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Heavy mineral analysis of the Turonian to Maastrichtian exotics-bearing deposits in the Western Carpathians: What has changed after the Albian and Cenomanian?

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Abstract: Turonian to Maastrichtian exotics-bearing deposits from the Pieniny Klippen Belt (Klape and Kysuca units) and from the Považský Inovec Mts. (Western Carpathians) were analyzed for heavy minerals and compared with similar, yet older Albian–Cenomanian deposits. The Turonian to Maastrichtian deposits are petrographically more variable in composition in the entire range, from quartz arenites to litharenites. Percentages of the main heavy minerals are similar on both stratigraphic levels, i.e., they are dominated by chrome-spinels, zircon, tourmaline, apatite, and rutile. Garnet is more common in the Turonian to Maastrichtian samples, while titanite, kyanite, monazite, hornblende, blue amphibole, pyroxenes, epidote, staurolite, and sillimanite are quite rare. Statistical factor analysis indicates dominance of ophiolites and older sediments in the source areas. One important factor is an influx of garnet, with the weakest factor being related to the influx of tourmaline and apatite, which may indicate low-grade metamorphics. Spinels were derived from harzburgites (supra-subduction peridotites). The majority of tourmalines were derived from metasediments, Fe^{3+}-rich quartz–tourmaline rocks, calc-silicate rocks, and metapelites and granitoids. Some had complex zonation with two phases of tourmaline (schorl–dravite and bosiite), or tourmaline intergrown with quartz. These were likely derived from ophiolitic sources. Garnets are predominantly almandinic and derived from rocks that had been metamorphosed up to the amphibolite facies, or magmatic rocks. Common pyrope–almandinic garnets indicate their source from granulites and eclogites. The main change after the Albian–Cenomanian period is the more expressed presence of the continental crust segments in the source area in comparison with ophiolites.

Keywords: Late Cretaceous, provenance analysis, exotics, ophiolites, tourmaline, Cr-spinel.

Introduction

During the end of the Early Cretaceous, as well as in the Late Cretaceous, convergence was the prevailing tectonic regime, which led to the gradual closure of the oceanic branches that had originated during the Jurassic period, such as the Alpine Tethys and its equivalents – the Ligurian, Penninic, and Vahic oceans, as well as the eventual emplacement of ophiolites obducted in the Late Jurassic–Early Cretaceous period from the Neothetys and its equivalents – the Meliata–Hallstatt, Vardar, and Maliac oceans (Stampfli & Borel 2002; Stampfli et al. 2002; Csontos & Vörös 2004; Schmid et al. 2008; Handy et al. 2010; Gawlick & Missoni 2019). The closure was often accompanied by the emersion of accretionary wedges and obduction of ophiolites. The obducted bodies often represented the topmost structures on accretionary wedges and were first destroyed by erosion. Sedimentary record is often the only witness; not only of the presence of emerged ophiolites, but also of many other rock suites whose provenance is uncertain to date. The general name given to this sedimentary material of unknown provenance is "exotics". The grain-size of this material ranges from boulders to silt. In the Western Carpathians, several thorough studies of psephitic material have been performed in exotics (Krivý 1969; Kamenický et al. 1974; Kamenický & Kráľ 1979; Mišík & Sýkora 1981; Mišík et al. 1981; Šímová 1982, 1985a, b, c; Šímová & Šamajová 1982; Mišík & Marschalko 1988; Birkenmajer et al. 1990; Ivan & Sýkora 1993; Uher & Marschalko 1993; Ivan et al. 2006; Zaťko & Sýkora 2006), whereas provenance analyses of psammites have been somewhat neglected. However, in the Eastern Alps, which shared a common Mesozoic evolution with the Western Carpathians, researchers have traditionally opted to devote more effort to the provenance analysis of psammites (Woletz 1963; Pober & Faupl 1988; Faupl & Pober 1991; Faupl & Wagreich 1992; Wagreich et al. 1995; Von Eynatten & Gaupp 1999; Wagreich 2003) rather than to pebble analysis (Löcsei 1974; Gaupp 1983).

In the Western Carpathians, the earliest occurrences of exotic ophiolitic detritus (Cr-rich spinels) were indicated in the form of intercalations of the Hauterivian sandstone turbidites in the Fatric and Hronic units (Jablonský 1992; Jablonský et al. 2001). Cr-spinels were also found in the Aptian pebbles in the Albian exotics (Mišík et al. 1980; Wagreich et al. 1995). The influx of exotics culminated in the Albian period. In the Central Western Carpathians, the Albian exotics-bearing flysch deposition preceded the main, Mediterranean orogenic phase and lasted until the Middle Turonian, when nappe thrusting took place. In the Pieniny Klippen Belt, Albian exotics were concentrated in the Klape Unit, which most likely represented a sedimentary accretionary wedge formed between the Central Western Carpathians and the Oravicum, which was an independent continental ribbon. The Klape Unit was most proximal to the emerged exotic source, since it contains rich pebbles to boulder material, which has been studied repeatedly by many authors (see the above citations regarding analysis of the psephitic material). A comprehensive heavy mineral analysis of Albian to Cenomanian sediments from the Central Western Carpathians and from the Klape Unit was done by Bellová et al. (2018) and Aubrecht et al. (2020b) – see Fig. 1. In the Oravic units, the exotic influx was believed to have begun later, during the Coniacian (Mišík & Marschalko 1988). Even the Turonian Snežnica Beds (which marked the first considerable terrigenous influx in Oravicum) were considered to be free of any ophiolitic material (Łoziński 1959). However, the presence of Cr-spinels was later registered in the Albian Trawne Member, having been attributed to the Kysuca (Branisko) Unit (Winkler & Ślączka 1994) and the Chmielowa Formation in the Czorsztyn Unit (Aubrecht et al. 2009), with both being the main Oravic units (Fig. 1).

During the Coniacian and Santonian periods, the Exotic influx (psammitic and psephitic) culminated in the Oravic Kysuca Unit (Sromowce Beds), but also remained active in the Klape Unit (Žadovec Formation, and later in the Hlboké Formation) – see Fig. 1. These were still pure exotics, with no material derived from the neighbouring Oravic or Central Carpathian Units. At the end of the Cretaceous, in the periods during and after the Maastrichtian Laramian collision between the Oravic and Central West Carpathian blocks, the deposition of exotics continued (Paleogene Jarmuta–Proč formations); however, this time they mixed with non-exotic material from

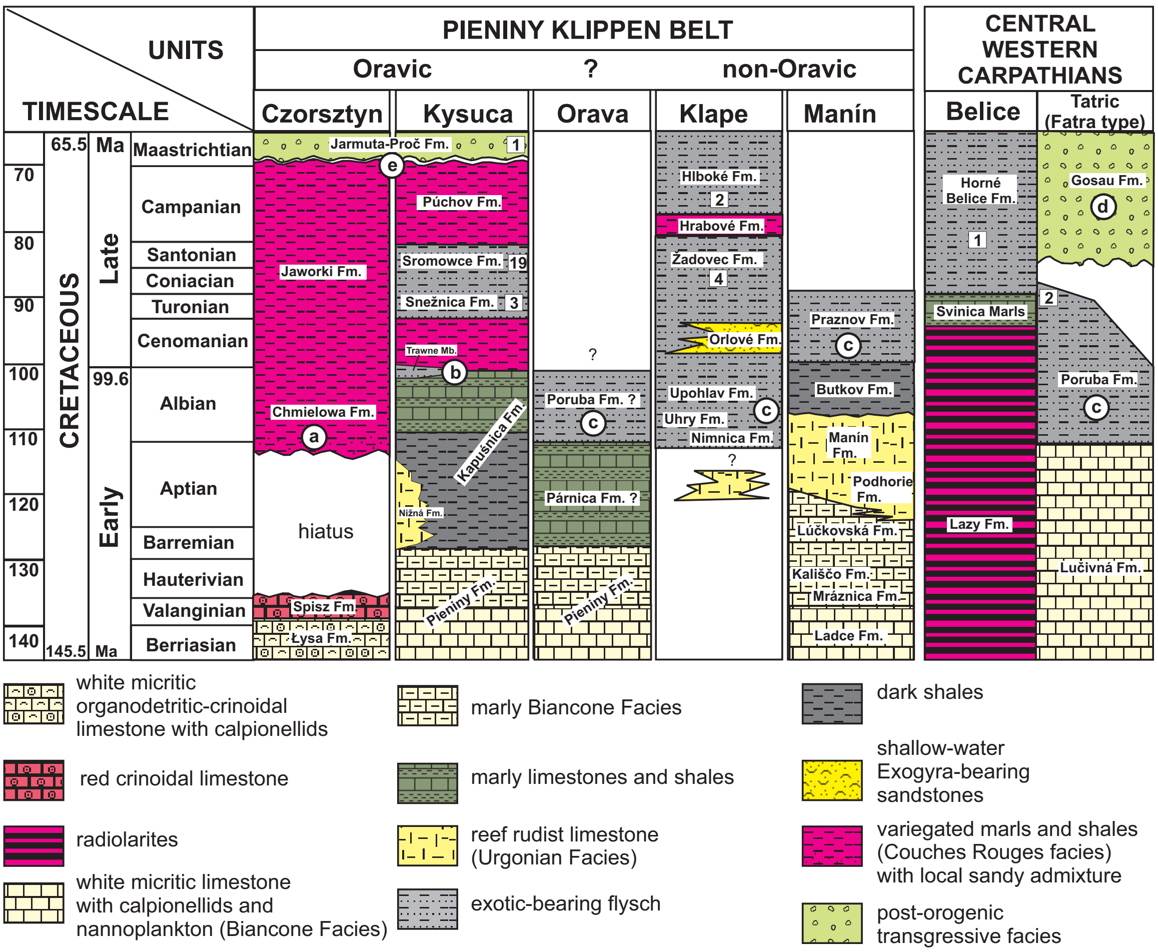

Fig. 1. Schematic lithostratigraphic columns of the exotics-bearing units in the Western Carpathians arranged approximately according to their present positions from north to south (left to right). The scheme is based on: Birkenmajer (1977), Plašienka et al. (1994), Aubrecht et al. (2009), Mello et al. (2011), Michalík et al. (2012), Pelech et al. (2017b), and Hók et al. (2019). The numbers in squares represent the numbers of samples analyzed from the individual formations. The letters in circles refer to the earlier heavy mineral analyses performed in the individual lithostratigraphic units: a – Aubrecht et al. (2009); b – Winkler & Ślączka (1994); c – Bellová et al. (2018), Aubrecht et al. (2020); d – Wagreich & Marschalko (1995), Stern & Wagreich (2013); e – Madzin et al. (2019).

the neighbouring emerged units (Aubrecht 1997). Exotic sources influenced the deposition in these formations until the Eocene (Mišík et al. 1991). Heavy minerals from the Paleogene Jarmuta–Proč formations were treated by Winkler & Ślączka (1992, 1994), Oszczypko & Salata (2005), Bónová et al. (2017, 2018), and Madzin et al. (2019). In the West Carpathian internides (Central and Inner Western Carpathians), after the main thrusting phase in the Turonian, the deposition generally ceased and locally reappeared in the form of Gosau-type post-tectonic sediments. Heavy minerals from these sediments in the Brezová Group (Brezovské Karpaty Mts.) were treated by Wagreich & Marschalko (1995) and Stern & Wagreich (2013). Highly rich ophiolitic detritus was found in the Gosau Group sediments in the basement of the Vienna Basin in the Gajary Ga-125 borehole (Mišík 1994). However, this part of the Gosau Group belongs to the Eastern Alps. The Gosau-type sediments from the vicinity of the Dobšiná Ice Cave in the Spiš–Gemer area were analyzed for heavy minerals by Sýkora et al. (2007). Interestingly enough, in the Považský Inovec Mts., despite being part of the West-Carpathian Internides, there are some occurrences of Coniacian–Santonian sediments which had been deposited even in pre-tectonic position. The first one was in the Belice Unit, which is a Coniacian–Santonian flysch incorporated into the thrust slice structures inside the crystalline rocks of the northern part of the mountains (Kullmanová & Gašpariková 1982; Plašienka et al. 1994; Plašienka 1995). Its interpretation, however, is still full of controversies (Pelech et al. 2016, 2017a; Plašienka et al. 2017). The second occurrence is in the central part of the mountains in the Striebornica Valley, where Coniacian siliciclastic sediments overlie the Albian–Turonian Poruba Formation (Pelech et al. 2017b), indicating that the nappe thrusting of the Mediterranean phase might have ended later than in other parts of the Central Western Carpathians.

From the given overview of the West-Carpathian Cretaceous units, there is still a considerable lack of heavy-mineral data from the Turonian to Maastrichtian deposits of the Oravic units (mainly the Kysuca Unit), Klape Unit, and occurrences from the Považský Inovec Mts. The main objective of this paper is to fill the gap in the data and present the results of the first comprehensive heavy mineral analysis of these deposits so that they may be compared with the data from the previous analyses of the Albian–Cenomanian and Maastrichtian–Paleogene deposits. A further objective of the paper is to emphasize changes that occurred after the Albian and Cenomanian periods. Although the term 'Senonian' is no longer valid in stratigraphy, for the purpose of brevity, we use it locally in the paper for the period covering the Coniacian to Maastrichtian stages.

