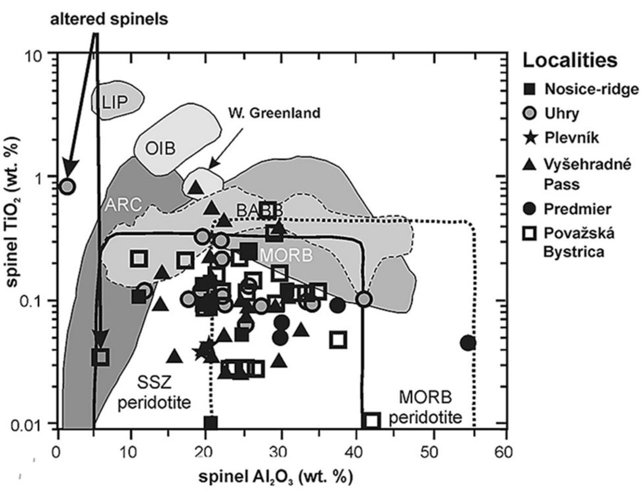

Fig. 5. Measured spinels plotted in the TiO_2 vs. Al_2O_3 diagram of Lenaz et al. (2000) and Kamenetsky et al. (2001). Explanations: LIP – large igneous provinces, OIB – ocean island basalts, ARC – island-arc magmas, BABB – back-arc basin basalts, MORB – middle ocean ridge basalts, SSZ – supra-subduction zone peridotites.

3.2.2. Tourmaline

Detrital tourmaline grains in the analyzed samples had brown to green but mostly khaki-green colour. They were mostly subhedral; euhedral grains were rare. Observations of BSE images show that the tourmaline grains are mostly unzoned but some possess distinct zonation (Fig. 6A-C, Tab. 3) and some even display a complex intergrowing pattern of two phases, attaining a mosaic appearance of the tourmaline grain (Fig. 6D-F).

According to classification diagrams of Henry et al. (2011), most of the tourmalines belong to the alkali and X-vacant groups (Fig. 7) with schorlitic-dravitic, less foititic and magnesio-foititic composition with higher proportion of X-site vacancies (Fig. 8). Discrimination diagrams of Henry & Guidotti (1985) revealed that the main portion of tourmaline grains were likely derived from metasediments, i.e. from metapelites and metapsammites coexisting, or not coexisting with an Al-saturating phase; some were also derived from Fe^{3+}-rich quartz-tourmaline rocks, calc-silicate rocks and metapelites (Figs. 9-10). The metasedimentary source rocks were mostly poor in Ca (Fig. 9B). There is also a group of tourmaline crystals (e.g. almost entire sample from Havranský vrch Hill) which show composition belonging to the field of Li-poor granitoid rocks and their associated pegmatites and aplites.

In the zoned crystals, the overgrowing zones are mostly situated in the metasediment fields (Fig. 10). However, in one grain (Fig. 6C), the overgrowing zone displayed magnesium-depleted composition, corresponding to Li-poor granitoid rocks (Fig. 10).

3.2.3. Blue amphiboles

Blue amphiboles were found only at the Predmier locality. They possess rich blue colour, with pleochroism up to violetish shades (Fig. 11). The grains are mostly broken and subhedral.

The microanalyses show that the amphiboles fulfill the parameters for ranking them to the group of sodic amphiboles (Tab. 4): $B(Na + Li)/\Sigma B \geq 0.75$, $BNa/\Sigma B \geq BLi/\Sigma B$ (Hawthorne et al., 2012). Because the resulting formulas show that $Al^{VI} \geq Fe^{3+}$, majority of the analyzed amphiboles was situated in the field of glaucophane and some to the ferroglaucophane fields (Fig. 12, Leake et al., 1997). Based on pressure estimation according to the sodium and aluminium contents (Brown, 1977), the measured amphiboles originated at the pressures between 6 and 7 kb, but closer to 7 kb (Fig. 13).

3.2.4. Pyroxenes

Pyroxenes were found in higher amounts (over 40 %) at Liptovská Osada and Balcová localities; several grains were found at Vývrat locality (over 10 %). Small amounts (over 1 %) were also found at Havranský vrch Hill and Stupné localities. The pyroxene grains are mostly of greenish-brown colour, with faint pleochroism, broken, mostly subhedral, but fully euhedral grains are also common (Fig. 14). Only pyroxenes from the Výwrat and Balcová localities have been analyzed yet (Tab. 5). According to Ca, Fe and Mg ratios (Fig. 15), most of them are likely classified as enstatite; only four grains were in the fields of augite and diopside (Morimoto et al., 1988).

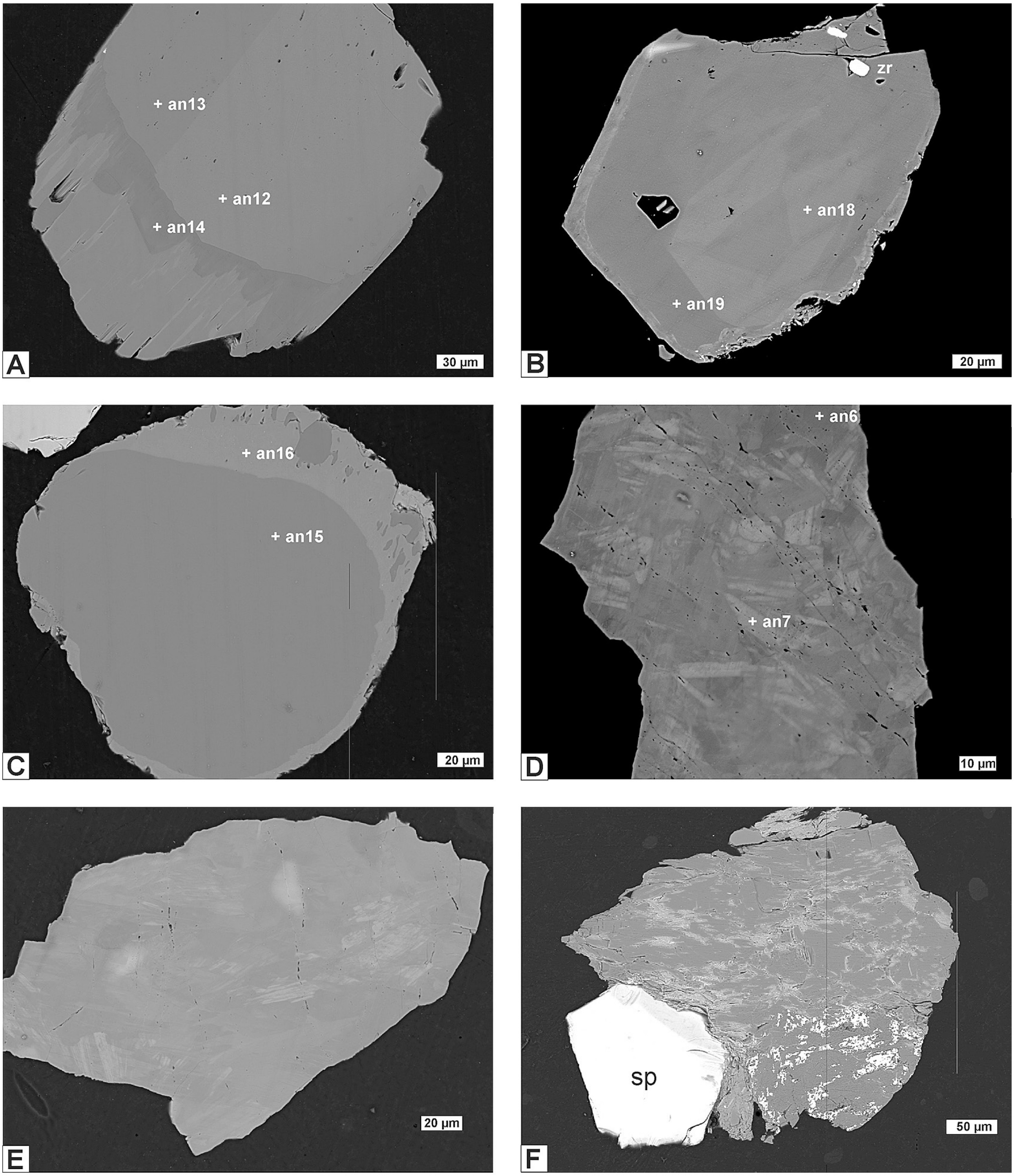

Fig. 6. BSE images of zoned tourmalines. A-C – Tourmaline grains with regular zoning formed by overgrowing of later rims onto earlier cores. The analyzed points are indicated (see the results in Tab. 3), A, C – Uhry, B – Plevník. D-F – Tourmaline grains with complex, mosaic zoning. The white grain in F is spinel. It is unclear whether the tourmaline and spinel grains were mutually attached already in the source rocks, or they were attached by pressure in the resulting sediment. D-E – Nosice - ridge, F – Plevník.

