Swiss Journal of Geosciences (2019) 112:55–81
https://doi.org/10.1007/s00015-018-0330-7

Meliatic blueschists and their detritus in Cretaceous sediments: new data constraining tectonic evolution of the West Carpathians

Dušan Plašienka[1] · Štefan Méres[2] · Peter Ivan[2] · Milan Sýkora[1] · Ján Soták[1,3] · Alexander Lačný[1] · Roman Aubrecht[1,3] · Simona Bellová[1] · Tomáš Potočný[1]

Received: 31 May 2018 / Accepted: 8 November 2018 / Published online: 22 November 2018

Abstract

The Western Carpathian Meliata Superunit (Meliaticum) includes a heterogeneous group of units—the blueschist-facies Bôrka Nappe and the very low-grade chaotic complexes—polygenous mélange containing material derived from various tectonic settings (Jaklovce Unit) and Jurassic oceanic sediments with olistostrome bodies (Meliata Unit s.s.). The high pressure/low temperature (HP/LT) metamorphism, development of tectonic mélanges and synorogenic sediments took place simultaneously during the Middle–Late Jurassic in connection with closing of the Meliata Ocean. We present some new data concerning composition of variegated mélanges related to the subduction–accretion processes of the Meliata Ocean and its continental margins. The polygenous mélange contains a mixture of fragments of HP/LT up to unmetamorphosed sedimentary and volcanic rocks, including blueschist-facies radiolarites. New electron microprobe chemical age data of monazites from metasediments of the Bôrka Nappe cluster in two peaks—earliest Cretaceous ages are interpreted in terms of post-exhumation, renewed burial during formation of the Meliatic accretionary wedge. The mid-Cretaceous ages might record the thermal relaxation during the thick-skinned nappe stacking and exhumation of the neighbouring Veporic metamorphic dome. In addition, we describe two distinct types of tourmalines and epidotes occurring in the Bôrka blueschists that document the prograde HP and retrograde LP metamorphic events. Detritus of the blueschist-facies rocks appears for the first time in the heavy mineral spectra of the Barremian–Aptian platform limestones. These limestones occur as clasts, together with glaucophanite pebbles, in the Albian–Cenomanian flysch formations of the Pieniny Klippen Belt (Klape Unit). We also review occurrences of other blueschist and ophiolitic erosional products in Cretaceous clastic formations and suggest that all have a Meliatic provenance.

Keywords Meliata Ocean · High pressure/low temperature metamorphism · Mélange · Olistostrome · Radiolarite · Monazite dating · Heavy minerals

1 Introduction

In terms of the plate tectonics theory, the blueschist facies metamorphic units, along with synorogenic wildflysch and ophiolite-bearing mélange complexes, play a crucial role in deciphering tectonic evolution of subduction–accretion zones and collisional orogenic systems. Fragments of high

Editorial handling: E. Gnos.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00015-018-0330-7) contains supplementary material, which is available to authorized users.

✉ Dušan Plašienka
dusan.plasienka@uniba.sk

1 Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia

2 Department of Geochemistry, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia

3 Earth Science Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia

pressure and relatively low temperature (HP/LT) metamorphosed, predominantly oceanic magmatic and sedimentary rocks are usually found in the axial zones of collisional orogens where they indicate position of fossil plate boundary, i.e. suture. Specific structural settings and processes are necessary to preserve at least partly the HP/LT metamorphic assemblages during their return to the Earth's surface. These include either a rapid, nearly isothermal exhumation by the corner flow and extension in the rear parts of accretionary wedges (e.g. Platt 1986, 1993), or more commonly a slow, buoyancy-driven exhumation within the subduction channel where heating is suppressed by the refrigerating effect of the cold descending slab (e.g. Ernst 1988).