Sampled sites and their geological setting

Samples from 31 localities of the Turonian to Maastrichtian exotics-bearing deposits were analyzed for heavy minerals (Fig. 2, Table 1). They are mostly from the Pieniny Klippen Belt (Klape and Kysuca units), but there are also three samples from the Považský Inovec Mts. (Hr, STR1, 368). The Pieniny Klippen Belt is the most complex tectonic zone of the Western Carpathians, and the attribution of the individual sampled sites to the units is sometimes problematic. As a rule, the Upper Cretaceous sediments are commonly detached from the Jurassic–Lower Cretaceous parts of the units. Long ago in the early stages of research in the Pieniny Klippen Belt, they were considered a "klippen envelope", resting unconformably on the deformed basement as a result of the pre-Albian Manín orogenic phase (Andrusov 1938). In later years, Birkenmajer (1953, 1957) rejected the existence of this phase by pointing to the continuous Jurassic–Cretaceous development of the Oravic units in some places (e.g., Scheibner 1958; Scheibner & Scheibnerová 1958). However, continuous sections are rare, and most of the occurrences do not continue to the Jurassic strata. Moreover, stratigraphic position of the individual sites is often uncertain. Therefore, it is necessary to provide an explanation of the parts from which the examined samples were derived. In Table 1, the samples are arranged according to the tectonic units and their age.

Most of the analyzed samples come from locations which are attributed to Kysuca Unit (first 22 samples in Table 1). The first 5 sampled sites (NS14-16, Vr, Vr-W) were located in the type section of the Kysuca Unit between the villages of Považský Chlmec and Vranie near the city of Žilina (Scheibner & Scheibnerová 1969; Marschalko et al. 1980). The samples Vr, Vr-M, and NS 15 were taken from the sandstones of the Turonian flysch of the Snežnica Beds; the samples NS16 and NS14 represented sandstones of the Coniacian–Santonian Sromowce Formation.

The samples NS5-11 were taken from the stripe of the Sromowce Formation spreading on the right side of the Váh River valley from the village of Vieska-Bezdedov up to the village of Hatné. The samples Pu1-3 and Pal are derived from the flat-lying, tectonically-overturned Santonian sandstones located on the boundary between the villages of Terchová and Zázrivá (Kysuce and Orava regions). These were originally interpreted by Haško & Polák (1978, 1979) as a part of the Manín Unit; however, in that time, the Manín Unit was defined differently than today, since it included the Klape and Drietoma units as well (Rakús & Hók 2005 and the references therein). However, according to recent knowledge, this development fits best to the Kysuca Unit. The samples K1-2, Rac, and ZD1-2 come from the stripe of the Sromowce Formation located in the Orava sector of the Pieniny Klippen Belt, NE of the young, N–S-trending Párnica Tectonic Line (i.e., NE of Istebné). The authors of this paper agree that these locations should be attributed to the Kysuca Unit (Gross et al. 1993). However, this is not fully certain, since the direct continuation of these strata down to the Jurassic has never been observed. This exotic flysch was also attributed to the Nižná Unit (Zemianska Dedina locations – ZD1-2), which is a subunit of the Kysuca Unit, having Urgonian-type of limestones (Nižná Limestone) in the Barremian–Aptian rather than black shales of the Koňhora Member (part of the Kapuśnica Formation

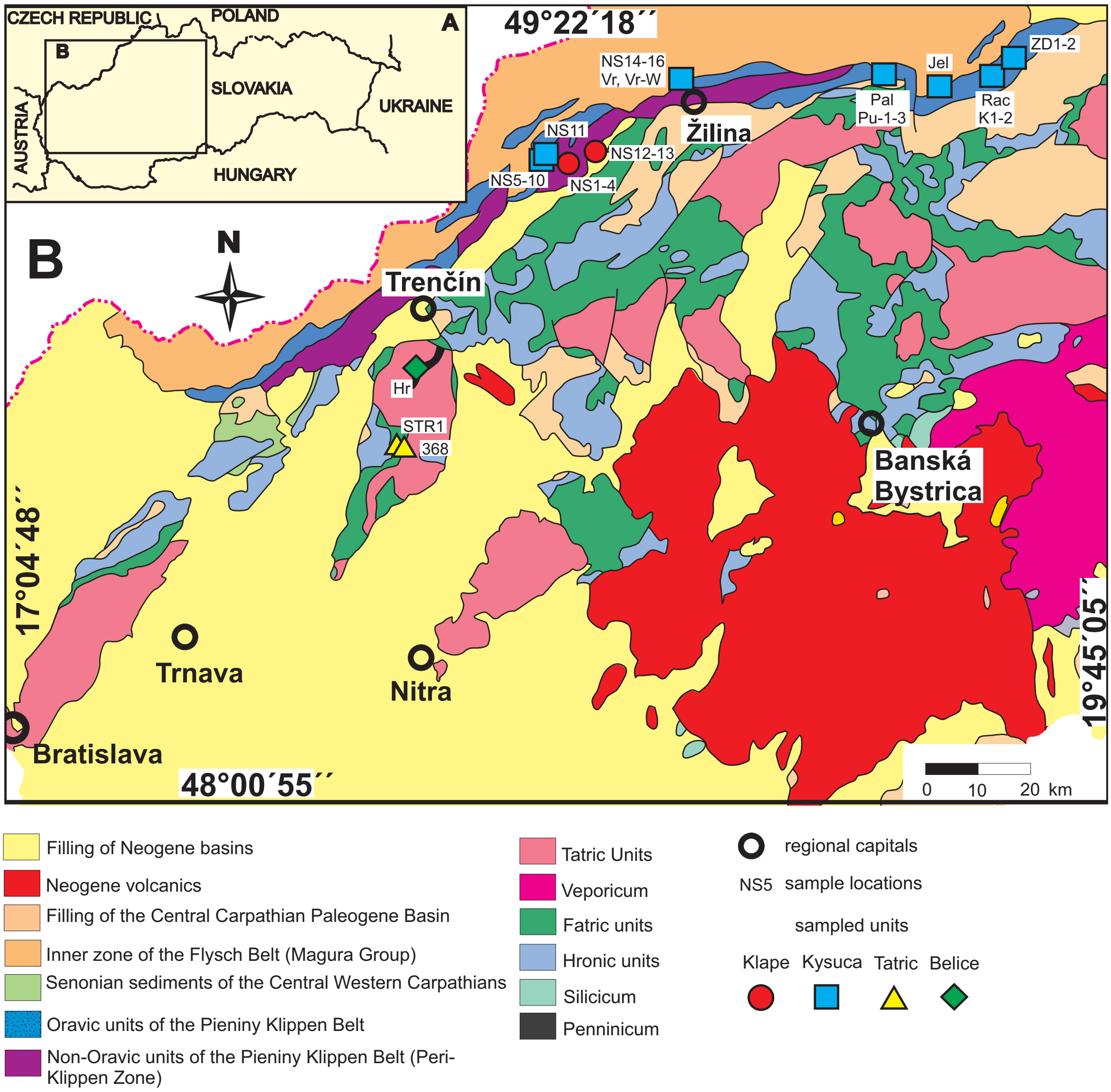

Fig. 2. Schematic geological map of western Slovakia (after Biely 1996 – simplified) and the location of the sites sampled.

– Scheibner 1967; Józsa & Aubrecht 2008, Starek et al. 2010); however, according to Scheibner (1967) deposition of the exotics began as early as the Albian. No differences in age interpretation appeared for the part between the villages of Krivá and Dlhá (K1-2 samples), where the Coniacian–Santonian age had already been proven (Salaj & Began 1963; Marschalko & Samuel 1977).

The samples NS1-4 were taken in the Coniacian–Santonian part of the Klape Unit between the town of Považská Bystrica and the village of Nosice. Although this exotic flysch does not differ from the older, Albian sediments, the latest interpretation presented in the geological map 1:50,000 (Mello et al. 2005) and its explanations (Mello et al. 2011) considers it as a part of the Kysuca Unit thrust over the Klape Unit. However, this interpretation contradicts all previous interpretations.

Two samples come from the Hlboké Formation, which represents Maastrichtian sediments of the Klape Unit. This part of the unit is considered a separate stage in the evolution of the Klape Basin, having changed transport directions, as well as supposed change in the source of detritus (Marschalko 1986). The Upper Campanian–Maastrichtian flysch of the Jarmuta–Proč Formation was also sampled near Jelšava (Dolný Kubín). At this locality, there are four tectonic slices containing synorogenic Laramian sediments that were dated by Jablonský & Halásová (1994). The sample was taken from the second, northernmost slice.

From the Považský Inovec Mts., two samples were taken from the Striebornica locality (STR1, 368), which is represented by Coniacian sediments of the Tatric Unit (the youngest sediments ever found in this unit), as well as one sample from the Campanian sediments of the Belice Unit (Hranty Beds – the upper part of the Horné Belice Formation), which is an enigmatic unit that is tectonically included in the slice structures of the northern part of the mountains.

Methods

The majority of the samples were point samples from scree, since the examined flysch units rarely form outcrops (Fig. 3). A thin-section was prepared from each sample, and the petrographic composition of every sample (planimetric analysis) was determined by ribbon-counting under a polarizing microscope, using an Eltinor point-counter. Percentages of the main components, such as the matrix, quartz grains, feldspars, lithic fragments, and microfossils were recorded. Quartz–feldspars–lithic fragment ratios were plotted on triangular diagrams.

The remainder of the sample (2 kg in average) was crushed, washed, and sieved to a fraction of 0.08–1mm. Heavy fraction was then separated by heavy liquids (bromoform, sodium polytungstate, with densities of around 2.8). The fraction 0.08 to 0.25 mm was studied in transmitting light, and percentual ratios of translucent heavy mineral assemblages were determined by ribbon point counting. Less translucent chrome-spinels were counted under the reflected light in the same solutions. Since most of the samples were fine-grained arenites, the studied fraction covered most of the grain size, and as a consequence, the heavy mineral spectrum obtained was close to reality. The raw data of the counted heavy minerals were used for statistical linear regression analysis of the individual pairs of heavy minerals. Heavy mineral percentages were processed in Past3 software (specialized for paleontological statistical analysis – Hammer et al. 2001) for cluster analysis (classical clustering) in order to reveal any similarities between the samples. The same software was used for CABFAC factor analysis to reveal the main factors which influenced the heavy mineral composition in the samples. For the factor analysis, exploratory factor analysis of all the recorded sums of the minerals was used. The factors were extracted by principal component analysis (PCA) with varimax rotation of the factor axes. Euclidean distance was chosen for quantification of object distance.

Selected minerals, such as spinels, tourmalines, and garnets were hand-picked, embedded in epoxy resin, polished, coated by carbon, and measured in micro-analyzer. Their chemical compositions were analyzed using a JEOL JXA-8530FE microprobe (Earth Science Institute of the Slovak Academy of Sciences in Banská Bystrica, Slovakia) and with a CAMECA SX-100 electron microprobe at the State Geological Institute of Dionýz Štúr in Bratislava. Analytical condition was the same for both devices: accelerating voltage 15 kV, sample current 20 nA, probe diameter 2–10 μm, counting time 10 s – peak and 5 s for background. Raw counts were corrected using a PAP routine on the CAMECA, and ZAF correction was used for JEOL probe. The standards used, including for JEOL were: Ca – diopside, Mn – rodonite, Si – quartz, Mg – olivine, F – fluorite, Na – jadeite, Al – kyanite, K – orthoclase, Fe – hematite, Ti – rutile, Cr – Cr_2O_3, Cl – tugtupite. All measured spectral lines are Kα. The standards used for the CAMECA were: 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. Selected representative analyses of spinels and garnets (see Tables 4, 5) cover all the typical chemical compositions. For tourmaline representative analyses, data can be found in Aubrecht at al. (2020a).

Results

Petrographic composition of the samples

The analyzed arenitic samples belong to the category of fine-grained psammites. Medium-grained sandstones were rare. The grains of the examined sandstones are angular, subangular to semi-oval, with relatively good sorting. The main components are grains of quartz, lithoclasts and matrix. Feldspars are rare, represented mostly by K-feldspars (e.g., microcline) and albite. From lithoclasts, the most common are basaltic volcanics (Fig. 4a), carbonate grains (Fig. 4b), quartzites (Fig. 4c), and mica-schists (Fig. 4d). Clasts of phyllites rarely occur. Bioclasts were almost completely absent; only a few agglutinated foraminifers were found. The matrix of the sandstones is calcareous (mostly micrite, partly recrystallized to microsparite), ranging between a few percent to nearly 50 vol. % of the rock. Therefore, the examined arenites were more calcareous sandstones rather than wackes. Carbonate lithoclasts were easily discernible from the matrix. Some samples even represented sandy limestones; however, these were not included in the planimetric evaluation.

According to the modal composition diagram by Pettijohn et al. (1987), the analyzed psammitic rocks of the examined samples belong predominantly to litharenites and sublitharenites, even extending to a quartz arenite field (Fig. 5). When compared with the previously analyzed Albian–Cenomanian sediments (Aubrecht et al. 2020b), the Turonian–Senonian sediments display wider variability in the quartz and lithic fragments ratio. In the provenance diagram by Dickinson (1985), all the analyzed arenites fall into the recycled orogen field and partially into the transitional arc and undissected arc fields (Fig. 6).