3.2.5. Garnet

The garnet grains were transparent, colourless to pale pink under microscope; they represented mainly fragments of crystals without preserved crystal faces or zonation. Only 5 grains from 3 localities have been analyzed so far (Fig. 16, Tab. 6). 3 grains show a clear dominance of almandine molecule (up to nearly 74 %); and two other grains possessed elevated pyrope contents (over 25 %).

Tab. 3. Representative analyses of the tourmaline grains.

Locality			Uhry			Plevník		Nosice	Havranský vrch	
Analysis No.	**Uh-12**	**Uh-13**	**Uh-14**	**Uh-15**	**Uh-16**	**Pl-18**	**Pl-19**	**N-r-6**	**H-138**	**H-139**
Mineral	**Dravite**	**Dravite**	**Dravite**	**Dravite**	**Schorl**	**Dravite**	**Dravite**	**Schorl**	**Schorl**	**Foitite**
SiO_2	35.09	35.65	36.90	35.45	35.08	35.87	36.14	35.25	34.77	34.08
TiO_2	0.92	0.86	0.03	0.69	0.17	0.64	0.30	0.14	0.40	0.22
B_2O_3 calc.	10.16	10.40	10.47	10.37	10.13	10.36	10.44	10.08	10.29	10.21
Al_2O_3	29.66	31.33	31.15	32.31	30.98	30.79	31.85	27.13	33.86	34.86
FeO	8.76	6.50	3.85	6.92	13.16	5.52	6.49	12.37	14.65	14.55
MnO	0.01	0.01	0.01	0.02	0.04	0.02	0.06	0.11	0.19	0.16
MgO	6.36	7.24	9.47	6.19	3.36	7.91	7.24	7.05	0.43	0.15
CaO	0.51	0.76	0.02	0.50	0.02	0.92	0.18	0.49	0.09	0.15
Na_2O	1.95	1.69	1.42	1.60	1.59	1.64	1.78	2.07	2.00	1.08
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2O calc.	3.51	3.59	3.62	3.58	3.49	3.58	3.60	3.48	3.55	3.53
Total	96.93	98.03	96.94	97.61	98.01	97.23	98.07	98.17	100.23	99.00
Formulae based on 15 Y + Z + T cations, 3 B cations and 4 (OH) anions										
Si	6.01	5.96	6.13	5.95	6.03	6.02	6.02	6.09	5.88	5.81
Al T	0.00	0.04	0.00	0.05	0.00	0.00	0.00	0.00	0.12	0.19
Sum T	6.01	6.00	6.13	6.00	6.03	6.02	6.02	6.09	6.00	6.00
B	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Ti	0.12	0.11	0.00	0.06	0.09	0.08	0.04	0.02	0.05	0.03
Al Y+Z	5.98	6.14	6.10	6.34	6.39	6.09	6.25	5.52	6.62	6.81
Fe	1.25	0.91	0.53	0.97	1.89	0.77	0.90	1.78	2.07	2.07
Mn	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.02	0.03	0.02
Mg	1.62	1.80	2.34	1.55	0.86	1.98	1.80	1.81	0.11	0.04
Sum Y+Z	8.98	8.96	8.98	8.92	9.23	8.93	9.00	9.15	8.88	8.98
Ca	0.09	0.14	0.00	0.09	0.00	0.16	0.03	0.09	0.02	0.03
Na	0.65	0.55	0.46	0.52	0.53	0.54	0.58	0.70	0.66	0.36
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vac.	0.25	0.31	0.54	0.39	0.46	0.30	0.39	0.21	0.32	0.61
Sum X	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sum cat.	18.99	18.96	19.12	18.92	19.25	18.95	19.02	19.23	18.88	18.97
OH	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
O total	31.09	31.13	31.05	31.05	31.08	31.13	31.23	30.88	31.17	31.27
Fe/(Fe+Mg)	0.44	0.33	0.19	0.39	0.69	0.28	0.33	0.50	0.95	0.98

4. DISCUSSION

4.1. Percentages of heavy minerals

The percentual ratios of heavy minerals in the examined samples are variable, but as a whole they are consistent and similar to each other. Except of some local excursions of some minerals like garnets, pyroxenes, apatites, or blue amphiboles, most of the samples are dominated by chrome-spinels, zircon, tourmaline, apatite and rutile, with generally less amount of garnet, titanite, kyanite, monazite and epidote. If compared with previous data of Jablonský (1986) and Jablonský et al. (2001), there is a significant inconsistence. Generally underestimated amount of Cr-spinels can be explained by the different methodics used. In the previous data, only translucent minerals were counted in transmitting light. As Cr-spinels are often opaque, or translucent only at the margins, their counting in transmitting light may bring incomplete data. Checking of spinel grains number by counting in reflected light is much closer to reality and the quantity of grains is considerably higher. More difficult is to explain a disproportion in zircons and tourmalines. In the works of Jablonský (1986) and Jablonský et al. (2001), zircon grains considerably dominate the rest of the heavy mineral assemblages and the number of tourmaline is systematically smaller. From the data presented herein it is

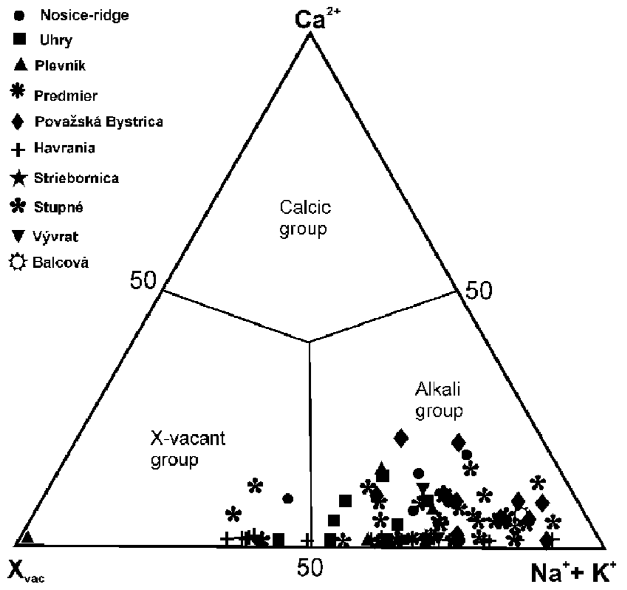

Fig. 7. $^{X}\square$ **(X-site vacancy) vs.** $Na^{+}+K^{+}$ **vs.** Ca^{2+} **classification diagram of tourmalines (Henry et al., 2011).**