In the Alpine–Carpathian mountain belt, the majority of (U)HP/LT units are related to the Paleogene subduction of the Pennine oceanic lithosphere and attached continental slivers. These are widespread in the Western Alps (e.g. Pleuger et al. 2007; Weber et al. 2015 and references therein); eastward they crop out only in tectonic windows from below the Austroalpine basement sheets—the Tauern window in the central Eastern Alps (Kurz et al. 1998; Nagel et al. 2013) and the Rechnitz–Kőszeg and Bernstein windows at their eastern extremity (Koller 1985; Ratschbacher et al. 1990). No eastward continuation of this Paleogene blueschist belt can be found at the present erosional surface of the Western Carpathians.

Following the fundamental works by Thöni and Jagoutz (1993), Neubauer (1994), Froitzheim et al. (1996) and Dallmeyer et al. (1996), the Late Cretaceous tectonism and eclogite facies metamorphism in the Austroalpine units of the Eastern Alps have been attributed to collisional processes resulting from closure of different oceanic domains—the (Neo)Tethys-related Meliata or Meliata–Hallstatt Ocean (Gawlick et al. 1999; Faupl and Wagreich 2000; Neubauer et al. 2000; Frisch and Gawlick 2003; Froitzheim et al. 2008 and many others). According to Schmid et al. (2004, 2008), the Eoalpine high-pressure belt represents a dividing element of former northern (lower plate) and southern (upper plate) margins of Triassic Meliata Ocean along an intracontinental suture zone continuing westward from the Meliata Ocean embayment, possibly related also to a Jurassic strike-slip wrench zone (Frank and Schlager 2006). Similarly, Janák et al. (2004) and Stüwe and Schuster (2010) ascribed the development of the Eoalpine eclogites to an intra-Austroalpine subduction of gravitationally unstable continental lithosphere due to its densification by Permian magmatic underplating of gabbroic bodies and post-extension thermal thickening of the mantle lithosphere.

Sharing an analogous structural position, Late Cretaceous age and tectonometamorphic evolution, the Veporic metamorphic complex of the Central Western Carpathians was correlated with the Eastern Alpine Eoalpine metamorphic units by Janák et al. (2001). The Cretaceous metamorphism of the Veporic Superunit was explained by post-collisional crustal thickening due to stacking of thick-skinned thrust sheets in the footwall of the Upper Jurassic blueschist- and ophiolite-bearing Meliatic units (Plašienka 1991, 1997; Plašienka et al. 1997; Janák et al. 2001; Plašienka in Froitzheim et al. 2008). In this conception, the Meliata and related units, including the high-pressure Bôrka Nappe, represent the accretionary complex in an allochthonous position rooted between the prowedge Central Carpathian (Austroalpine) basement-cover thrust stack and the retrowedge Internal Carpathian Pelso Megaunit with the South-Alpine and Dinaric links (Transdanubian and Bükk units, respectively—cf. Haas et al. 1995).

The overall structure, tectonic division and evolution of the Western Carpathians has been reviewed in several papers, e.g. Andrusov (1968), Maheľ (1986), Plašienka et al. (1997), Froitzheim et al. (2008), or Hók et al. (2014). However, views on tectonics of the southern Carpathian zones and, particularly, on the positions, relationships and palaeogeographic settings of the Meliatic and related units remain controversial. The fundamental question concerns the origin of the Meliata Ocean either as an independent Triassic back-arc basin developed inboard the active European margin during northward subduction of Palaeotethys (e.g. Stampfli and Borel 2002; Stampfli and Kozur 2006; Stampfli and Hochard 2009), or as the north-western embayment of Neotethys (e.g. Haas et al. 1995; Frisch and Gawlick 2003; Schmid et al. 2008; Missoni and Gawlick 2011). Consequently, these different models result in two different interpretations of Jurassic subduction of the Triassic Meliata Ocean: (1) It represents the result of subduction below an active margin of variously interpreted "southern continent" (Adria or the Pelso Megaunit including the Bükk element as its eastern promontory, Tisia terrane, or an island arc—e.g. Channell and Kozur 1997; Faryad and Henjes-Kunst 1997; Plašienka et al. 1997; "unknown block" of Lexa et al. 2003); (2) It is the result of subduction underneath the obducted Jurassic ophiolite nappes with the Meliata-type mélange complexes at their base (Dinaric model—Schmid et al. 2008; Missoni and Gawlick 2011).