Percentages of heavy minerals

The dominant minerals in the analyzed samples are invariably Cr-spinels, zircon, tourmaline, rutile, apatite, and garnet. However, their ratios vary. Those that are much less represented (only a few grains per mount) include monazite, staurolite, kyanite, pyroxenes, hornblende, bluish amphiboles, epidote, and sillimanite (Fig. 7, Table 1). The ZTR index (ultrastable assemblage of zircon–tourmaline–rutile – Hubert 1962) is from 14 to over 50 %. However, this does not fully reflect the maturity of the heavy-mineral assemblage, since there is a considerable number of Cr-spinels, which may also be considered ultrastable. If added to the ZTR, the amount of ultrastable minerals rises up to more than 90 %. In some samples, chloritoid grains were present, although they were

Table 1: Percentage ratios of heavy minerals in the samples analyzed. Abbreviations of mineral names – see Fig. 7. ZTR=sum of the percentages of the ultrastable trinity zircon–rutile–tourmaline (ZTR index). Tu= Turonian, Co=Coniacian, Sa=Santonian, Ca=Campanian, Ma=Maastrichtian.

Sample	Location	Age	Unit	N-latitude	E-longitude	Spl	Zrn	Tur	Ap	Rt	Grt	Mnz	Spn	St	Ky	Px	Amp	B-Amp	Ep	Sil	ZTR	ZTR +Spl
Vr	100 m in front of the Vranie village – Snežnica Beds sandstone - scree	Tu	Kysuca	49°14’55.4”	18°44’28.2”	28.1	9.4	34.4	12.5	7.8	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7	0.0	51.6	79.7
Vr-W	between Považský Chlmec and Vranie – at the end of the highway wall – Snežnica Beds sandstone – outcrop	Tu	Kysuca	49°14’44.6”	18°44’18.0”	28.9	24.4	15.6	11.1	8.9	4.4	2.2	0.0	0.0	0.0	2.2	2.2	0.0	0.0	0.0	48.9	77.8
NS15	between Považský Chlmec and Vranie – scree at the road – the uppermost occurrence Snežnica Beds sandstone	Tu	Kysuca	49°14’37.14”	18°44’11.94”	44.9	10.1	19.6	16.7	2.9	0.7	0.0	0.0	0.7	0.0	0.7	2.9	0.0	0.7	0.0	32.6	77.5
NS16	between Považský Chlmec and Vranie – sandstone of the Šromowce Formation – scree	Co–Sa	Kysuca	49°14’36.74”	18°44’15.12”	32.8	7.8	17.7	23.3	3.0	3.9	1.7	0.4	1.3	0.0	0.0	2.6	0.0	4.7	0.9	28.4	61.2
NS14	between Považský Chlmec and Vranie – sandstone of the Šromowce Formation – younger level – scree	Co–Sa	Kysuca	49°14’33.15”	18°44’13.38”	16.9	6.0	35.9	32.0	2.5	4.3	0.0	0.0	0.2	0.0	0.0	0.6	1.0	0.6	0.0	44.3	61.2
NS5	weathered sandstones on a slope of a valley north of Vieska-Bezdedov – scree	Co–Sa	Kysuca	49°08’23.24”	18°18’34.48”	1.8	7.1	36.6	0.9	13.4	35.7	2.7	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	57.1	58.9
NS6	calcareous sandstones in a roadcut in the valley north of Vieska-Bezdedov – outcrop	Co–Sa	Kysuca	49°08’33.45”	18°18’49.64”	34.9	10.5	25.6	0.0	5.8	19.8	1.2	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	41.9	76.7
NS7	calcareous sandstones at a ravine near a creek in the valley north of Vieska-Bezdedov – scree	Co–Sa	Kysuca	49°08’48.42”	18°19’02.43”	22.8	20.4	11.8	10.2	14.4	11.2	1.8	2.1	2.6	0.0	0.4	0.7	0.7	0.9	0.0	46.6	69.4
NS8	calcareous sandstones on a forest road below Zalazište – scree	Co–Sa	Kysuca	49°08’47.92”	18°19’36.47”	26.5	12.8	5.0	6.4	5.0	40.2	0.0	0.5	0.9	0.0	2.3	0.0	0.0	0.5	0.0	22.8	49.3
NS9	calcareous sandstones at a crossing of forest road with a high-voltage power line – scree	Co–Sa	Kysuca	49°08’48.52”	18°19’17.03”	44.1	15.9	18.8	0.0	12.9	4.1	0.0	0.0	0.0	0.0	0.0	1.8	2.4	0.0	0.0	47.6	91.8
NS10	sandstones in a small forrest above a meadow north of Nimnica – scree	Co–Sa	Kysuca	49°09’26.78”	18°20’37.97”	9.2	27.1	18.7	0.0	12.0	26.4	2.5	2.8	0.0	0.0	0.0	0.0	0.0	1.4	0.0	57.7	66.9
NS11	sandstones at the road between Klieštiny and Hatné – scree	Co-Sa	Kysuca	49°11’09.02”	18°22’01.95”	13.0	8.7	37.4	3.1	8.7	24.8	0.8	0.8	0.0	0.0	0.0	0.8	0.8	1.2	0.0	54.7	67.7
Rac	sandstones of the Sromowce Formation in a roadcut near the Racibor guest-house at Široká – outcrop	Co–Sa	Kysuca ?	49°15’15.96”	19°20’23.58”	83.8	7.1	6.1	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	14.1	98.0
K1	sandstones of the Sromowce Formation in a railway-cut between Krivá and Dlhá – outcrop	Co–Sa	Kysuca ?	49°16’44.9”	19°27’33.3”	15.8	11.5	16.4	9.1	4.2	39.4	1.2	1.2	0.0	0.0	0.0	0.6	0.0	0.6	0.0	32.1	47.9
K2	sandstones of the Sromowce Formation between Krivá and Dlhá in a roadcut above the railway – outcrop	Co–Sa	Kysuca ?	49°16’32.8”	19°27’32.6”	37.1	19.1	10.1	10.1	5.6	14.6	1.1	0.0	0.0	0.0	1.1	0.0	0.0	1.1	0.0	34.8	71.9
Pal	sandstones on the top of Pálenica hill at Zázrivá – scree	Co–Sa	Kysuca ?	49°17’02.5”	19°08’25.7”	21.9	14.5	17.2	26.9	7.1	7.7	1.0	0.3	0.0	0.0	3.0	0.0	0.0	0.3	0.0	38.7	60.6
Pu1	sandstones in a creek at the toe of the Pupov Hill at Zázrivá-Dolina – scree	Co–Sa	Kysuca ?	49°17’01.0”	19°06’55.9”	26.5	20.5	13.6	19.7	12.9	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	47.0	73.5
Pu2	sandstones in a forest roadcut on the eastern side of the Pupov Hill – scree	Co–Sa	Kysuca ?	49°16’51.2”	19°06’58.4”	20.5	24.0	21.6	5.8	15.2	9.9	0.6	1.8	0.0	0.0	0.0	0.6	0.0	0.0	0.0	60.8	81.3
Pu3	sandstones in a forest roadcut on the southeastern side of the Pupov Hill – outcrop	Co–Sa	Kysuca ?	49°16’30.5”	19°06’48.1”	13.2	34.7	12.4	18.2	14.9	5.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	62.0	75.2
ZD1	Zemianska dedina 1 – at a temporary building material storage – sandstones of the Sromowce Formation – scree	Co–Sa	Kysuca ?	49°19’21.3”	19°31’53.7”	67.5	10.3	16.2	2.6	0.0	2.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.5	94.0
ZD2	Zemianska dedina 2 – the lowermost occurrences of the Sromowce Formation in a quarry – scree	Co–Sa	Kysuca ?	49°19’28.1”	19°31’53.4”	68.3	6.3	19.0	4.8	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.4	93.7

Table 1 (continued)

Sample	Location	Age	Unit	N-latitude	E-longitude	Spl	Zrn	Tur	Ap	Rt	Grt	Mnz	Spn	St	Ky	Px	Amp	B-Amp	Ep	Sil	ZTR	ZTR +Spl
NS1	between Nosice and Považská Bystrica – top of a ridge towards Húštie – sandstones and pebbles – scree	Co–Sa	Klape	49°6'22.97"	18°22'48.16"	62.4	20.2	3.1	0.0	2.2	6.7	1.4	1.7	0.0	0.0	0.0	1.4	0.6	0.3	0.0	25.6	87.9
NS2	between Nosice and Považská Bystrica – at the end of the ridge near Húštie – sandstones and pebbles – scree	Co–Sa	Klape	49°6'8.46"	18°23'26.70"	42.1	10.5	30.3	2.6	1.3	5.3	1.3	0.0	0.0	2.6	0.0	0.0	1.3	2.6	0.0	42.1	84.2
NS3	between Nosice and považská Bystrica – sandstones in the forest road cut – outcrop	Co–Sa	Klape	49°6'10.77"	18°23'15.66"	55.6	23.4	5.8	0.0	2.9	1.8	0.0	3.5	0.0	0.0	0.0	0.0	6.4	0.6	0.0	32.2	87.7
NS4	between Nosice and Považská Bystrica – sandstones and conglomerates on a ridge towards Cerov settlement – scree	Co–Sa	Klape	49°6'28.73"	18°23'11.95"	48.1	16.3	23.8	9.4	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.6	0.0	40.0	88.1
STR1	sandstones above the Poruba Formation – Striebornica valley – Považský Inovec Mts.	Co–Sa	Tatricum	48°36'42.84"	17°54'27.06"	8.1	31.2	10.9	23.9	25.1	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.2	75.3
368	sandstones above the Poruba Formation – Striebornica valley – Považský Inovec Mts.	Co–Sa	Tatricum	48°36'39.48"	17°54'23.70"	6.0	36.8	8.8	19.1	27.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	72.5	78.6
Hr	Hranty – Campanian sandstone of the Belice Unit – Považský Inovec Mts. – outcop at a forest road	Ca	Belice	49°16'44.9"	19°27'33.3"	18.1	23.9	30.4	10.9	14.1	1.8	0.0	0.0	0.7	0.0	0.0	0.0	0.2	0.0	0.0	68.3	86.4
Jel	Campanian–Maastrichtian flysch sandstones at Jelšava neat Dolný Kubín – outcrop	Ca-Ma	Kysuca ?	49°14'20.4"	19°18'24.4"	10.3	0.0	12.1	20.6	1.9	54.2	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0	24.3
NS12	scattered sandstone blocks the Dolina settlement Hlboké Formation (Podhájska succession) – Maastrichtian	Ma	Klape	49° 9'37.59"	18°31'16.95"	28.6	21.1	16.1	21.7	5.6	3.7	0.6	1.2	0.0	0.0	0.6	0.6	0.0	0.0	0.0	42.9	71.4
NS13	scattered sandstone blocks the Dolina settlement Hlboké Formation (Podhájska succession) – Maastrichtian at the road in front of Jablonové	Ma	Klape	49°11'28.28"	18°33'33.11"	32.7	3.8	17.3	0.0	1.9	11.5	0.0	0.0	0.0	0.0	9.6	9.6	0.0	13.5	0.0	23.1	55.8

not included in the percentages since only bluish-grey varieties could be distinguished under the microscope, which does not cover all the possible varieties of their appearance. Chloritoid was represented the most in the NS9 sample; however, a few grains were also found in the NS6, NS10, NS11, and Rac samples.

Statistical analysis

The statistical linear regression analysis of the individual pairs of heavy minerals (Table 2) shows a strong, positive correlation between zircon and rutile (0.91), as well as a moderate positive correlation between tourmaline and apatite (0.69). The tourmaline had only a weak positive correlation with the zircon and rutile. Apatite had a weak positive correlation with zircon and rutile. A positive correlation between Cr-spinels and pyroxenes, and garnet and staurolite, indicate that some of their grains share common sources as well. However, staurolite and pyroxenes were found in very small amounts, and therefore, this correlation can be neglected in interpretations. A weak, positive correlation between the Cr-spinels and zircon is surprising, and thus one may speculate whether part of them had been recycled from older sediments.

Cluster analysis revealed some similarities between the samples taken from the sites that are localized close to each other (Fig. 8) or in the same region, such as NS3-NS1, ZD1-ZD2-Rac, and 368-Str. However, the rest of the samples show neither regional, nor stratigraphic linkage. The Turonian samples Vr, Vr-W, and NS 15, as well as the upper Campanian–Maastrichtian samples NS12, NS13, and Jel are scattered across the tree and intermixed with the rest of the Coniacian–Santonian samples from all of the regions.