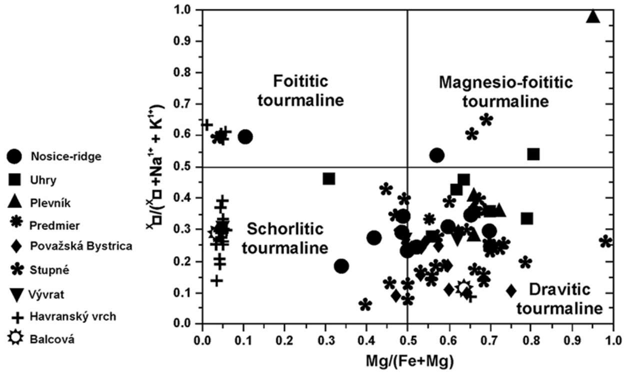

Fig. 8. $Fe/(Fe+Mg)$ **vs.** $^{X}\square/(^{X}\square+Na^{1+}+K^{1+})$ **classification diagram of tourmalines (Henry et al., 2011).**

obvious that the average amount of zircon and tourmaline is more or less the same, of course in varying proportions. Reason of this disproportion is difficult to assess. Presumably it also arose from a different methodical approach, although according to the description of counting methods used by Jablonský (l.c.) they appear to be similar as those used in this paper. There was a difference in sieves used to separate the fraction needed for microscopic preparates. Jablonský (1986) used the 0.1-0.5 mm fraction, whereas 0.08-0.25 mm fraction was used in this research. This, however does not explain the difference, because zircon grains are generally much smaller than those of tourmaline and using slightly coarser fraction would lead to enrichment of tourmaline, not zircon. Another eventual possibility is a kind of sorting by pouring the minerals during sample preparation.

Despite the mentioned differences it can be stated that the heavy mineral assemblages consist of two parts coming from different sources. The first source is similar to the source of Jurassic clastics in the Central Western Carpathians (Aubrecht, 2001). The source was most likely represented by older sediments, from which the ultrastable trinity of zircon, tourmaline and rutile was reworked. The second source is exotic, which did not appear in

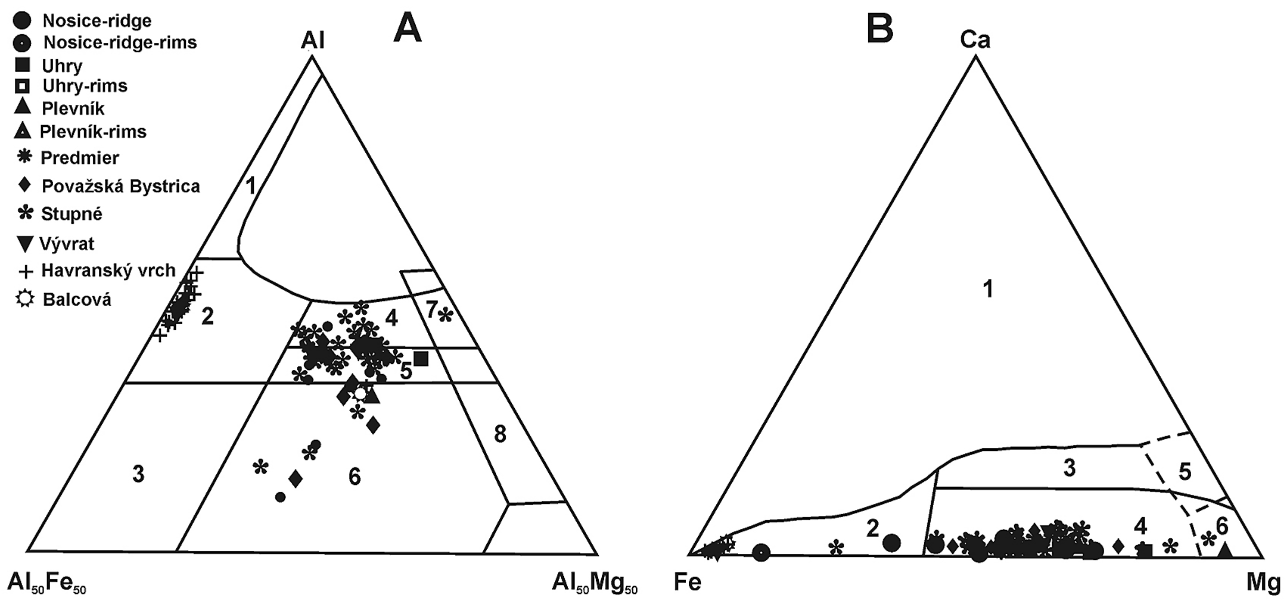

Fig. 9. Ternary diagrams exhibiting Al, Fe, Mg and Ca molecular proportions of the analyzed tourmalines (after Henry & Guidotti, 1985). Explanations of the diagram fields: Al-Fe(tot)-Mg diagram (A): 1. Li-rich granitoid pegmatites and aplites. 2. Li-poor granitoids and their associated pegmatites and aplites. 3. Fe^{3+}**-rich quartz-tourmaline rocks (hydrothermally altered granites) 4. Metapelites and metapsammites coexisting with an Al-saturating phase. 5. Metapelites and metapsammites not coexisting with an Al-saturating phase. 6.** Fe^{3+}**-rich quartz-tourmaline rocks, calc-silicate rocks and metapelites. 7. Low-Ca metaultramafics and Cr, V-rich metasediments. 8. Metacarbonates and meta-pyroxenites. Ca-Fe(tot)-Mg diagram (B): 1. Li-rich granitoid pegmatites and aplites. 2. Li-poor granitoids and associated pegmatites and aplites. 3. Ca-rich metapelites, metapsammites and calc-silicate rocks. 4. Ca-poor metapelites, metapsammites and quartz-tourmaline rocks. 5. Metacarbonates. 6. Metaultramafics.**

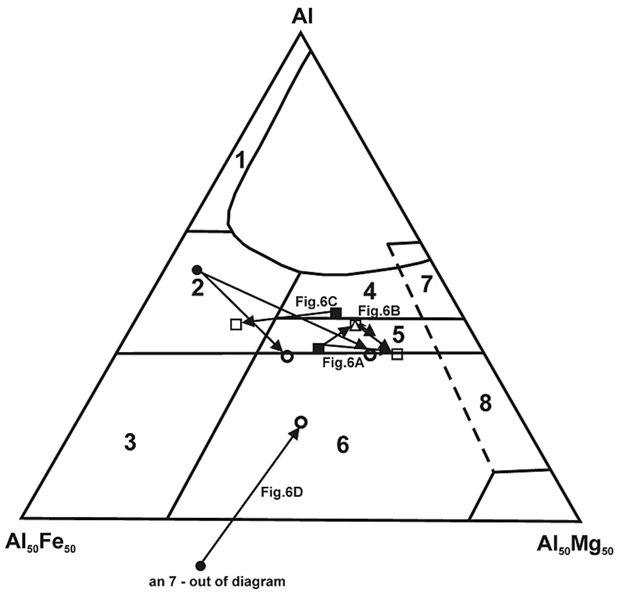

Fig. 10. Al-Fe(tot)-Mg diagram showing differences between the chemical compositions in some zoned tourmalines (the arrows start in the older, inner zones and end in the younger, outer zones). Some analyses of the zoned tourmalines from Fig. 6 are indicated. For explanations of the field numbers and sample symbols see Fig. 9.

older detritic sediments. It is represented by a younger, ophiolitic input characterized by strong prevalence of spinels (mainly Cr-spinels), locally accompanied by pyroxenes and blue amphiboles. Scarcer minerals, like garnet, kyanite, staurolite and sillimanite reflect also some presence of continental-crust metamorphics. This proportion well reflect the data from pebble analysis, where sedimentary, ophiolitic and acidic magmatic rocks dominate (see the Introduction chapter and the citations therein), whereas medium- to high-grade metamorphics are rare. Heavy mineral percentages presented herein are also highly consistent (almost identical) with those from the Hauterivian to Cenomanian exotic flysches of the Eastern Alps (Von Eynatten & Gaupp, 1999). If compared with heavy minerals in the Late Aptian-Early Albian sediments in the Czorsztyn Unit (Aubrecht et al., 2009), the non-ophiolitic source is different, dominated by garnet and less zircon, rutile and tourmaline. It reflects the continental crust of the Oravic crustal block which also yielded heavy minerals during the Jurassic period (Aubrecht, 1993, 2001).