Diverse opinions exist also about the relations of the Late Jurassic closure of the Meliata Ocean to the Cretaceous Carpathian orogeny. The following models have been proposed: (1) the Meliatic units were emplaced during an older Wilson cycle (Cimmerian orogeny according to Kozur 1991; Kozur and Mock 1997; Lexa et al. 2003) that is not related to the Cretaceous–Paleogene Alpidic cycle; (2) they represent an obduction-related Middle–Upper Jurassic fold-thrust belt with sequential development of frontal trench-like synorogenic basins (Neotethyan Belt of Missoni and Gawlick 2011); (3) the Cretaceous orogeny was driven by continuing post-obduction subduction of the Austroalpine lower crust and mantle lithosphere attached to the sinking Meliata slab until the Late Cretaceous (Stampfli and Hochard 2009; Handy et al. 2010); or analogously (4) The Meliatic complexes formed during a similar subduction scenario following collision of Central Carpathian domain and the southern continental block (Adria-related Pelso) that drove the post-collision shortening of the central Carpathian zones (Plašienka 1991; Plašienka in Froitzheim et al. 2008). Additional uncertainties concern the palinspastic settings of the Turnaic and Silicic cover nappe units overlying the Meliatic elements. They have been assigned to the lower Austroalpine plate (i.e. northern margin of Meliata—Kovács et al. 1989, 2011; Kozur 1991; Kozur and Mock 1997; Less 2000; Schmid et al. 2008), to the upper plate (southern margin—Hók et al. 1995; Rakús 1996; Neubauer et al. 2000; Lexa et al. 2003; Csontos and Vörös 2004; Dallmeyer et al. 2008), or emplaced by the sinistral strike-slip translation with or without the attached Meliatic units (Frank and Schlager 2006; Kövér and Fodor 2014; Kövér et al. 2018).

To resolve ambiguous interpretations of the position and evolution of Meliatic complexes, new stratigraphic, sedimentological, structural and metamorphic data are indispensable. Meliatic rocks crop out only in scattered occurrences of both tectonic mélanges and chaotic sedimentary units with very complex internal structure; therefore any new data may provide crucial information for constraining their tectonometamorphic evolution and relationships to adjacent units.

In this paper, we present new results regarding the composition of a polygenous mélange unit that involves also fragments of blueschist-facies radiolarites, new monazite age data from the HP Bôrka Unit, and manifestation of blueschist detritus in the Lower Cretaceous clastic sediments of several Western Carpathian units. These findings are discussed in the context of tectonometamorphic evolution of the Meliatic subduction/accretion complexes, including their exhumation and erosion revealed by the sedimentary record. In the present paper, we do not address the recently widely discussed problems of regional relationships and correlation of the Meliatic units and their paternal Meliata Ocean with similar occurrences in the Alps, Dinarides and particularly in north-eastern Hungary. In this aspect, the reader is advised to the topical works by Kövér et al. (2018) and Plašienka (2018), and to references therein.

2 Regional framework

Our study concerns two remote, but mutually related areas—the Meliatic units in the southern Carpathian zones, and the Klape and related units in the so-called Peri-Klippen Zone adjoining the classic Pieniny Klippen Belt at the boundary between the Central and External Western Carpathians (Fig. 1). While the first area exposes the blueschist-facies metamorphic rocks affiliated with Meliatic units in their original tectonic position, their erosional products in the form of blueschist pebbles and detrital blue amphiboles occur in Cretaceous flysch formations of the second region.