Factor analysis revealed that there are four main factors responsible for most of the variance (96.1) within the heavy mineral percentages (Table 3). The best interpretation of the factors is that they represent the individual heavy mineral sources that are mixed in various proportions. The strongest source is the source of Cr-spinels (ophiolitic source – either primary, or recycled) represented by Factor 1, with the eigenvalue 23.2, which is responsible for 72.6 % variance in the samples. This source is best manifested by Rac, ZD1-2, NS1 and NS3 samples (Fig. 9, Table 3). The second source (Factor 2: eigenvalue 3.7, variance 11.6 %) yielded zircon, rutile, tourmaline, and apatite and may represent older clastic sediments. It is best manifested by the samples from the Striebornica locality (STR1, 368) and the Pu3 sample. The third source (Factor 3: eigenvalue 2.5, variance 7.9 %) is typical due to the influx of garnet and tourmaline, i.e., most likely medium-grade to high-grade metamorphics or acidic to intermediate magmatics. It is best manifested

Fig. 3. View of some selected exposures of the formations sampled. **a** — Exposure of turbidites of the Sromowce Formation, locality K1 – above the railway between Krivá and Dlhá villages, Kysuca Unit. **b** — Thin-bedded sandstone turbidites of the Snežnica Beds. Locality Vr-W – road between Považský Chlmec and Vranie villages – the type section of the Kysuca Unit. **c** — Thin-bedded sandstone turbidites of the Sromowce Formation in a forest road on the Pupov hill – locality Pu2. **d** — Steeply-inclined turbiditic sandstones of the Sromowce Formation in a quarry road near Zemianska dedina (ZD1 locality).

by the samples Jel, K1, and NS5. The weakest source of the four main ones (eigenvalue 1.3, variance 4 %) shed mainly tourmaline and apatite and is represented the most by the samples NS14 and Vr. The source might have been represented by low-grade (maximum greenschist facies) metasediments.

Cross plots of the individual factors (Fig. 9) show some aspects that are evident also from the cluster analysis, i.e., a close similarity between some samples that are regionally or locally close to each other. In all of the diagrams, the samples from the Striebornica locality (STR1, 368) are consistently close to each other and influenced predominantly by Factor 2 (reworking from older sediments). Moreover, the samples from Zemianska Dedina (ZD1-2) and Racibor (Rac) are consistent in all the diagrams as well and influenced mainly by Factor 1 (ophiolites). Samples from the Pupov hill (Pu) and Pálenica Hill (Pal) between Terchová and Zázrivá are also consistently close, except for the Pu3 sample, which is positioned slightly differently in the diagram. These samples are influenced predominantly by Factor 2 and less by Factors 1 and 4. The samples from the Klape Unit (NS1-4) are also consistently close to each other, but they split once Factor 4 is involved (Fig. 9c, e, f). The diagrams also reveal some trends in the sampled units caused by the individual factors.

If we compare Factors 1 and 2 (Fig. 9a), the samples of the Kysuca Unit from the Váh Valley (NS5-11) show an elongated trend with a relatively low, but stable influence by Factor 2 and a large dispersion in Factor 1 (in comparison, for instance, with the samples NS5 and NS6, which are geographically close to each other, but display a strong difference in Factor 1). A similar trend is evident for the samples from the Kysuca Unit type section, with a slightly higher representation of Factor 2.

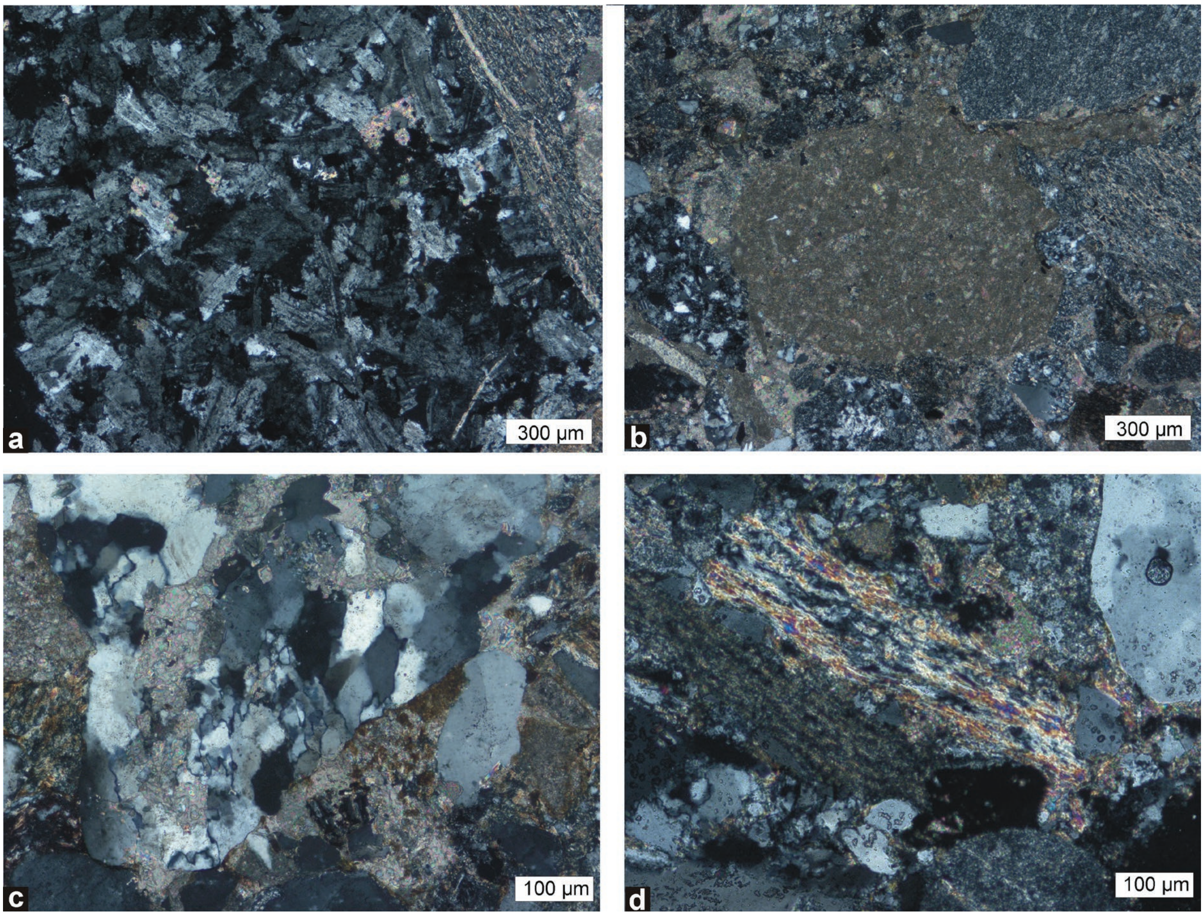

Fig. 4. Some examples of lithic fragments in the samples analyzed. **a** — Fragment of basaltic rock, sample NS4. **b** — Limestone lithoclast, sample NS4. **c** — Fragment of quartzite, sample NS10. **d** — Fragment of mica-schist, sample from Racibor location. Transmitting polarized light, crossed polars.

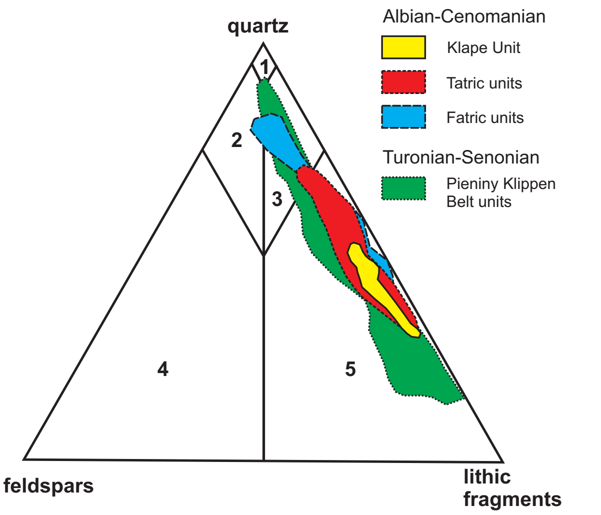

Fig. 5. Plot of the petrographic composition obtained by point-counting of the analyzed samples thin-sections in the sandstone classification diagram by Pettijohn et al. (1987). Although the examined sandstones often contain >15 % of matrix, it is calcareous, and they do not belong to wackes. The data are compared with previously analyzed Albian–Cenomanian arenites (Aubrecht et al. 2020b). 1 – quartz arenite, 2 – subarkose, 3 – sublitharenite, 4 – arkosic arenite, 5 – litharenite.

In Fig. 9b, when comparing Factors 1 and 3, the Váh Valley samples show a similar trend of dispersion in Factor 1, but with a slight, negative correlation with a better-represented Factor 3. A similar, slightly negative correlation is recorded from the Kysuca Unit type section, with low influence by Factor 3. A strong, negative correlation of these factors is shown in the Klape Unit samples.

The diagram in Fig. 9c shows a comparison of Factors 1 and 4. The Klape Unit type section samples show a strong negative correlation. A similar trend, but with much more dispersion, can be seen for the Váh Valley samples too.

A comparison of Factors 2 and 3 (Fig. 9d) shows an elongated trend in some of the Váh valley samples with relatively stable lower values of Factor 2 and dispersed Factor 3. A somewhat negative correlation is displayed by the samples taken between the villages of Terchová and Zázrivá. Other samples are clustered without any significant trend.

A comparison of Factors 2 and 4 (Fig. 9e) shows generally negative trends in all the clusters. On the other hand, a comparison between Factors 3 and 4 (Fig. 9f) shows generally positive correlation trends in most of the clusters, although most of the values tended to be closer to zero because these two factors were the weakest ones evaluated.

Some samples, e.g., Jel, Hr, NS12-13, Vr-W, K1-2 and NS7, show no preferential relationship with others, being generally isolated and plotted in different places in the diagrams.

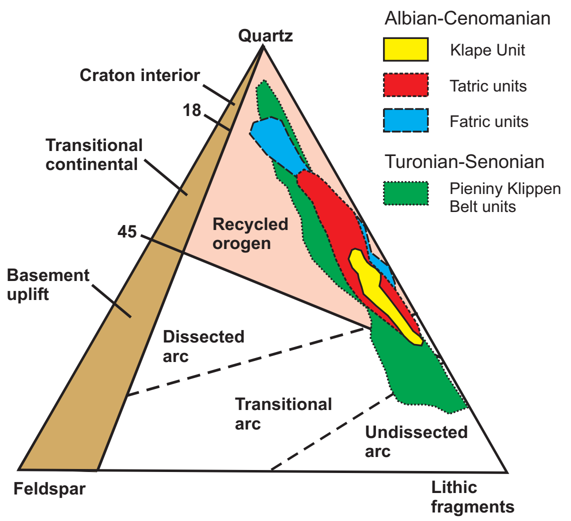

Fig. 6. Plot of the petrographic composition obtained by point-counting in the arenite provenance diagram by Dickinson (1985).

Chemical composition of selected heavy minerals

Composition of detritic Cr-spinels

The analyzed spinel fragments were mostly homogeneous and unzoned. Only a few grains with internal zonation were registered (Fig. 10a). Some grains possessed alteration rims (Fig. 10b); one grain was almost completely altered (Fig. 10c). The altered spinel grains commonly contain small vugs caused by dissolution of the unstable inclusions. Only one grain contained preserved inclusions of olivine and pyroxenes (Fig. 10d).

For the provenance of spinels, chemical variability of stable elements, such as Mg, Fe, Cr, Al, and Ti is important (Table 4). Two types of diagrams are used. The first, a diagram of $Mg/(Mg+Fe^{2+})$ vs. $Cr/(Cr+Al)$ was introduced by Dick and Bullen (1984). It has 3 distinguished fields that indicate various types of ophiolites: (1) Type I ophiolites representing peridotites for which $Cr/(Cr+Al)$ is below 0.60 (mid-oceanic ridge peridotites), (2) Type III ophiolites representing peridotites with spinels having more than 0.60 $Cr/(Cr+Al)$, representing the early stages of arc formation, (3) Type II ophiolites bearing spinels with a wide range of $Cr/(Cr+Al)$, representing transitional phases. Herein, we use a modified diagram by Pober & Faupl (1988) to distinguish spinels derived from