4.2. Source of the spinels

Cr-spinels are the most typical indicators of ophiolitic source rocks. From all typical minerals contained in ophiolitic suites

Tab. 4. Representative analyses of the blue amphiboles.

Analysis number	Pm1	Pm2	Pm3	Pm4	Pm5	Pm6	Pm7	Pm8	Pm9	Pm10
SiO_2	55.04	56.64	56.26	56.37	56.40	53.85	53.54	55.52	56.64	55.41
TiO_2	0.05	0.03	0.03	0.11	0.10	0.13	0.11	0.11	0.03	0.07
Al_2O_3	8.60	9.41	9.02	8.58	11.33	8.43	9.59	9.31	9.49	8.52
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	9.43	9.90	8.22	10.34	5.42	8.03	7.45	8.37	7.87	9.72
FeO	11.82	5.20	7.19	3.05	7.89	14.38	15.78	8.53	7.23	10.68
MnO	0.05	0.05	0.13	0.03	0.10	0.28	0.20	0.11	0.03	0.11
MgO	5.51	9.43	8.88	10.73	8.18	5.10	3.25	7.52	8.36	6.15
CaO	0.16	0.39	0.51	0.38	0.32	2.10	0.76	0.29	0.07	0.22
Na_2O	5.89	5.87	6.07	5.86	6.02	5.04	5.53	5.87	5.89	5.80
H_2O^*	2.09	2.16	2.13	2.14	2.14	2.07	2.05	2.11	2.13	2.10
TOTAL	98.61	99.09	98.43	97.60	97.90	99.40	98.26	97.74	97.73	98.77
Formulae based on 23 oxygens with Fe^{2+}/Fe^{3+} estimation assuming 13 cations										
Si	7.912	7.862	7.911	7.885	7.903	7.797	7.844	7.904	7.978	7.916
Al IV	0.088	0.138	0.089	0.115	0.097	0.203	0.156	0.096	0.022	0.084
Al VI	1.368	1.402	1.406	1.300	1.774	1.235	1.500	1.466	1.553	1.349
Ti	0.005	0.003	0.003	0.012	0.010	0.014	0.012	0.012	0.003	0.008
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{3+}	1.020	1.034	0.870	1.089	0.571	0.875	0.821	0.897	0.834	1.045
Fe^{2+}	1.421	0.604	0.846	0.357	0.925	1.741	1.933	1.016	0.851	1.276
Mn	0.006	0.006	0.015	0.004	0.012	0.035	0.025	0.013	0.003	0.013
Mg	1.180	1.951	1.861	2.238	1.708	1.100	0.709	1.597	1.755	1.309
Ca	0.024	0.058	0.077	0.056	0.049	0.326	0.119	0.045	0.010	0.034
Na	1.642	1.579	1.654	1.589	1.635	1.414	1.572	1.620	1.609	1.607
OH^*	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
TOTAL	16.666	16.637	16.731	16.646	16.683	16.739	16.691	16.665	16.619	16.641
Na (B)	1.642	1.579	1.654	1.589	1.635	1.414	1.572	1.620	1.609	1.607
$Mg/(Mg+Fe^{2+})$	0.454	0.764	0.688	0.863	0.649	0.387	0.268	0.611	0.673	0.506

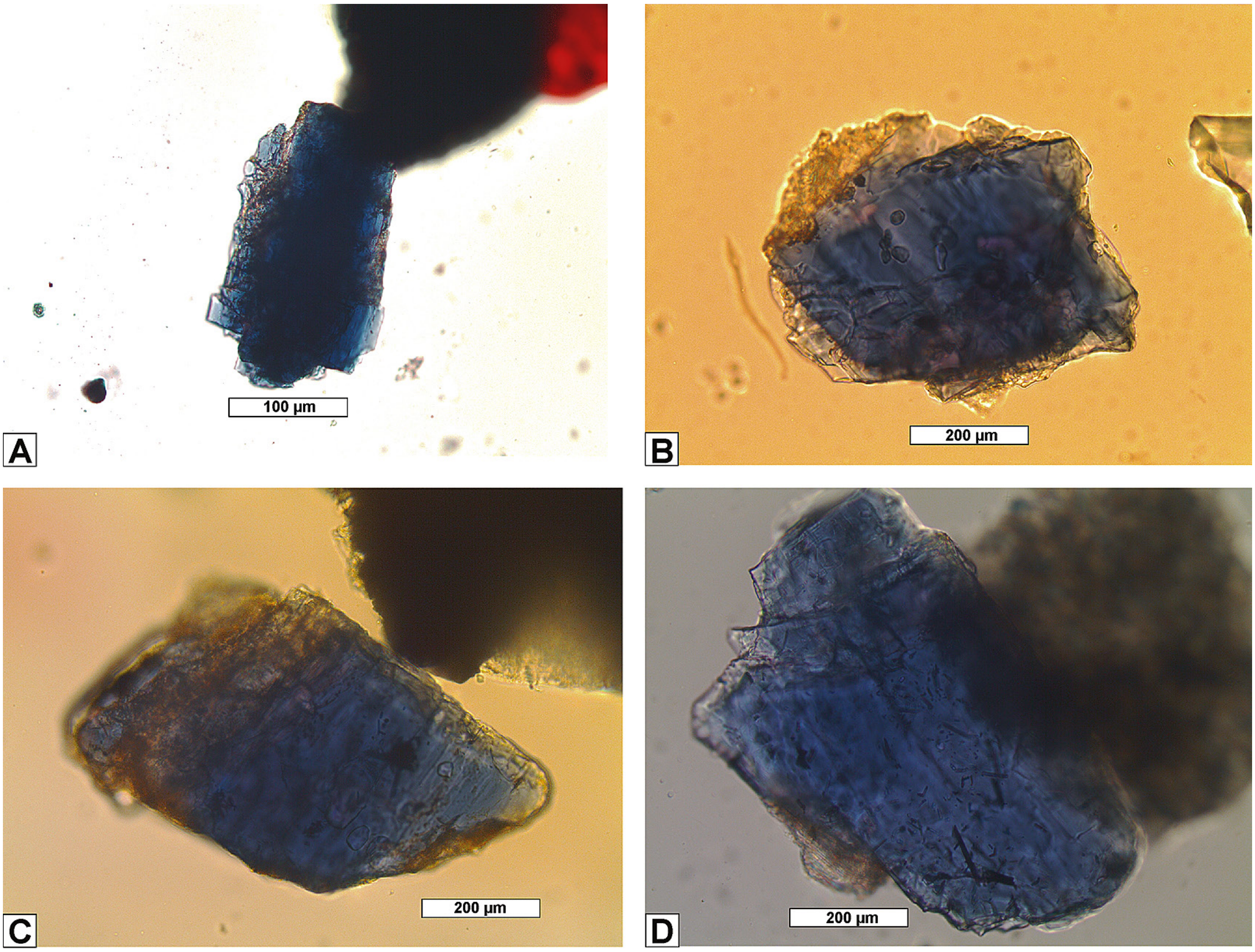

Fig. 11. Microphotos of the blue amphiboles from Predmier locality. Parallel nicols.