The investigated area in the Slovak–Aggtelek Karst of the Slovakian–Hungarian borderland represents a transitional zone between the southern Austroalpine units of the Central and the South Alpine–Dinaric units (Transdanubian and Bükk, respectively) of the Internal Western Carpathians occurring to the south (Figs. 1, 2). The lowermost structural position is occupied by the Upper Austroalpine Gemer Superunit (Gemericum) composed of mostly low-grade Lower Paleozoic volcano-sedimentary formations overlapped by Pennsylvanian, Permian and Lower–Middle Triassic, chiefly continental and shallow-marine clastic formations (e.g. Ivanička et al. 1989; Vozárová and Vozár 1988). At the contact with the underlying basement and cover rocks of the Vepor Superunit (Veporicum) along the Lubeník thrust fault (Fig. 2), the partially independent Gemeric zone is formed by the Ochtiná Unit. This unit is composed of Mississippian mafic volcanites, shales and carbonates (including magnesite bodies; cf. Vozárová 1996).

The Gemeric basement-cover sheet is overridden by a stack of cover nappes involving the Meliatic, Turnaic and Silicic units from bottom to top (Fig. 2). Based on rock composition and metamorphic characteristics, the Meliata Superunit (Meliaticum) was differentiated into three types of units (Lačný et al. 2016): (1) HP/LT Bôrka Unit in the lower structural position, which is overridden by and partly imbricated with (2) ophiolite-bearing polygenous and serpentinitic mélanges of the Jaklovce Unit, and (3) sedimentary complex with olistostrome bodies almost devoid of ophiolitic material (Meliata Unit s.s. or Meliata Olistostrome Formation—Mello et al. 1997).

The high-pressure metamorphism and paleotectonic significance of blueschist facies rocks affiliated with the Meliata Unit s.l., currently assigned to the *Bôrka Nappe* (Leško and Varga 1980; Mello et al. 1998), were for the first time described by Reichwalder (1970, 1982). Their detailed petrological studies were later completed by Faryad (1995a, b, 1999), Faryad and Henjes-Kunst (1997); Faryad and Hoinkes (1999) and Mello et al. (1998). It was shown that the Meliatic complexes consist of assorted mélanges with ophiolitic material, deep-water sediments, olistostromes, blocks and slices with distinct composition and metamorphic histories.

The tightly imbricated and dismembered Bôrka Nappe embraces metasediments and metavolcanics of Permian