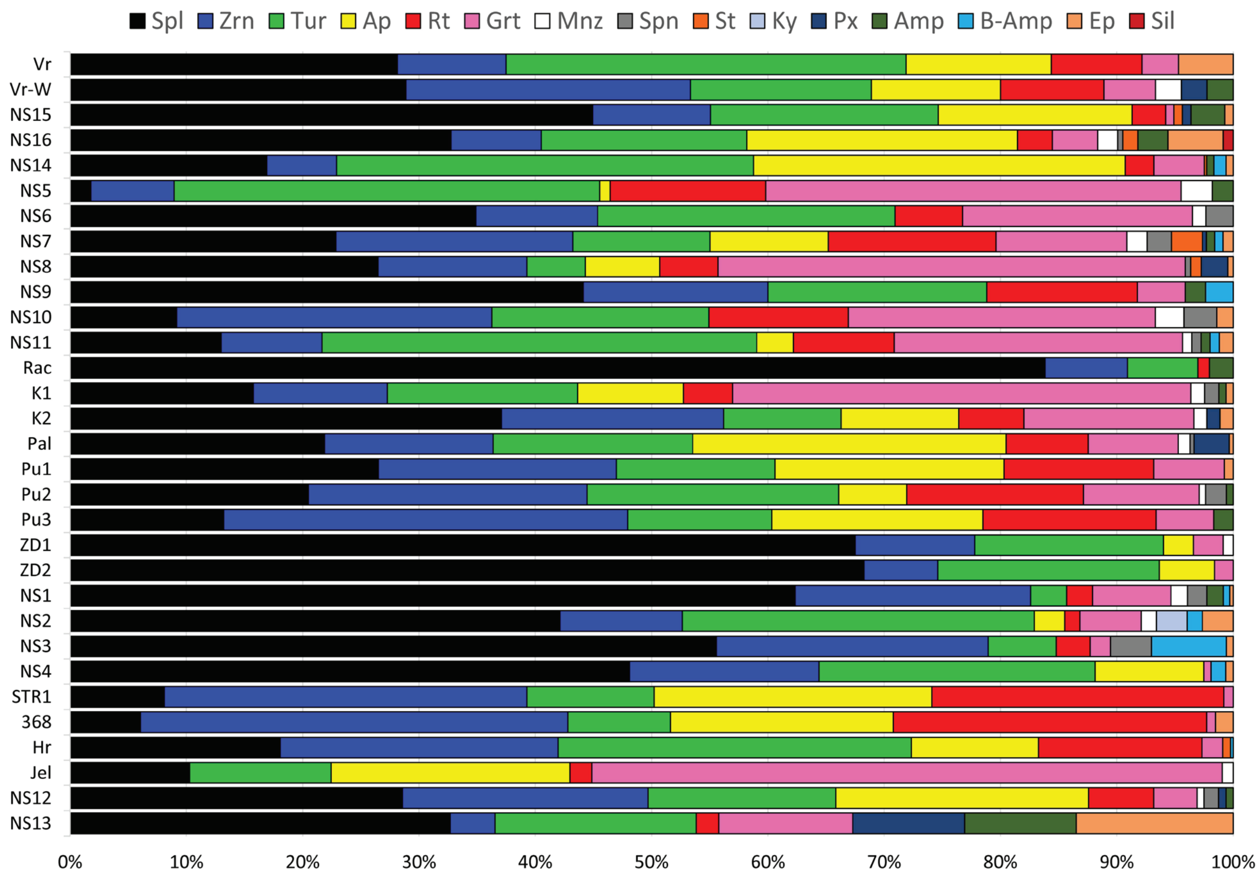

Fig. 7. Percentage ratios of the heavy minerals in the samples analyzed. Mineral abbreviations (from Whitney & Evans 2010): Spl – spinel, Zrn – zircon, Tur – tourmaline, Ap – apatite, Rt – rutile, Grt – garnet, Mnz – monazite, Spn – titanite, St – staurolite, Ky – kyanite, Px – pyroxene, Amp – amphibole, B-Amp – blue amphibole, Ep – epidote, Sil – sillimanite.

Table 2: Results of statistical linear regression analysis of the individual pairs of heavy minerals.

Mineral pair	Correlation coefficient (r)	Degree of correlation
Zrn–Ru	0.91	high positive correlation
Tur–Ap	0.69	moderate positive correlation
Spl–Px	0.45	weak positive correlation
Rt–Ap	0.44	weak positive correlation
Zrn–Ap	0.42	weak positive correlation
Zrn–Tur	0.34	weak positive correlation
Rt–Tur	0.34	weak positive correlation
Grt–Strl	0.32	weak positive correlation
Zrn–Spl	0.32	weak positive correlation
Grt–Tur	0.18	no linear relationship
Tur–Spl	0.15	no linear relationship
Grt–Rt	0.12	no linear relationship
Grt–Ep	0.12	no linear relationship
Spl–Ap	0.12	no linear relationship
Grt–Zrn	0.11	no linear relationship

harzburgites, lherzolites, podiform chromitites, and cumulates (Fig. 11). Most of the grains match the harzburgitic field, with some overlap on the fields of podiform chromitites and cumulates. Some spinels outside the distinguished fields were most likely altered or metamorphosed. It is important to note that no analyses were plotted on the non-overlapping part of the lherzolite field having Cr/(Cr+Al) less than 0.3.

The second type of diagram which is used for provenance purposes is a diagram of Al_2O_3 vs. TiO_2, introduced by Lenaz et al. (2000) and Kamenetsky et al. (2001). The principle of the diagram is based on the fact that most of the mantle rocks spinels have TiO_2 lower than 0.2 wt. %, and most of the volcanic spinels have TiO_2 higher than 0.2 wt. % (for a complete overview, see Lenaz et al. 2009). The diagram indicates that most of the spinels were derived from the supra-subduction zone peridotites; only one grain had higher TiO_2 content and was plotted on the oceanic island basalts. No grains are plotted on the non-overlapping part of the MORB peridotites field (Fig. 12).

Chemistry of the altered grain (Fig. 10c) is shifted towards high Cr, Ti, and low Al content (Figs. 11, 12) and a relatively increased content of Mn, Zn, Ni, and V (Table 4).

Composition of detritic tourmaline

Detrital tourmaline grains in the analyzed samples had a 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 predominantly unzoned. However, some display distinct zonation displaying a complex intergrowing pattern of two phases of tourmaline, or tourmaline with quartz, attaining thus a complex-zoned mosaic appearance (Fig. 13). These were found in the samples from the Klape Unit (NS1-5) and from the Racibor locality (Aubrecht et al. 2020a).

According to classification diagrams of Hawthorne & Henry (1999), most of the tourmalines belong to the alkali and

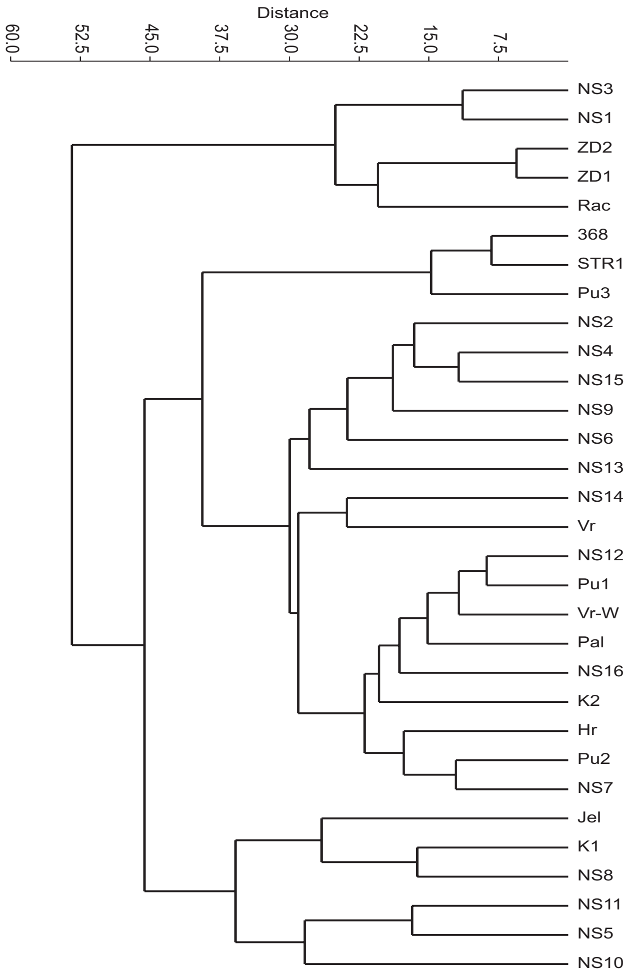

Fig. 8. Cluster diagram of the analyzed samples based on percentages of heavy minerals (classical clustering, Euclidean similarity index).

X-vacant groups (Fig. 14) with schorl–dravitic, less foititic and magnesio-foititic composition with higher proportion of X-site vacancies (Fig. 15). The discrimination diagrams by Henry & Guidotti (1985) revealed that the main portion of tourmaline grains were likely derived from metasediments, i.e., from metapelites and metapsammites, which either coexist or do not coexist with an Al-saturating phase; some were also derived from Fe^{3+}-rich quartz–tourmaline rocks, calc-silicate rocks, and metapelites (Fig. 16). A group of prevalent schorlitic composition was plotted to the field of Li-poor granitoid rocks and their associated pegmatites and aplites.

The complex-zoned tourmaline grains represent two types: (1) grains with fabric consisting of several tourmaline phases that are arranged chaotically as laths, (2) grains displaying a fine intergrowth of tourmaline and quartz (Fig. 13). The first type of tourmaline shows a continuous trend of Al and its substitution by Fe^{3+} at the Y and Z sites, thus shifting from a schorl–dravitic composition to one of bosiite. The second type consists of dominating schorl–dravitic tourmaline, but with scarce occurrence of Al-enriched oxy-dravitic, foititic,

Table 3: Results of statistical factor analysis of the heavy mineral percentages (factors and scores are displayed in rotated loads).

	Factors			
Sample	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**
NS13	0.76046	0.09756	−0.42622	−0.27518
NS12	0.61127	0.6547	−0.22873	−0.32789
Jel	0.096036	0.097079	−0.90444	−0.084395
Hr	0.38562	0.69489	−0.29824	−0.47333
368	0.08799	0.97868	−0.13812	−0.051754
STR1	0.12249	0.9598	−0.14512	−0.15983
NS3	0.92116	0.34323	−0.12256	0.034333
NS2	0.79569	0.23572	−0.31464	−0.42465
NS1	0.94508	0.26718	−0.17174	0.067965
ZD2	0.951	0.13699	−0.14547	−0.224
ZD1	0.95862	0.16519	−0.15351	−0.16269
Pu3	0.27227	0.91544	−0.24812	−0.12363
Pu2	0.46463	0.68418	−0.44968	−0.24537
Pu1	0.56803	0.71399	−0.28202	−0.25419
Pal	0.46512	0.62861	−0.31941	−0.43205
K2	0.76966	0.46654	−0.41788	−0.073535
K1	0.28167	0.26527	−0.9059	−0.095815
Rac	0.98743	0.097983	−0.070017	−0.040555
NS11	0.24763	0.2687	−0.75522	−0.49661
NS10	0.19386	0.5727	−0.74975	−0.029629
NS9	0.83344	0.38728	−0.25692	−0.18744
NS8	0.47286	0.2404	−0.81574	0.13049
NS7	0.54875	0.69292	−0.4371	−0.11832
NS6	0.69499	0.241	−0.59412	−0.27929
NS5	−0.001721	0.21976	−0.8707	−0.37457
NS4	0.85132	0.34138	−0.18361	−0.33806
NS14	0.2933	0.42714	−0.28787	−0.7695
NS16	0.68991	0.41588	−0.22644	−0.462
NS15	0.83153	0.35088	−0.16362	−0.37743
Vr-W	0.65502	0.66487	−0.2727	−0.20839
Vr	0.57216	0.39577	−0.32005	−0.63079

	Scores			
Mineral	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**
Spl	3.8233	0.086361	−0.16147	−0.010468
Zrn	0.24669	2.991	−0.22943	1.061
Tur	0.099404	0.30798	−1.1994	−3.2788
Ap	−0.29553	1.6257	0.19207	−1.4586
Rt	−0.37719	1.7791	−0.29299	0.27452
Grt	−0.20918	−0.34862	−3.65	0.91575
Mnz	0.0096852	0.031515	−0.11977	0.013148
Spn	0.037765	0.048925	−0.09305	0.11661
St	0.0083379	0.026701	−0.01192	0.009149
Ky	0.011525	−0.015098	0.001303	−0.027667
Px	0.084477	−0.046932	−0.0731	−0.017726
Amp	0.1048	−0.054751	−0.05389	−0.091868
B-Amp	0.076261	0.0011379	0.013312	0.029266
Ep	0.11307	−0.11167	−0.07526	−0.23983
Sil	0.0022275	−0.0012352	0.003851	−0.012989

	Principal components	
	Eigenvalue	**% variance**
1	23.227	72.58
2	3.7036	11.57
3	2.5317	7.91
4	1.2949	4.05
5	0.8808	2.75
6	0.17834	0.56
7	0.12902	0.4
8	0.015961	0.05
9	0.011417	0.04
10	0.010858	0.03

and magnesio-foititic compositions. A bosiite trend (Al-depletion, Fe^{3+} enrichment) was also registered in some unzoned tourmalines from the K1-2, NS16, and Hranty localities (Fig. 16). For representative analyses, see Aubrecht et al. (2020a).

Composition of detritic garnet

The garnet grains were transparent, colourless to pale pink under microscope; they represented mainly fragments of grains without preserved crystal faces or zonation. Measuring of the centres and margins of the grains did not reveal any hidden zonation. Garnets from the two richest localities in garnet were analyzed – K1 and NS8 (Fig. 17, Table 5). Most of the examined detrital garnet grains from the K1 sample show a clear dominance of the almandine molecule; the grains of the NS 8 sample possessed increased pyrope contents, thus attaining a pyrope–almandine composition.

Interpretations and discussion

The data presented in this paper combined with data from existing literature show that the ophiolitic detritus in the form of Cr-spinels is not exceptional in the West Carpathian Cretaceous. On the contrary, we can say that since the Albian onward, there hasn't been any Cretaceous detritic formation free of it. The only lacking information is from three Senonian occurrences in the West Carpathian internides – in the Kršteňany section (Soták et al. 2021), the Miglinc Valley in the Slovak Karst area (Mello & Salaj 1982), and from the vicinity of the village of Šumiac in the Hron river valley (Bystrický 1959; Biely & Salaj 1966; Andrusov 1976). The mass occurrence of ophiolitic material in the Cretaceous shows just how huge the obducted ophiolitic complex was and how much tectonic information was destroyed by erosion.