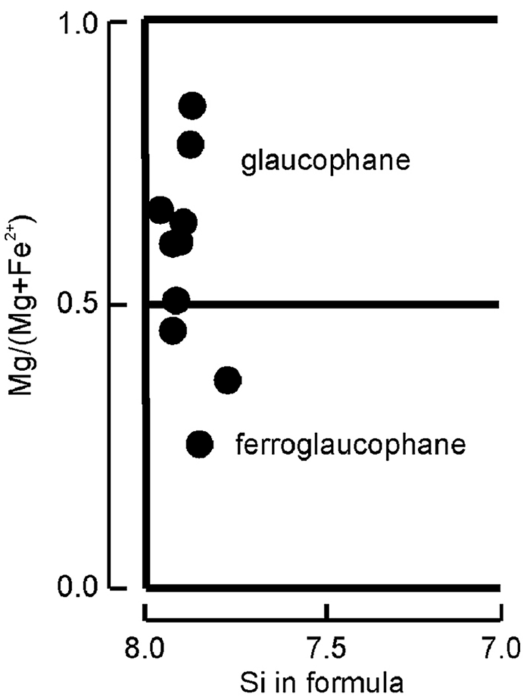

Fig. 12. Si vs. Mg/(Mg+Fe^{2+}) diagram of the analyzed blue amphiboles from Predmier locality (Leake et al., 1997).

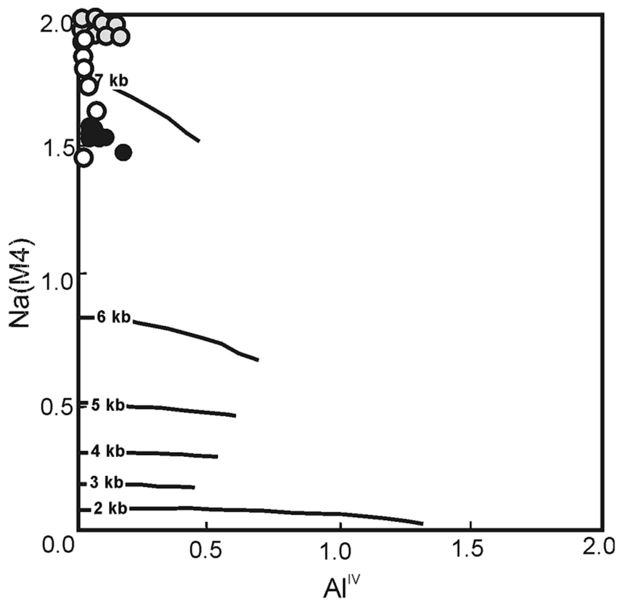

Fig. 13. Na (M4) vs. Al^{IV} diagram of blue amphiboles (Na (M4) = Na (B)) showing estimated pressure conditions under which the mineral originated (Brown, 1977). The blue amphiboles from present study (black circles) are compared with those from the Fatric Unit in the Humenské pohorie Mts. (grey circles - Ivan & Sýkora, 1993) and Klape Unit from the Smolinské 27 borehole in the Vienna Basin (white circles – Sýkora et al., 1997).

(e.g. olivine, pyroxenes, amphiboles, spinels) they are most stable and resistant during the whole process of weathering, transport, sedimentation and intrastratal dissolution during diagenesis. As such, part of them may be recycled from older sedimentary cycles. However, if compared with older detritic sediments (e.g. Jurassic - Aubrecht, 2001), mass input of Cr-spinels is new and vast majority of the grains were likely derived from primary source-rocks. Cr-spinels started to appear in the detritic sediments with the closure of the Triassic Neotethys ocean branches during the Late Jurassic (Árgyelán & Császár, 1998; Mock et al., 1998; Gawlick et al., 2015). Older occurrences of Cr-spinels in Triassic sediments in the Western Carpathians (Jablonský et al., 2001; Aubrecht et al., 2017) are interpreted as being of extra-Carpathian origin, north of the stable European shelf, from the Central European Basin (Germanic Triassic Basin) and Scandinavia. New input of Cr-spinels then culminates in early- to mid-Cretaceous time (Árgyelán, 1995; Von Eynatten & Gaupp 1999; Mikes et al., 2008; Lužar-Oberiter et al. 2012) and slowly fades down in Late Cretaceous and Paleogene times (Woletz, 1963; Lužar-Oberiter et al. 2012; Stern & Wagreich, 2013; Madzin, 2015).

The analyzed spinels show chemical variability in elements which are diagnostic of their provenance, such as Mg, Fe, Cr, Al, and Ti. According to the discriminating diagrams, the chemistry of spinels revealed their main provenance from harzburgitic sources and related volcanics; therefore the oceanic crust that originated rather in arc to back-arc, or supra-subduction ophiolites (SSZ) settings, than in mid-oceanic ridge. Harzburgitic sources vastly predominate in most of the Cretaceous synorogenic flysches (Pober & Faupl 1988; Árgyelán 1996; Von Eynatten & Gaupp 1999; Jablonský et al. 2001; Lužar-Oberiter et al. 2009), but also in the Jurassic sediments (Árgyelán & Császár, 1998; Gawlick et al., 2015) all over the Alpine-Carpathian-Dinaridic belt. There is a large overlap among the fields in the diagrams, but it is obvious that the spinels with Cr# < 0,3 and Al_2O_3 > 40 wt.% are rare or missing. The absence of this sort of spinels may be explained primarily as dominance of harzburgites in mixed ophiolitic belts (Mikes et al., 2008; Gawlick et al., 2015). However, there is also a possibility of secondary absence of these spinels. The present outcrops of primary ophiolitic rocks of Meliatic and Penninic provenance show mostly lherzolitic and MORB

Tab. 5. Representative analyses of the pyroxenes.

locality			Vývrat					Balcová		
mineral	opx	opx	opx	opx	cpx	opx	opx	opx	cpx	cpx
analysis number	V-106	V-108	V-110	V-113	V-114	Ba-an3	Ba-an5	Ba-an9	Ba-an12	17-an17
SiO_2	52,61	51,75	52,14	52,70	52,45	52,90	52,13	55,01	52,08	55,38
TiO_2	0,28	0,18	0,13	0,10	0,52	0,17	0,27	0,15	0,63	0,20
Al_2O_3	1,15	1,65	1,23	0,86	1,62	1,41	1,31	2,27	2,08	7,70
FeO	23,06	25,33	22,82	23,91	11,02	19,84	24,28	10,65	10,42	1,75
MnO	0,35	0,60	0,53	0,59	0,36	0,32	0,57	0,24	0,37	0,00
MgO	21,26	19,09	21,02	20,51	13,80	23,05	19,62	29,99	14,78	12,61
CaO	1,34	1,63	1,39	1,16	20,43	1,52	1,61	1,61	19,93	18,77
Na_2O	0,02	0,05	0,03	0,03	0,17	0,01	0,03	0,01	0,18	3,49
K_2O	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cr_2O_3	0,00	0,02	0,02	0,03	0,00	0,04	0,03	0,39	0,02	0,06
TOTAL	100,06	100,28	99,31	99,88	100,37	99,26	99,85	100,31	100,50	99,96
Formulae normalized to 6 oxygens.										
Si^{4+}	1,97	1,96	1,97	1,98	1,96	1,97	1,97	1,94	1,94	1,97
Al^{4+}	0,03	0,04	0,03	0,02	0,04	0,03	0,03	0,06	0,06	0,03
Ti^{4+}	0,01	0,01	0,00	0,00	0,01	0,00	0,01	0,00	0,02	0,01
Al^{3+}	0,02	0,03	0,02	0,02	0,03	0,03	0,03	0,03	0,03	0,30
Fe^{3+}	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
Cr^{3+}	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
Fe^{2+}	0,72	0,80	0,72	0,75	0,35	0,62	0,77	0,30	0,32	0,05
Mn^{2+}	0,01	0,02	0,02	0,02	0,01	0,01	0,02	0,01	0,01	0,00
Mg^{2+}	1,19	1,08	1,18	1,15	0,77	1,28	1,10	1,58	0,82	0,67
Ca^{2+}	0,05	0,07	0,06	0,05	0,82	0,06	0,07	0,06	0,79	0,72
Na^{+}	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06
K+	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
TOTAL	4,00	4,00	4,00	4,00	3,99	4,00	3,99	4,00	4,00	3,80
Wo	2,73	3,36	2,84	2,38	42,09	3,07	3,34	3,11	40,73	49,71
En	60,12	54,85	59,86	58,42	39,55	65,01	56,46	80,51	42,05	46,47
Fs	37,14	41,79	37,30	39,21	18,36	31,92	40,20	16,38	17,23	3,82