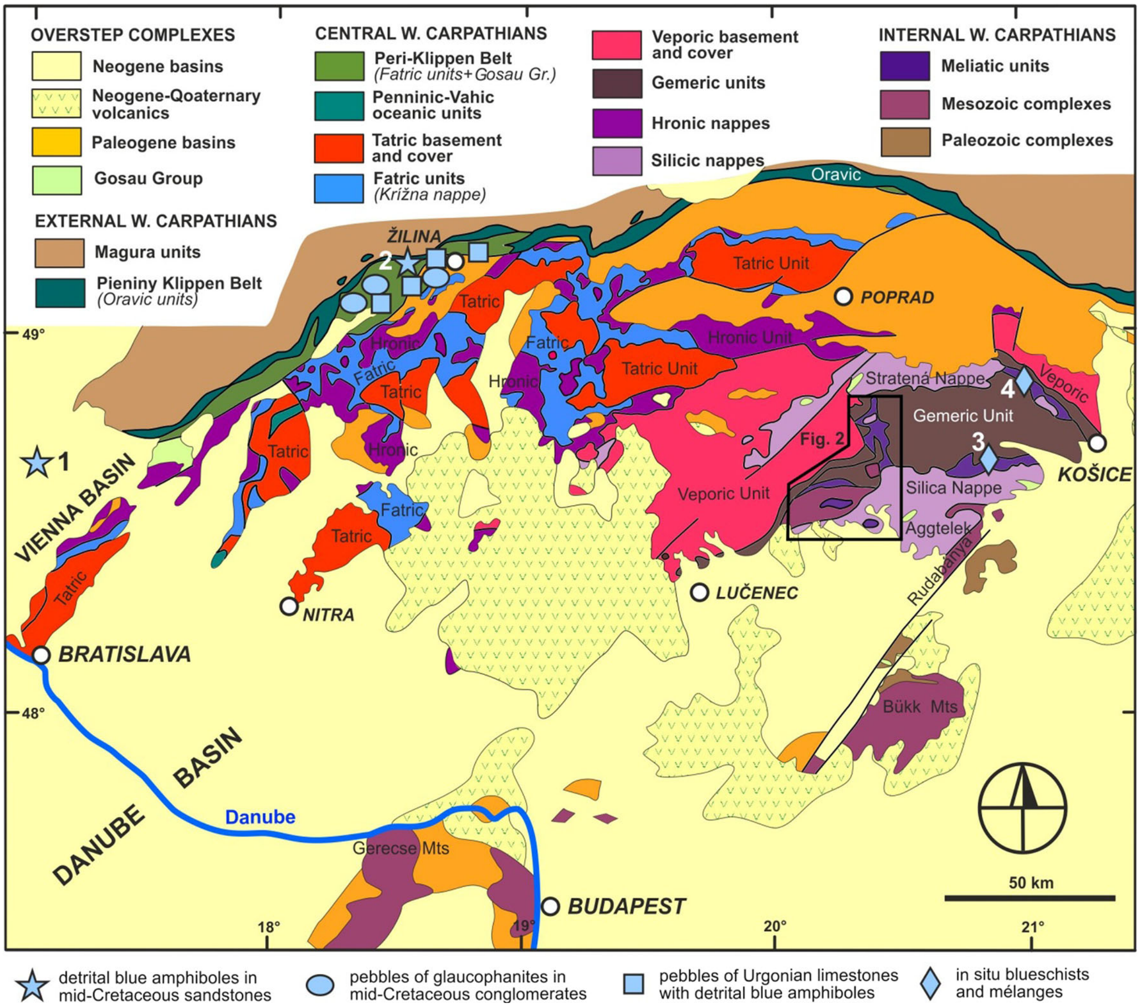


Fig. 1 Tectonic sketch map showing distribution of the principal Western Carpathian tectonic units and occurrences of blueschist-facies complexes and their detritus: 1—in the substratum of the Vienna Basin (Sýkora et al. 1997); 2—Klape Unit (Bellová et al., 2018). Other sites mentioned in the text: 3—classic area of the Bôrka Nappe (locality Hačava); 4—Jaklovce area. The inserted polygon outlines area depicted in Fig. 2

and Triassic age, and possibly also of Jurassic age (Mello et al. 1998). The approximate age assignment is based on the lithological correlations only, since all metasediments are devoid of determinable fossils due to the HP/LT metamorphic recrystallization and ductile deformation. From the lithotectonic point of view, the unit was divided into two complexes. The lower complex rocks are consisting of Upper Paleozoic volcano-sedimentary formations like siliciclastic conglomerates, sandstones, shales and 266 Ma old rhyolites (SHRIMP zircon ages; Vozárová et al. 2012) and Lower Triassic quartzites, slates and calcareous schists. The upper structural complex starts with probably lower Anisian pale marbles and dolostones. The first, syn-rift volcanism appears in the upper part of the carbonate complex in a form of mixed carbonate-volcaniclastic material including basaltic lapilli, hyaloclastites and peperites, followed by massive and pillowed basaltic submarine lava flows. The mafic volcanic rocks, associated with abyssal sediments, show a geochemical evolution from back-arc basalts (BABB) to the enriched and normal mid-oceanic ridge basalts (E-MORB and N-MORB, respectively) associated with abyssal sediments (Ivan 2002a, b; Faryad et al. 2005). Black, phyllitic and siliceous slates containing some olistostrome bodies form the upper metasedimentary complex of the Bôrka Nappe of the inferred Late Triassic, and possibly also Jurassic age (Mello et al. 1998). Tectonic fragments derived from the Variscan, possibly Gemeric basement (gneisses and amphibolites—Faryad 1988; Faryad and Frank 2011), overprinted by blueschist-facies metamorphism, indicate intimate relationships of the Bôrka Unit with the continental margin. Owing to continental basement slices and continental character of the lower pre-rift complex and its lithological similarities with the southern Gemeric