What has changed since the Albian–Cenomanian?

The analyzed Turonian and Senonian sediments show larger variability when compared with those from the Albian–Cenomanian (Bellová et al. 2018; Aubrecht et al. 2020b). This variability is displayed in both petrographic analysis and heavy minerals. The first shows a much wider span of the quartz/lithic fragments ratio. The second mainly concerns the influx of garnets and associated heavy minerals from continental metamorphics and magmatics (Factor 3 in the factor analysis). This source was unevenly and much less

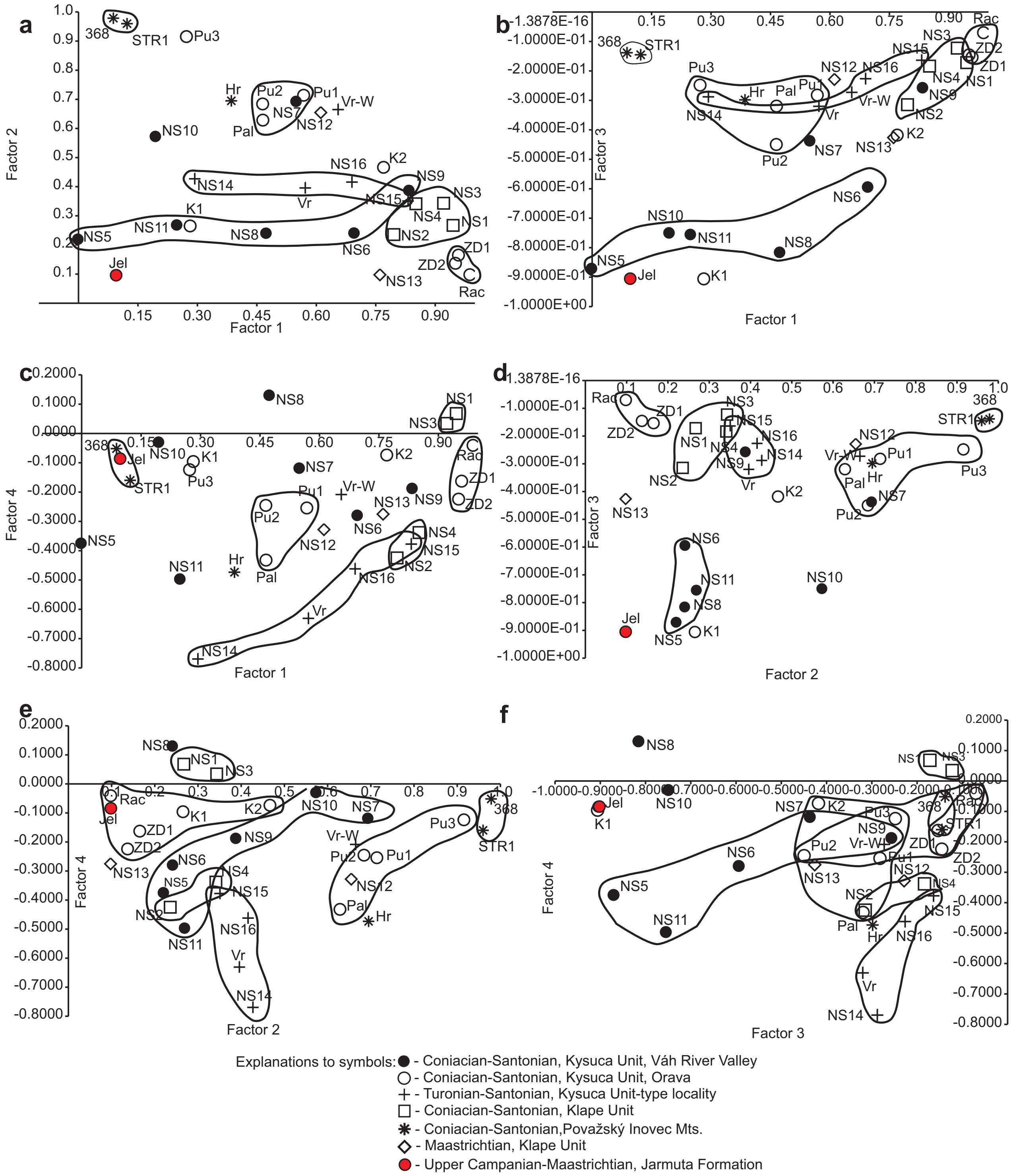

Fig. 9. Factor analysis diagrams of heavy-mineral percentages showing cross plots of influences of four main factors to the individual samples. **a** — Factor 1 vs. Factor 2; **b** — Factor 1 vs. Factor 3; **c** — Factor 1 vs. Factor 4; **d** — Factor 2 vs. Factor 3; **e** — Factor 2 vs. Factor 4; **f** — Factor 3 vs. Factor 4.

represented in the older sediments (Bellová et al. 2018; Aubrecht et al. 2020b).

The ophiolitic source represented by Cr-spinels was still the most important source influencing all the sedimentary area (Factor 1 in the factor analysis). Our data show that the Turonian Snežnica Beds already contain this material, despite earlier data from Łoziński (1959). Cr-spinels were generally overlooked in earlier analyses because of their semi-opaque character, and their importance was not recognized prior to the appearance of the plate tectonics theory. As a rule, the spinels from pure MORB (lherzolitic) ophiolites are absent in the studied exotics (in Albian–Cenomanian sediments, there were only a few grains found – Aubrecht et al. 2020b). Therefore, back-arc (supra-subduction) harzburgites were considered to be the only source of the ophiolitic detritus in the exotics (see the discussions in Gawlick et al. 2015, 2020; Bellová et al. 2018). Since Power et al. (2000) presented a case from the Rum-layered intrusion in the Inner Hebrides (Scotland), where spinels from chromite seams cover the entire spectrum of spinel chemistry, while there was a shift towards Cr- and Fe-enrichment versus Al-depletion in the grains separated from sediments of the streams draining the intrusion body, the validity of spinels as a provenance indicator has been challenged. However, our first, yet unpublished preliminary results from the Senonian ophiolite-bearing conglomerates in the vicinity of the Dobšiná Ice Cave show that Cr-spinels in the sand fraction and those in the pebbles show no difference. They all cover the entire spectrum of chemistry and indicate that stability of the Cr- spinels under hypergenic processes is equal, no matter what chemistry they have. Therefore, we can state that the lack of pure MORB ophiolites in the exotic source was primary. Other minerals, which might have been derived from the ophiolitic source as well, such as blue amphiboles and pyroxenes are rare (only in the NS13 sample did the content of pyroxenes increase to over 9 %). Their presence or absence, however, cannot be considered primary, since they represent the most unstable heavy minerals under hypergenic conditions. In the older, Albian exotics (Bellová et al. 2018; Aubrecht et al. 2020b), an excess of enstatite, augite, and diopside pyroxenes was identified in some of the samples. Theoretically, the last two might have been derived from ophiolites, but the enstatite was interpreted as being derived possibly from coeval volcanics. Chloritoid, which may accompany HP metamorphics (mainly Mg-chloritoid – Kienast & Messiga 1987; Negulescu 2009; Pourteau et al. 2014) is also relatively rare, except for

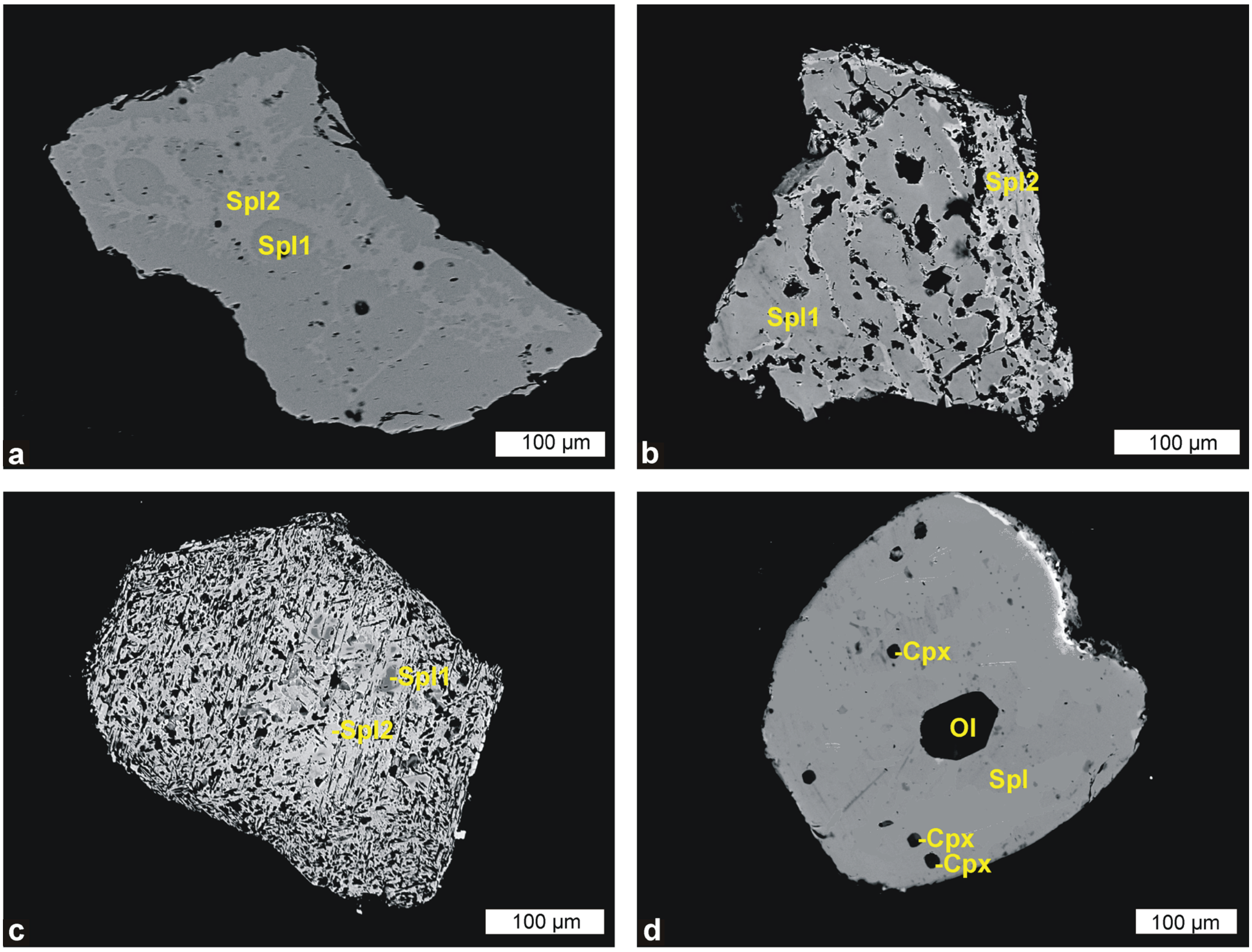

Fig. 10. BSE images of polished spinel grains with visible inner structure. For abbreviations of mineral names in the figures see Whitney & Evans (2010). **a** — Spinel with visible zonation, with darker zone (Spl1) enriched in Mg with respect to the lighter zone (Spl2). Racibor, Kysuca Unit. **b** — Altered spinel with voids, showing two zones. The zone SPL2 is enriched in Cr and depleted in Al with respect to the zone Spl1. The change was most likely caused due to alteration. Racibor, Kysuca Unit. **c** — Altered and weathered spinel (SPl2) with relics of the original spinel (Spl1) and voids after inclusions. The altered spinel is also marked in the diagrams. NS4 – between Nosice and Považská Bystrica, Klape Unit. **d** — Spinel with preserved olivine and clinopyroxene inclusions. Racibor, Kysuca Unit.

Table 4: Representative microprobe analyses of the spinels (in wt. %). The formula is based on three cations. alt.=altered spinel – see Fig. 10c.