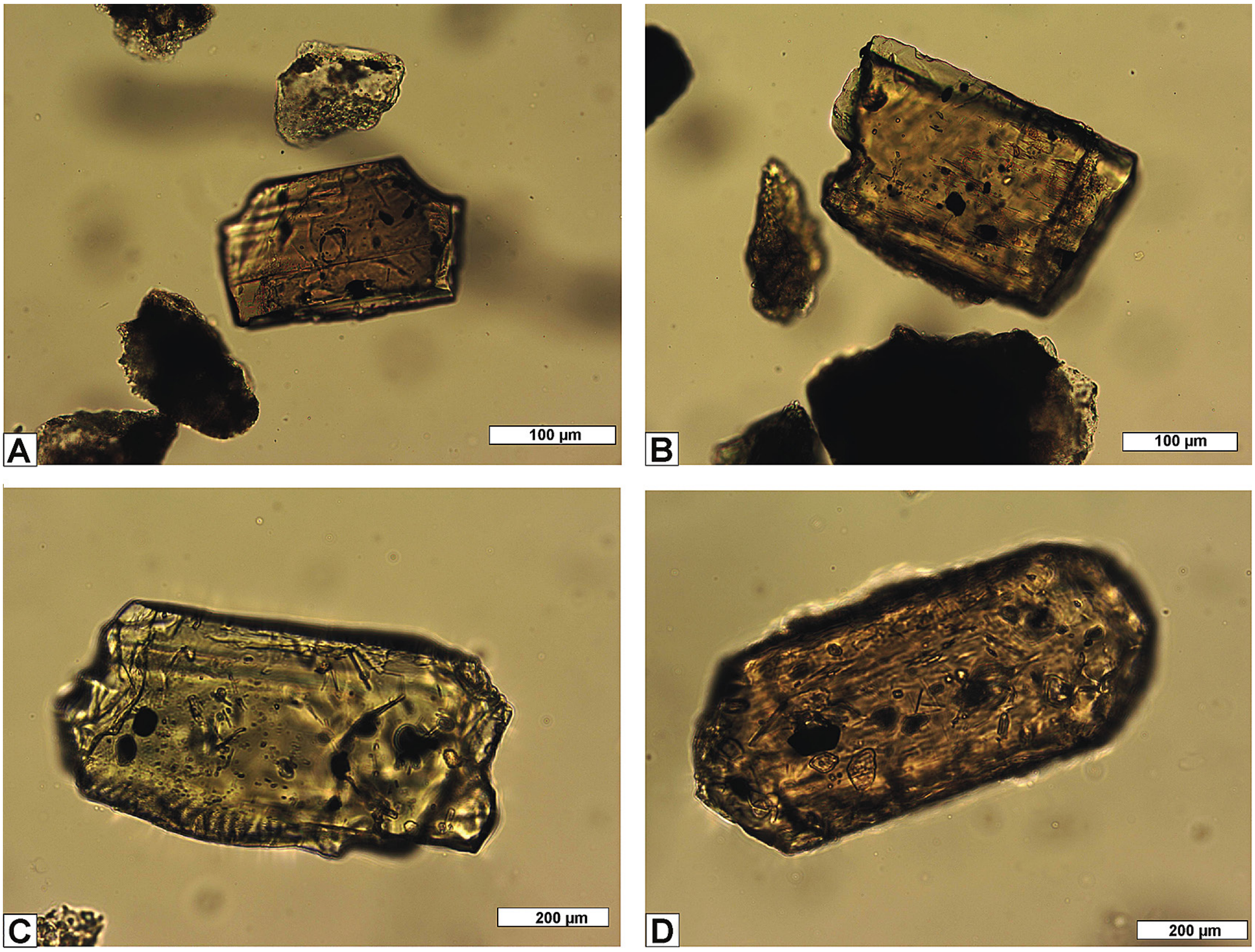

Fig. 14. Microphotos of the pyroxenes from Balcová locality. Parallel nicols.

origin (Mikuš & Spišiak 2007) and their spinel chemistry is commonly outside the range of the samples from the examined exotic flysches. Power et al. (2000) introduced a case from the Rum layered intrusion in the Inner Hebrides, Scotland, where spinels from chromite seams cover the entire Mg/(Mg + Fe^{2+}) vs. Cr/(Cr + Al) diagram. They also recorded a strong shift of spinel chemistry towards Cr- and Fe-enrichment, versus Al-depletion in the grains separated from sediments of the streams draining the intrusion body. It would indicate that the spinels with lower Cr and higher Al content are less resistant to hypergenic processes such as weathering and transport than the spinels with low Al and higher Cr contents. In such case, validity of the discrimination diagrams used for provenance determination would be partly doubtful (see also the discussion in Gawlick et al., 2015). Further research is necessary to resolve this problem.

4.3. Source of the blue amphiboles and pyroxenes

Amphiboles and pyroxenes belong to less stable and resistant heavy minerals (Pettijohn, 1941, 1975; Morton, 1984). They are especially sensitive to intrastratal dissolution during diagenesis and their occurrence in older sediments may be a matter of special diagenetic conditions rather than their presence or absence in source rocks. Enrichments in pyroxenes at Balcová and Liptovská Osada, and in blue amphiboles at Predmier locality then may indicate: 1) random local input of these minerals; or 2) local preservation of otherwise widespread minerals. The second possibility seems to be more likely in our case.

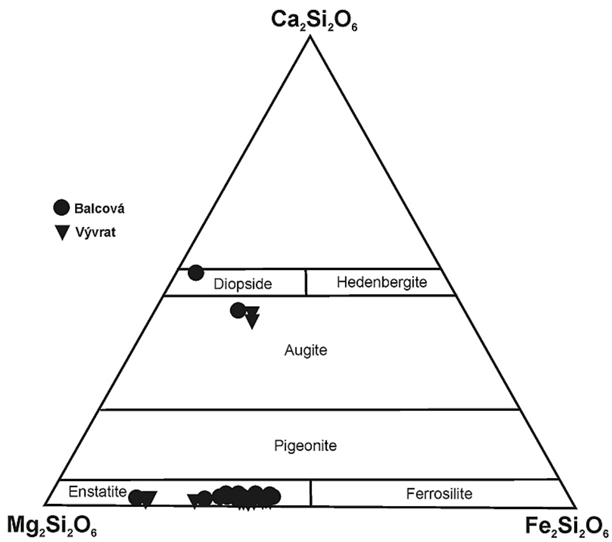

Fig. 15. Classification diagram of the analyzed pyroxenes (Morimoto et al., 1988).