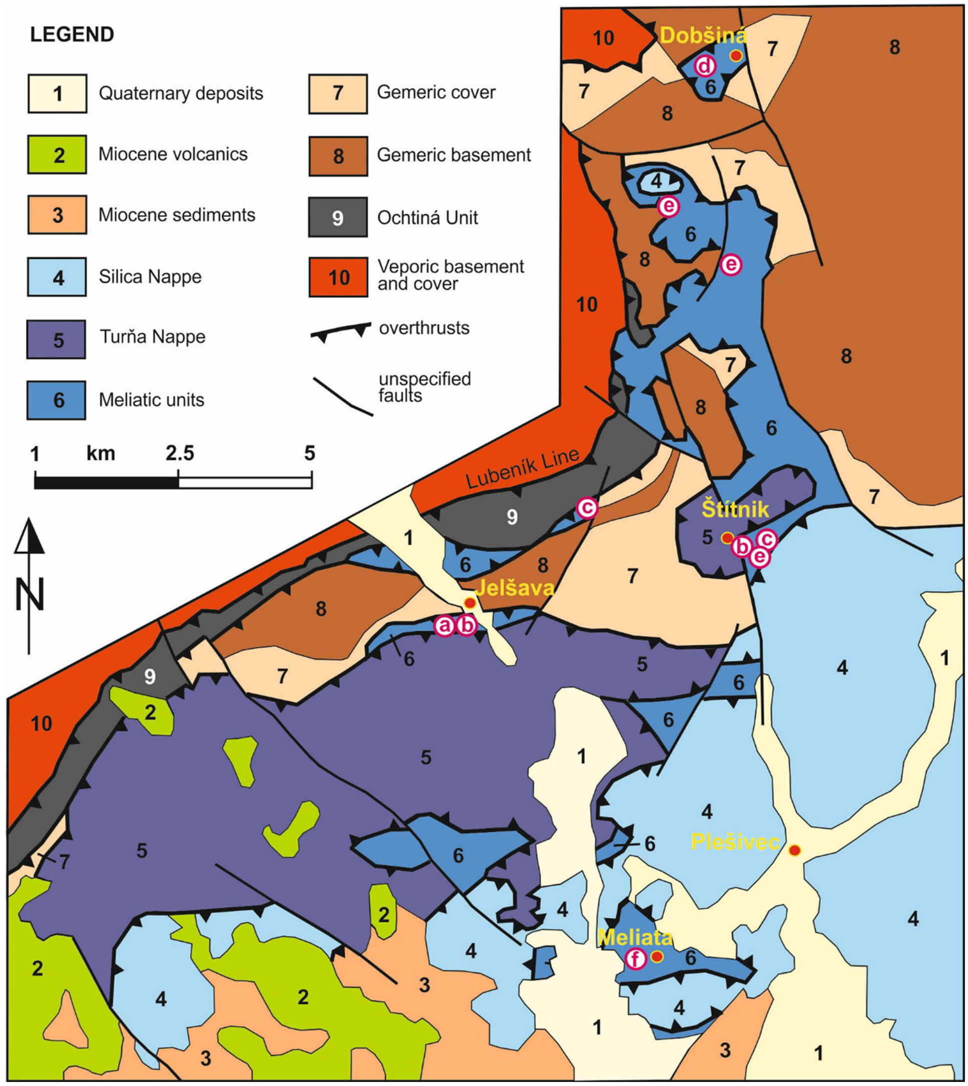


Fig. 2 Geological map of the contact area of the underlying Veporic complexes and the overriding Gemeric–Meliatic–Turnaic–Silicic thrust stack in central Slovakia (see Fig. 1). Modified after Mello et al. (2008). Position of localities described in the text (red circles): (a) Polygenous mélange near Jelšava town (localities Nandráž and Tri peniažky); (b) Blueschist facies radiolarites (localities Nandráž and Štítnik-Honce); (c) Sites with monazite dating (Honce and Hrádok); (d) Phyllites with two generations of tourmaline and epidote (Dobšiná-Stirn); (e) Glaucophanites (Brdárka, Kobeliarovo, Honce); (f) Meliata type locality (e.g. Mock et al. 1998)

Permian—Lower Triassic cover, the Bôrka Unit is palaeogeographically interpreted as fragment of the distal passive continental margin facing the Meliata Ocean which rifted in the Anisian (Mello et al. 1998; Plašienka 1998, 2018).

Detailed microstructural, petrological and geochronological investigations of the HP/LT Bôrka Nappe were carried out by a number of authors (Maluski et al. 1993; Dallmeyer et al. 1996, 2008; Faryad 1995a, b, 1999; Faryad and Henjes-Kunst 1997; Mello et al. 1998; Faryad and Hoinkes 1999; Árkai et al. 2003; Faryad et al. 2005; Vozárová et al. 2008; Putiš et al. 2011a, 2014, 