Sample	NS-1	NS-4	NS-4	NS-Rac2	NS-Rac2	NS-Rac2	NS-Rac2	NS-Rac2
Analysis No.	1/1	8/1 – alt.	9/1	46/1	47/1	48 / 1	49 / 1	50 / 1
SiO_2	0.09	0.00	0.06	0.06	0.01	0.16	0.00	0.03
TiO_2	0.06	2.35	0.17	0.22	0.22	0.08	0.07	0.08
Al_2O_3	32.40	0.81	25.40	31.07	31.03	14.36	14.05	14.77
Cr_2O_3	36.97	38.99	39.79	35.55	35.33	59.29	57.75	59.00
FeO	15.55	34.33	25.52	17.71	18.20	16.58	18.02	17.03
MnO	0.27	16.15	0.91	0.29	0.25	0.41	0.41	0.37
MgO	15.65	1.57	8.18	14.86	14.92	7.59	11.16	7.68
ZnO	0.11	3.21	1.17	0.10	0.15	0.12	0.15	0.13
NiO	0.13	0.20	0.01	0.16	0.18	0.10	0.05	0.02
V_2O_3	0.19	0.71	0.18	0.24	0.24	0.26	0.23	0.24
TOTAL	101.42	98.32	101.40	100.25	100.53	98.95	101.90	99.35
Si	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Ti	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.10	0.04	0.93	1.07	1.07	0.56	0.53	0.58
Cr	0.84	1.14	0.97	0.82	0.82	1.56	1.45	1.55
Fe^{2+}	0.32	0.32	0.57	0.34	0.34	0.61	0.46	0.61
Fe^{3+}	0.06	0.74	0.09	0.09	0.11	0.00	0.02	0.00
Mn	0.01	0.50	0.02	0.01	0.01	0.01	0.01	0.01
Mg	0.67	0.09	0.38	0.65	0.65	0.38	0.53	0.38
Zn	0.00	0.09	0.03	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
V	0.00	0.02	0.00	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
Sum B	2.00	2.00	2.00	2.00	2.00	1.99	2.00	2.00
$Mg/(Mg+Fe^{2+})$	0.68	0.22	0.40	0.66	0.66	0.38	0.54	0.39
Cr/(Cr+Al)	0.43	0.97	0.51	0.43	0.43	0.73	0.73	0.73

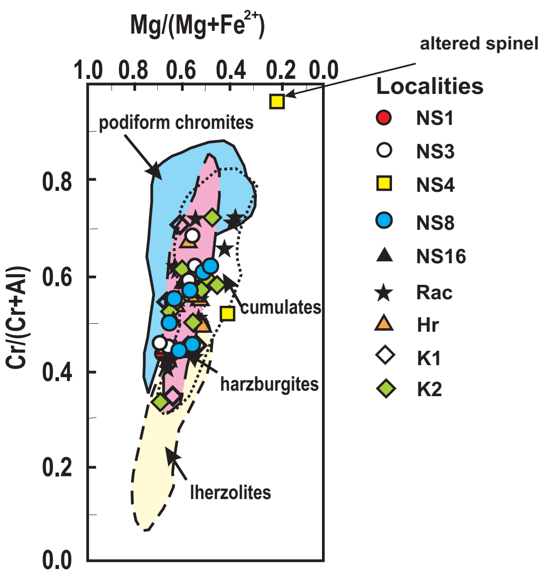

Fig. 11. The spinels measured from the individual units plotted in the $Mg/Mg + Fe^{2+}$ vs. Cr/Cr + Al diagrams with fields distinguished by Pober & Faupl (1988). Diagram fields: solid line – podiform chromites, dotted line – cumulates, dashed line (short dashes) – lherzolites, dashed line (long dashes) – harzburgites.

the NS9 sample, which also has a moderately increased Cr-spinel content.

Still, the reworking of older clastics was also an important source in the studied clastics (Factor 2), which is seen from the high positive correlation between zircon and rutile. A vast majority of the zircon grains are abraded and rounded; those with preserved crystal faces are rare. However, tourmaline correlates weakly with the rest of the ultrastable trinity, which is a deviation from the data obtained from the Albian–Cenomanian sediments. This is an indication that the older sediments, which shed the reworked material to the Senonian basins, had been relatively depleted in tourmaline. Another deviation is visible from the linear regression analysis, indicating that there is no correlation between the tourmaline and spinel. In the Albian–Cenomanian sediments, they had a moderate, positive correlation (Aubrecht et al. 2020b). Factor analysis also shows that tourmaline is in fact involved in three of the four strongest factors, thus indicating an increased variability in tourmaline sources. The source of complex-zoned tourmalines (schorl–dravite+quartz, or schorl–dravite+bosiite) was still present in significant amounts, however, their connection to the Cr-spinel bearing ophiolites, as presented by Aubrecht et al. (2020a) is here questionable, if we look solely on the statistics. On the other hand, the samples with complex-zoned tourmalines (Aubrecht et al. 2020a) were those which were most influenced by the spinel influx (Factor 1), except for the NS5 sample. The moderate positive correlation between tourmaline and apatite (Factor 4) indicates that they may have been derived from greenschist facies metamorphics. In the Western Carpathians, source rocks with a dominance of tourmaline and apatite were found in the Gemeric Unit (Aubrecht 1994; Aubrecht & Krištín 1995 and the references therein).

The garnet data show that along with ordinary almandine, there is an important source of pyrope–almandine garnets,

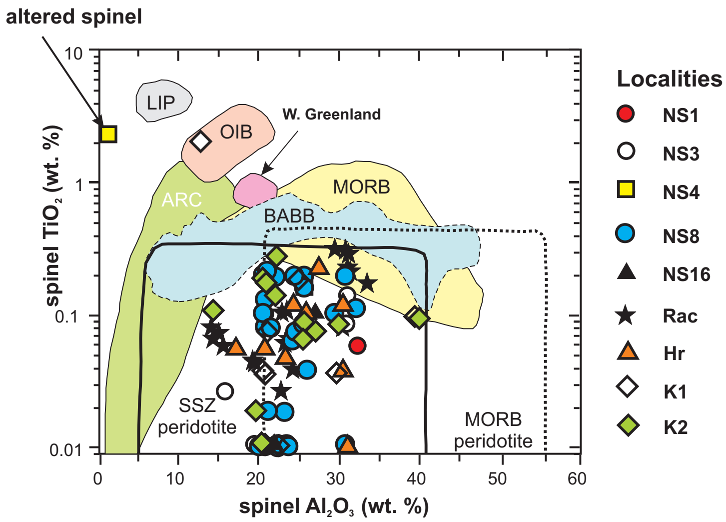

Fig. 12. The spinels measured from the individual units plotted in the TiO_2 vs. Al_2O_3 diagram of Lenaz et al. (2000) and Kamenetsky et al. (2001). Explanations: LIP – large igneous provinces, OIB – ocean island basalts, ARC – island-arc magmas, BABB – back-arc basin basalts, MORB – mid ocean ridge basalts, SSZ – supra-subduction zone peridotites.

which are typical of granulites and eclogites, i.e., rocks of the lower continental crust. Pyrope–almandine garnets occur all over the West Carpathian externides (Otava et al. 1997, 1998; Aubrecht & Méres 1999, 2000; Salata 2004; Oszczypko & Salata 2005; Grzebyk & Leszczyński 2006; Aubrecht et al. 2009; Salata 2013a; Bónová et al. 2019) and on the adjacent Bohemian Massif (Hartley & Otava 2001; Čopjaková et al. 2001, 2005; Kowal-Linka & Walczak 2018) and the Polish Platform (Aubrecht et al. 2007; Biernacka & Józefiak 2009; Méres et al. 2012; Biernacka 2012; Salata 2013b). Eclogites are one of the sources of the complex-zoned tourmalines (Smith 1971; Altherr et al. 2004; Marschall et al. 2006, 2008; Kadarusman et al. 2007; Konzett et al. 2012; Shimizu & Ogasawara 2013; Broska et al. 2019; Aubrecht et al. 2020a and citations therein) and this source may appear independently from the oceanic ophiolites. Eclogite pebbles were also found in the Cretaceous exotics (Šímová 1982). The mass appearance of pyrope-almandine garnets in the West-

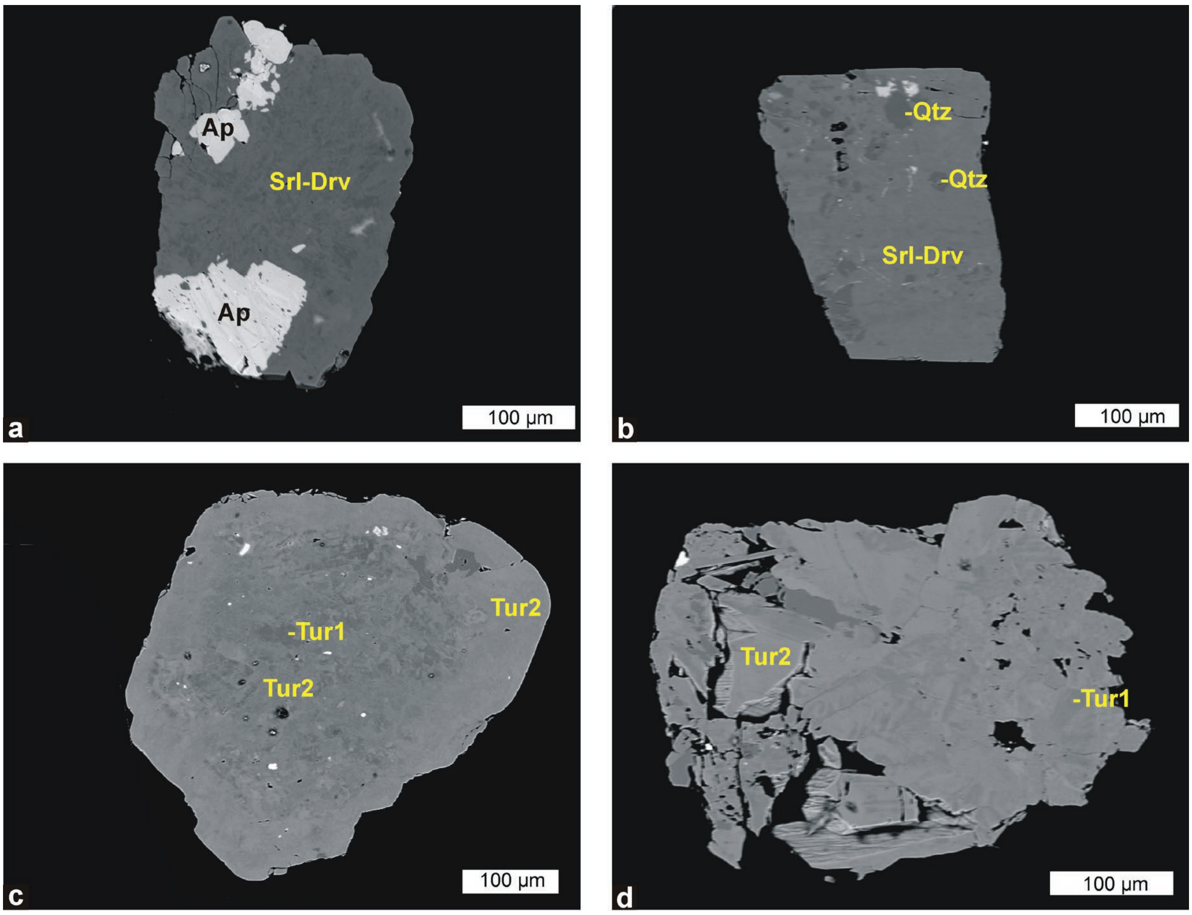

Fig. 13. BSE images of the analyzed tourmaline grains with visible complex inner structure. **a** — Schorl-dravitic tourmaline with inclusions of apatite (Srl-Drv – schorl-dravite). Rac sample. **b** — Schorl-dravitic tourmaline intergrown with quartz. NS1 sample. **c** — Complex-zoned tourmaline. The darker zone (Tur1) is schorl-dravitic tourmaline; the pale zone (Tur2) displays a slight bosiite trend (Al-depletion). Rac sample. **d** — Complex-zoned tourmaline. The darker zone (Tur1) and the pale zone (Tur2), both displaying a slight bosiite trend (Al-depletion). Rac sample.

Carpathian Cretaceous exotics is recorded for the first time; previous works presented only minor amounts of this type of garnet (Madzin et al. 2019; Aubrecht et al. 2020b). More of them were found in the Cretaceous exotics-bearing flysches in Croatia (Lužar-Oberiter et al. 2012), or in Bosnia (Mikes et al. 2008). Presence of the pyrope–almandine garntes shows that the continental crust segments that shed garnets (Factor 3) were different from the crystalline complexes of the West-Carpathian internides (Aubrecht & Méres 2000 and discussion therein). They might have been derived either from the granulites and eclogites of the crustal segments, which form the basement of the Outer Carpathians (most likely Moldanubian in origin), or from lower crustal segments related to the newly-obducting ophiolitic sources. The data of pebble analyses also show that until the deposition of the Upper Campanian–Maastrichtian Jarmuta Beds, exotic sedimentation occurred exclusively (Birkenmajer 1958, 1960; Aubrecht 1997).

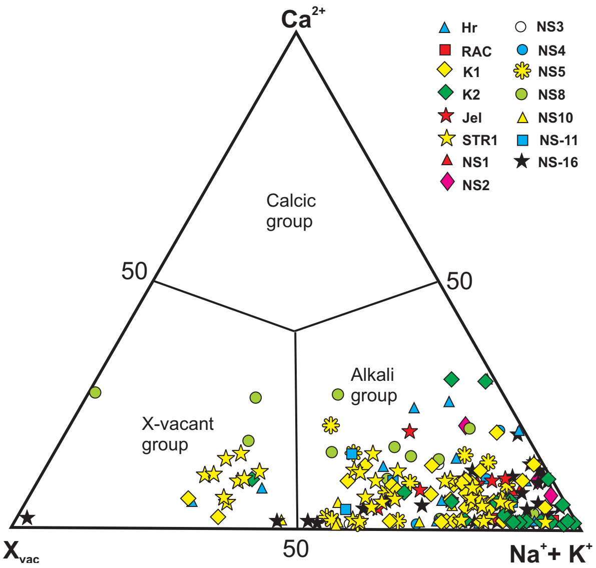

Fig. 14. Classification diagram of the tourmalines measured showing the relationship of $^{x}\square$ (X-site vacancy) vs. $Na^{+}+K^{+}$ vs. Ca^{2+} (Hawthorne & Henry 1999).