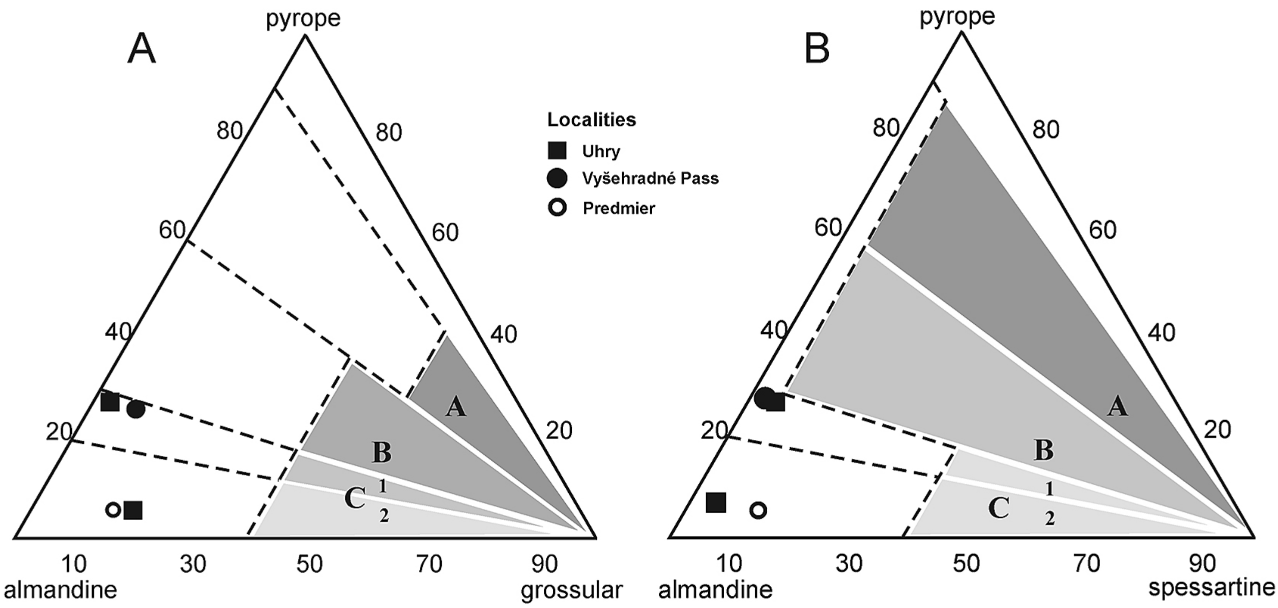

Fig. 16. Plot of the measured garnet composition in the pyrope-almandine-grossular (A) and pyrope-almandine-spessartine (B) discrimination diagrams of Méres (2008). Explanations: **Sector A.** White field – garnets from UHP/HP conditions. Position around No. 1a - Grt derived from UHP eclogites, garnet peridotites and kimberlites. Position around No. 1b - Grt derived from UHP eclogites. **Sector B.** White field – garnets from eclogite and granulite facies conditions. Position around No. 2 – Grt derived from HP eclogites and HP mafic granulites. Position around No. 3 – Grt derived from HP felsic and intermediate granulites. **Sector C.** White field – garnets from amphibolite facies conditions: Sector C1 – transitional subgroup between granulite and high amphibolite facies conditions. Position around No. 4 – Grt derived from gneisses metamorphosed under P-T transitional to granulite and amphibolite facies conditions. Position around No. 5 - Grt derived from amphibolites metamorphosed under transitional P-T granulite to amphibolite facies conditions. Sector C2 – subgroup amphibolite facies conditions. Position around No. 6 – Grt derived from gneisses metamorphosed under amphibolite facies conditions. Position around No. 7 – Grt derived from amphibolites metamorphosed under amphibolite facies conditions. In the C2 subgroup Grt from many other sources integrate, e.g. Grt from igneous rocks (granitoids, syenites), Grt from HP/LT metamorphic rocks, Grt from contact-metamorphosed rocks. **Grey fields** - immiscibility gap of Grt end-members composition: A – from UHP/HP conditions, B – from eclogite and granulite facies conditions, C – from amphibolite facies conditions.

Because of instability and low resistance, there are more findings of glaucophanite rock pebbles than blue-amphibole grains dispersed in the sediment (c.f. Ivan & Sýkora, 1993; Ivan et al., 2006; Sýkora et al., 1997; Von Eynatten & Gaupp, 1999). The analyzed blue amphiboles represent glaucophane to ferroglaucophane. Formerly, crossite was commonly reported as a blue amphibole in the exotics (e.g. Ivan & Sýkora, 1993; Von Eynatten & Gaupp, 1999), but this amphibole name was later abolished (Leake et al., 1997). The Na content in the analyzed blue amphiboles indicates that they originated in the same pressure conditions as those described by Sýkora et al. (1997), and in slightly lower pressure than those from pebbles in the Poruba Formation found in the eastern Slovakia (Ivan & Sýkora, 1993). Formerly, the glaucophanite rocks in the exotic pebbles were considered to be different from the similar rocks in the Inner Western Carpathians (Bôrka Nappe belonging to the Meliata Unit s.l.) because of differences in the lawsonite content (Šímová & Šamajová, 1982; Šímová, 1985[c]) and in the protolith of the high-pressure metamorphics (Faryad & Schreyer, 1997; Faryad, 1998). However, radiometric datings that revealed Jurassic age of the metamorphism (Dal Piaz et al., 1995) and more thorough analyses showed that the differences are minimal and the exotic source area was derived from a suture zone after closure of a Triassic ocean, not Jurassic (Ivan et al., 2006). Suture zones that remained after the closed Neotethys (Triassic) ocean branches are also the most likely source of Cr-spinels and both minerals were then derived from the same ophiolite belt.

Source of the pyroxenes is more problematic. Most of them are orthopyroxenes (enstatite) and some grains are clinopyroxenes (augite and diopside). Orthopyroxenes are common constituents of gabbroic rocks in ophiolitic suite (Deer et al., 2013) and normally might have been derived from the same ophiolite source as Cr-spinels and blue amphiboles. Orthopyroxenes are also known from some metamorphosed ultramafic rocks in the West Carpathian Variscan crystalline complexes (Ivan et al., 1996). However, common euhedral habitus of the pyroxenes in the analyzed rocks indicates that their origin was rather in volcanic rocks than in deep-seated igneous rocks. Fresh, unaltered appearance indicates more likely a subaerial than submarine volcanism. Moreover, lack of rounding indicates proximity of the source. Orthopyroxenes occur also in volcanics that are not necessarily of alkaline origin; their presence in calc-alkaline rocks, from basalts through dacites to andesites is common, too (e.g. Barley, 1987; Li et al., 2013; Ghose et al., 2017). Moreover, they commonly coexist with augitic to diopsidic pyroxenes, too. The analyzed pyroxenes then might have been derived from different source than the Cr-spinels and blue amphiboles, likely from volcanics that might be synsedimentary and coeval with the deposition of

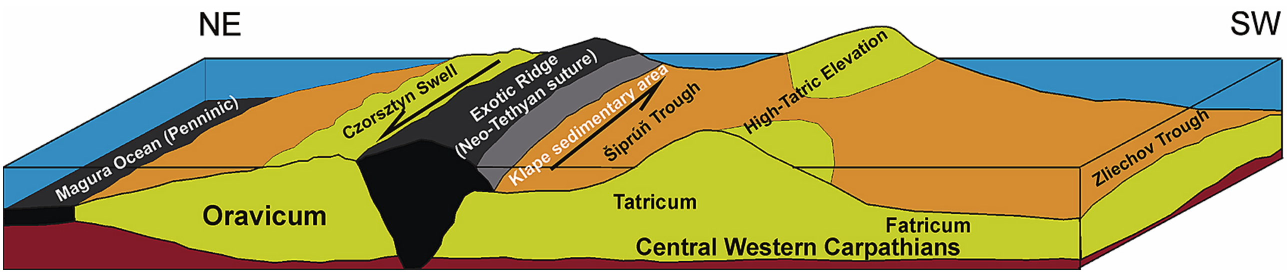

Fig. 17. Paleogeographic block-diagram sketch showing position of the examined units and source of the ophiolitic clastics – the Exotic Ridge. The sketch is a modification of the fig. 13 in Aubrecht et al. (2009), where readers can get the general information about the arguments which led to its construction.

the exotic-bearing flysches. Hyaloclastitic lavas are common in the Poruba Formation and in the underlying Barremian-Aptian sediments (one occurrence was even recorded near the Vývrat locality), but their pyroxenes, if preserved, are represented solely by clinopyroxenes (Hovorka & Spišiak, 1988). Question of the pyroxenes origin then remains open.

Tab. 6. Representative analyses of the garnets.