2015; Németh et al. 2012; Li et al. 2014). The maximal P–T conditions of HP/LT metamorphism were detected in glaucophane-bearing metabasalts (Faryad 1995a; Faryad and Hoinkes 1999). Textural relationships reveal that the Bôrka Nappe experienced a prograde burial path with increasing P–T conditions from ca 0.5 GPa and 350 °C up to maximum pressures of at least 1.2 GPa and temperatures up to 460 °C. These were calculated from the association of glaucophane, epidote, albite, jadeite-rich Na-pyroxene, phengite, paragonite and garnet. Comparable P–T conditions were estimated for the metapelites, using glaucophane, chloritoid, paragonite, phengite, albite, chlorite, Na-pyroxene and garnet (Faryad 1995b). However, the HP metamorphic assemblages are not uniformly distributed within the whole unit, some parts record slightly lower P–T conditions, and others show exhumation-related, greenschist facies re-equilibration. Ivan (2002a, b, 2007) distinguished several lithotectonic units of the Bôrka Nappe and characterized their metamorphic histories and geochemical signatures.

The HP/LT metamorphic conditions were attained at ca 155 Ma (mean of $^{39}Ar/^{40}Ar$ ages of phengitic micas; Maluski et al. 1993; Dallmeyer et al. 1996, 2008; Faryad and Henjes-Kunst 1997). However, these white mica ages