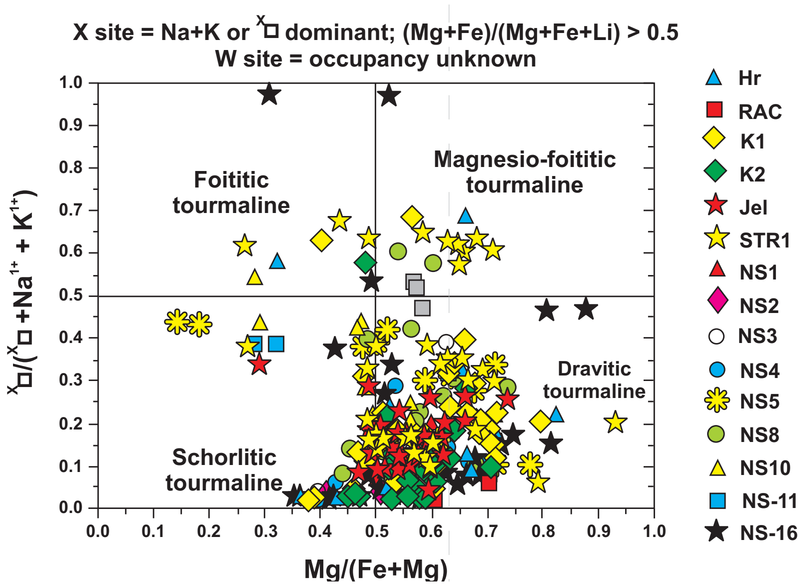

Fig. 15. Fe/(Fe+Mg) vs. $^{x}\square/(^{x}\square+Na^{1+}+K^{1+})$ classification diagram of the tourmalines measured (Henry et al. 2011).

When compared with other existing data from the Late Cretaceous Gosau Group (Stern & Wagreich 2013) and the Jarmuta–Proč Formation (Winkler & Ślączka 1992, 1994; Oszczypko & Salata 2005; Bónová et al. 2017, 2018 and Madzin et al. 2019), the same pattern of a decreasing portion of ophiolitic material and an increasing amount of material from older sediments and the continental crust metamorphics is evident. In the Gosau Group, Cr-spinels nearly disappeared after the Campanian (Stern & Wagreich 2013). The chemical composition of the individual minerals is generally similar to the present study, except for a relatively higher proportion of lherzolitic spinels in the Coniacian to Campanian period of the Gosau Group (Stern & Wagreich 2013).

Is there any difference between the analyzed units?

At first glance, results of the heavy-mineral analysis show no principal differences in assemblages from different units. Statistical factor analysis showed that clustering is mainly visible for some samples taken close to each other, that is, the geographic aspect is sometimes more important. Most of the Klape Unit samples (NS1-4) are clustered together, unless Factor 4 is involved. Afterwards, they split into two smaller groups according to local increased influx of tourmaline and apatite. It is difficult to estimate whether the clustering of the Klape Unit samples is caused by attribution to the unit, or to their geographically-close occurrences.

The samples from the Kysuca Unit are also locally clustered based on their regional position, e.g., ZD1–ZD2–Rac samples and samples from the area between the villages of Terchová and Zázrivá. Other Kysuca unit samples show elongated linear trends rather than closed clusters.

The samples from the Považský Inovec Mts. (the only studied samples from the West-Carpathian internides) display depletion in the ophiolitic source material (Factor 1), and their heavy mineral assemblage was influenced predominantly by the reworking of older clastics (Factor 2). When compared with older, Albian sediments from the Tatric of the Považský Inovec Mts. (Aubrecht et al. 2020b – PI-NL sample taken relatively close to the STR and 368 samples studied here), the latter has a relatively higher content of Cr-spinels (by10 %), although the rest of the heavy minerals shows a considerable influx from the reworked older clastics as well.

For the Upper Campanian–Maastrichtian sediments of the Klape Unit, a change in paleocurrents was presented by Marschalko

(1986), assuming a change in the sources occurred as well. For the Jarmuta beds and their equivalents, a new influx of non-exotic material was presented (Birkenmajer 1958, 1960). The cluster and factor analyses show that the samples from the Klape Unit (Hlboké Formation – NS12-13) and from the Jarmuta Beds (Jel) show no clustering with each other or with the other samples. The latter displays a considerable depletion in the ophiolitic material and prevalence of the material from other sources, including a considerable influx of garnet (Factor 3). The NS12-13 samples have more Cr-spinels; however, the influx from other sources prevails.

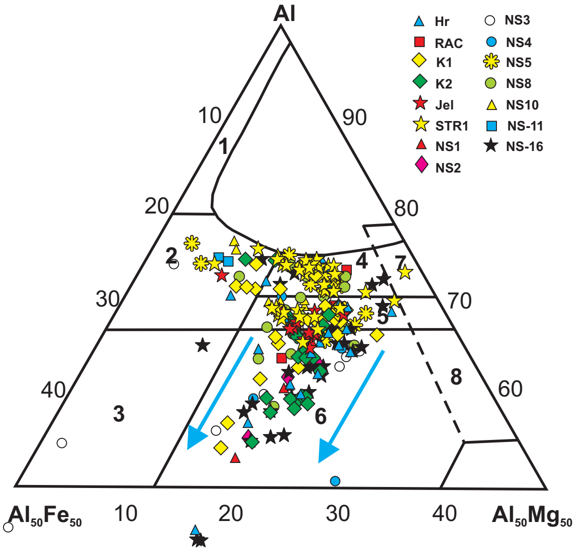

Fig. 16. Ternary diagram exhibiting Al, Fe, and Mg molecular proportions of the tourmalines analyzed from the individual units (from Henry & Guidotti 1985). The blue arrows show the bosiite trend. The analyses that are plotted outside (below) the diagram belong to bosiite. Explanations of the diagram fields: 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 metasedimentary rocks. 8 – Metacarbonates and meta-pyroxenites.

Conclusions

Samples from the Turonian to Maastrichtian exotics-bearing deposits from the Pieniny Klippen Belt (Klape and Kysuca units) and West Carpathian internides were analyzed and

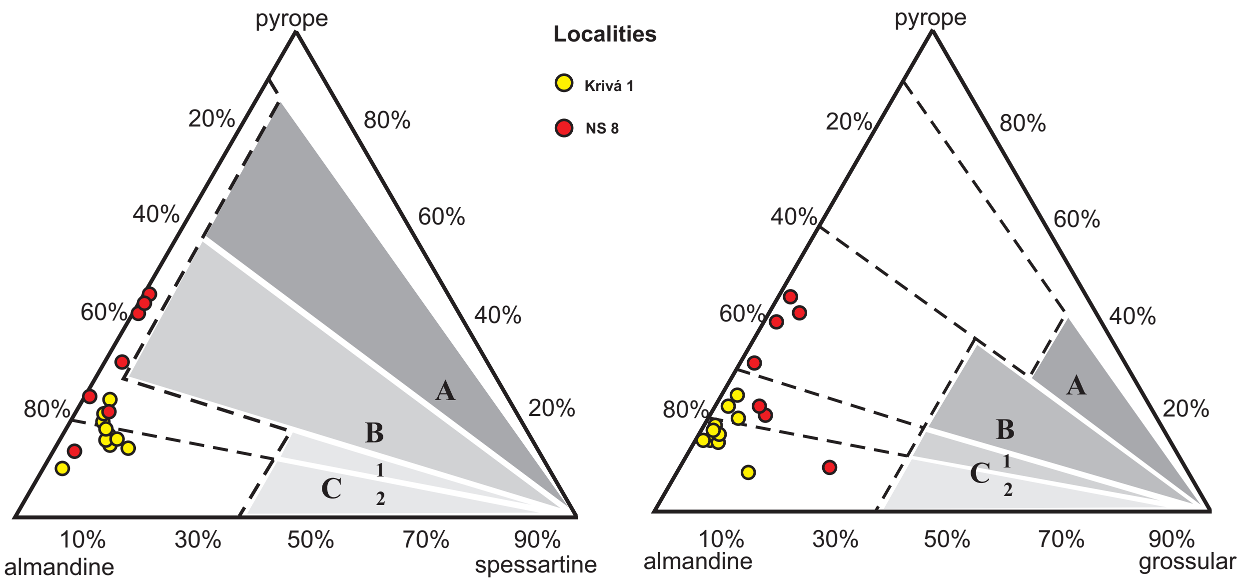

Fig. 17. Plot of the measured garnet (Grt) composition in the pyrope–almandine–grossular and pyrope–almandine–spessartine classification diagrams by Méres (2008). Explanations: **Sector A.** White field – garnets from UHP/HP conditions. Position around No. 1a – Grt derived from UHP eclogites, garnet 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 integrates, 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-member compositions: A – from UHP/HP conditions, B – from eclogite and granulite facies conditions, C – from amphibolite facies conditions.

Table 5: Representative microprobe analyses of the garnets (in wt. %). Formula is based on 12 oxygens and with Fe^{2+}/Fe^{3+} calculated assuming full site occupancy.

Analysis number	K-1-G-1	K-1-G-2	NS-8-G- 3	NS-8-G-4	NS-8-G-5
SiO_2	37.406	37.133	39.29	38.77	39.36
TiO_2	0.041	0.124	0.00	0.00	0.04
Al_2O_3	20.954	20.752	22.08	22.45	22.01
Cr_2O_3	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	0.03	0.55	0.30	0.35	0.45
FeO	33.22	33.85	26.46	24.98	24.49
MnO	3.70	1.33	0.37	0.29	0.43
MgO	3.30	1.97	10.33	11.92	10.75
CaO	1.30	4.78	1.51	0.73	2.53
TOTAL	99.70	99.58	100.35	99.48	100.07
Si	3.01	2.99	2.99	2.96	2.99
Al IV	0.00	0.01	0.01	0.04	0.01
Al VI	1.99	1.95	1.98	1.98	1.97
Ti	0.00	0.01	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	0.00	0.03	0.02	0.02	0.03
Fe^{2+}	2.23	2.28	1.69	1.59	1.56
Mn	0.25	0.09	0.02	0.02	0.03
Mg	0.40	0.24	1.17	1.36	1.22
Ca	0.11	0.41	0.12	0.06	0.21
TOTAL	7.99	8.01	8.01	8.02	8.01
End members					
Almandine	74.08	74.91	55.88	51.52	51.48
Andradite	0.10	1.68	0.87	1.01	1.30
Grossular	3.64	12.04	3.26	1.00	5.58
Pyrope	13.20	7.87	39.19	45.84	40.72
Spessartine	8.40	3.03	0.80	0.63	0.92
Uvarovite	0.00	0.00	0.00	0.00	0.00
% cations	99.43	99.51	99.77	98.30	99.72

compared with similar, but older Albian–Cenomanian deposits. The petrographic analysis of arenites showed that the Turonian to Maastrichtian deposits are more variable in composition, encompassing the entire range from quartz arenites, through sublitharenites to litharenites. The Albian–Cenomanian deposits have a narrower range from sublitharenites to only the upper part of litharenites.

Percentual ratios of the main heavy minerals are similar to those from the Albian–Cenomanian deposits, i.e., the samples are dominated by chrome-spinels, zircon, tourmaline, apatite, and rutile. On the other hand, unlike in the Albian–Cenomanian deposits, garnet is more common in the examined younger samples. Titanite, kyanite, monazite, amphibole, blue amphibole, pyroxenes, epidote, staurolite, and sillimanite are quite rare (much rarer than in the Albian–Cenomanian deposits, rarely exceeding 1 %). The statistical factor analysis indicates two main sources (Factors 1 and 2): ophiolites (mainly Cr-spinels) and older sediments (zircon, rutile and part of the tourmaline). The regression analysis shows a high correlation between the zircon and rutile, which also indicates their source from older sediments. The third important factor is an influx of garnet which is much more common and evenly distributed than in the Albian–Cenomanian deposits. The fourth, weakest factor is related to the influx of tourmaline and apatite, which may indicate low-grade metamorphosed sediments.

Chemical analyses of the minerals showed that the spinels were predominantly derived from harzburgites (supra-subduction peridotites). Most of the tourmalines were derived from metasediments, Fe^{3+}-rich quartz–tourmaline rocks, calc-silicate rocks and metapelites, as well as granitoids. Some had a complex zonation with two phases of tourmaline (schorl–dravite and bosiite), or tourmaline intergrown with quartz. These were likely derived from ophiolitic sources. Garnets are predominantly almandinic, indicating their derivation from the rocks metamorphosed up to the amphibolite facies or magmatic rocks. However, there are also common pyrope–almandinic garnets indicating their source from granulitic and eclogitic metamorphic facies.

The cluster and factor analyses show clustering of some samples that are based mostly on a geographic factor (proximity of the samples) rather than dependence on the individual units. The only unit where the samples are consistently clustered together is the Klape Unit; however, it is not yet clear whether this is caused by derivation from one unit, or by geographic proximity. The position of the Kysuca Unit samples in the statistical diagrams depends mostly on the sampled areas. The samples from the Považský Inovec Mts. are relatively depleted in ophiolitic detritus, but enriched in detritus derived from older sediments.

The predominant change after the Albian–Cenomanian period is the more expressed presence of the continental crust segments in the source area in comparison with the ophiolitic ones. This may be an expression of continuing orogenic movements and nappe stacking, where obducted ophiolites played a less important role than in earlier stages of evolution.

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