Analysis number	Uhry 1	Uhry 2	VP	Predm. 1	Predm. 2
SiO_2	36.42	37.72	38.72	36.34	36.39
TiO_2	0.17	0.08	0.01	0.11	0.07
Al_2O_3	20.46	21.26	22.02	20.61	20.54
Cr_2O_3	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	0.97	0.62	0.32	1.50	1.31
FeO	33.30	30.31	30.09	31.65	31.38
MnO	1.05	1.36	0.49	4.02	3.89
MgO	1.74	7.17	6.98	1.35	1.27
CaO	5.60	1.06	2.99	5.72	5.88
TOTAL	99.70	99.58	101.61	101.29	100.73
Formulae based on 12 oxygens and with Fe^{2+}/Fe^{3+} calculated assuming full site occupancy					
Si	2.96	2.97	2.98	2.93	2.94
Al IV	0.04	0.03	0.02	0.07	0.06
Al VI	1.92	1.95	1.98	1.89	1.91
Ti	0.01	0.00	0.00	0.01	0.00
Cr	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.06	0.04	0.02	0.09	0.08
Fe^{2+}	2.26	2.00	1.94	2.13	2.12
Mn	0.07	0.09	0.03	0.27	0.27
Mg	0.21	0.84	0.80	0.16	0.15
Ca	0.49	0.09	0.25	0.49	0.51
TOTAL	8.03	8.02	8.01	8.05	8.04
End members					
Almandine	73.96	65.62	63.80	68.22	68.42
Andradite	2.99	1.86	0.92	4.67	4.06
Grossular	13.48	1.14	7.35	12.19	13.26
Pyrope	7.12	28.33	26.86	5.55	5.21
Spessartine	2.45	3.05	1.06	9.36	9.06
Uvarovite	0.00	0.00	0.00	0.00	0.00
% cations	98.39	98.98	99.18	97.05	97.66

4.4. Source of the tourmalines

Most of the measured tourmalines have dravitic composition indicating possible metamorphic origin, according to the discriminating diagrams of Henry & Guidotti (1985). Vast majority of them plots in the fields of metapelites and metapsammites and Fe^{3+}-rich quartz-tourmaline rocks, calc-silicate rocks and metapelites (Fig. 9A - fields No. 4-6). Very low-magnesian schorlitic tourmalines from Li-poor granitoid rocks are relatively rare, with one exception – Havranský vrch Hill, where nearly all measured grains were plotted to this field. In the Western Carpathians, tourmaline is common only in late- to post-Variscan Permian granitoids in the Gemeric Zone (Aubrecht & Krištín, 1995 and the literature cited therein; Faryad & Jakabská, 1996; Kubiš & Broska, 2005). Schorlitic tourmalines were also reported from siderite-quartz-sulphide hydrothermal veins in the Gemeric Zone (Bačík et al., 2018). However, all these rocks are recently outcropped only in small areas and they do not represent a potentially significant source. Metamorphic tourmalines are more common in the metamorphosed rocks in this zone (see summarization in Aubrecht & Krištín, 1995). In the Tatric and Veporic zones, primary occurrences of tourmaline in the crystalline rocks are rare. However, tourmalines are strikingly one of the most common heavy minerals in the Jurassic and Triassic sediments of the Central and Inner Western Carpathians and their provenance is uncertain. Vast majority of them plots into the fields No. 4-6 of Henry & Guidotti (1985) and very rarely to the granitoid fields (see the discussions in Aubrecht & Krištín, 1995; Aubrecht, 2001 and the citations therein). Therefore, the chemistry of tourmalines from the Havranský vrch Hill is exceptional in the provenance research.

Similarly exceptional is the mosaic texture of some tourmaline grains revealed in the analyzed samples. It can be stated that tourmalines possessing this texture are typical of Cretaceous exotics-bearing rocks, as they are common also in the younger, Coniacian-Santonian exotics of the Pieniny Klippen Belt (unpublished data). On the other hand, they were so far not described from the pre-Cretaceous Mesozoic detritic sediments of the Western Carpathians (Aubrecht & Krištín, 1995; Aubrecht, 2001). Similar tourmalines were described from some rare eclogitic and eclogite-related rocks (Konzett et al., 2012; Broska et al., 2015), which may be also a clue to their provenance. They then may have been derived from the same ophiolitic complex as the Cr-spinels and blue amphiboles.

4.5. Source of the garnets.

Provenance of the measured garnet grains cannot be ascertained on such a small number of analyses (further analyses are under preparation). Generally, the almandine-dominant garnets are among the most common types and are not very provenance-indicative. They are typical for a wide spectrum of common metapelitic to metapsammitic rocks of amphibolite facies metamorphism (mainly mica schists and paragneisses), orthogneisses, peraluminous calc-alkaline granitic rocks with S-type affinity and their aplitic to pegmatitic derivates as well as some acid to intermediate volcanic rocks (e.g., Deer et al., 1997; Broska et al., 2012, and references therein). Almandinic garnets are ubiquitous all around the Western Carpathians and in all adjacent areas.

4.6. Final remarks

The data in this paper are preliminary and, therefore, the discussion is limited to possible source rocks and comparison with Western Carpathian units. There are no large differences between the heavy minerals among the individual units and they most likely shared the same ophiolitic source. We keep the idea of Aubrecht et al. (2009) about the doubled suture after a closed Triassic (Neotethys) oceanic branch which emerged as the so-called Exotic Ridge (known also as Andrusov Ridge) placed between the West-Carpathian internides and internides (Fig. 17).

5. CONCLUSIONS

The first systematic heavy-mineral analysis of the oldest exotics-bearing units in the Western Carpathians brought new data:

1. Most units are dominated by chrome-spinels, zircon, tourmaline, apatite and rutile in various ratios. Garnet appears in small amounts but in a few samples its ratio raises up to 78%. At Havranský vrch Hill there is a considerable excursion of kyanite. In some samples there are important occurrences of blue amphiboles and pyroxenes. Presence of chloritoid is noteworthy.

2. The analyzed spinel grains match harzburgite field, with some overlap to the fields of podiform chromitites and cumulates in the Mg/(Mg + Fe^{2+}) vs. Cr/(Cr + Al) diagram. The TiO_2 vs. Al_2O_3 diagram indicates the predominant origin of spinels in the supra-subduction zone peridotites for most of the analyses, whereas the other, aluminium-depleted and higher-titanium grains best match the arc volcanic field.

3. The analyzed blue amphiboles from the Predmier locality belong to glaucophane to ferroglaucophane and were most likely derived from HP/UHP metamorphosed basaltic rocks in a subduction zone. Their appearance and chemistry is consistent with the previously published glaucophanite pebbles in the exotics.

4. Pyroxenes from the Balcová a Vývrat are mostly represented by orthopyroxenes (enstatite) and less by clinopyroxenes (augite, diopside). Their common euhedral shape and fresh appearance indicate that they were probably not derived from the same ophiolitic source as the Cr-spinels and blue amphiboles, but rather from some adjacent and nearly coeval volcanics which might be of calc-alkaline origin.

5. According to discrimination diagrams, most of the tourmaline grains were derived from metasediments, i.e. from metapelites and metapsammites coexisting, or not coexisting with an Al-saturating phase; some were also derived from Fe^{3+}-rich quartz-tourmaline rocks, calc-silicate rocks and metapelites. Almost all tourmaline grains from Havranský vrch Hill locality were plotted to the field of Li-poor granitoid rocks, which is unusual in the Western Carpathians. The tourmalines with mosaic appearance are also uncommon. Tourmalines of similar appearance occur in some eclogites and eclogite-related rocks, which may eventually become an important provenance indicator in the future.

6. Final assessment of the analyzed heavy mineral spectra points to large input of minerals of dominantly ophiolitic provenance, such as Cr-spinels, blue amphiboles, and eventually mosaic tourmaline. Zircon, rest of the tourmaline and rutile were likely derived from older sediments. Garnet, staurolite, kyanite, and sillimanite occurring in relatively small amounts, were mostly derived from metamorphic rocks of various degrees of metamorphism. No significant differences between the heavy minerals were observed among the individual units and they most likely shared the same source.

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