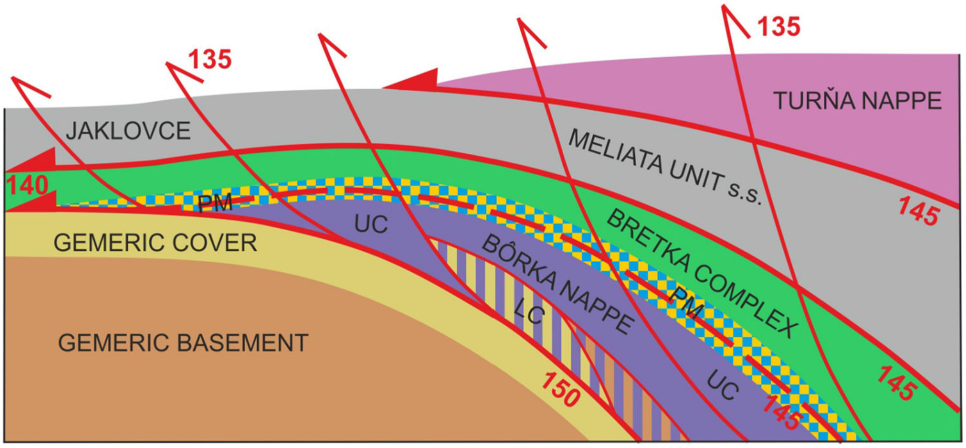


Fig. 3 Structural position and relationships of various Meliatic elements. Gemeric Lower Paleozoic basement and Permian–Triassic cover rocks underwent greenschist-facies metamorphism. Bôrka Nappe is a former distal passive continental margin affected by HP/LT metamorphism: LC—lower complex of Gemeric-type basement and cover rocks; UC—upper complex of Triassic sediments and basalts. PM—polygenous tectonic mélange composed of various fragments derived from the footwall and hangingwall units. Bretka Complex—very low-grade Triassic ophiolitic mélange. Jaklovce Unit—tectonized Jurassic pelagic sediments with olistoliths and olistostromes incl. Triassic ophiolite fragments. Meliata Unit s.s.—very low-grade Jurassic pelagic sediments with olistoliths and olistostromes. Turňa Nappe—very low- to low-grade Upper Paleozoic to Triassic passive margin succession. Numbers denote the approximate age of principal thrust structures shown in red (± 5 Myr): 150 Ma—exhumation of the Bôrka Unit; 145—stacking of Meliatic units and the Turňa Nappe in the developing accretionary wedge; 140 Ma—thrusting of the Meliatic stack over the Gemeric Unit; 135—out-of-sequence folding and thrusting during protracting overriding of the Gemeric Unit. The Silica nappe (not shown) was emplaced considerably later showing a distinct structural and metamorphic discordance with respect to the underlying Meliatic–Turnaic units

might record early stages of cooling during slow exhumation within the subduction channel as well, since the peak metamorphic temperatures reached ca 460 °C, i.e. at the upper limit of closure temperatures of K–Ar system in phengites. On the other hand, Ar/Ar dating of phengites from the lower complex of the Bôrka Nappe, which is composed of Upper Paleozoic siliciclastic and acid volcaniclastic formations, yielded slightly older ages around 172 Ma (Faryad and Henjes-Kunst 1997). Monazite electron microprobe (EMPA) chemical age dating yielded ages of 167 ± 12 Ma up to 190 ± 16 Ma, though with a wide scatter, for the underlying south Gemeric Paleozoic rocks (Vozárová et al. 2008, 2014; Hurai et al. 2015). However, the chemical monazite dating should be treated with caution, since for example the EMPA age spectra from the Gemeric albitite metasomatites scatter between 185 and 78 Ma, whereas LA-ICPMS $^{206}Pb/^{238}Pb$ isochron lower intercept from the same monazites yielded 139 ± 1 Ma, which corroborates the supposed involvement of the Gemericum in the thrust stacking processes. Consequently, the meaning of monazite ages older than ca. 160 Ma is unclear and their interpretation as a distinct tectono-thermal event might be misleading (Hurai et al. 2015).

Mélanges of the *Jaklovce Unit* contain fragments of basalts, serpentinites, acid volcanites, radiolarites of Middle–Upper Triassic and Jurassic age, and various Triassic shallow- and deep-water carbonates (Mock et al. 1998; Ivan et al. 2006, 2009; Ivan and Méres 2009; Putiš et al. 2011a, b; Németh and Radvanec 2014). All these blocks and slices are embedded in a Jurassic radiolarite-shaly-marly-sandy matrix, showing variably strong tectonic overprinting of the chaotic sedimentary complexes.

A distinct mélange type is represented by the typical tectonic, ophiolite-bearing mélanges. In places, they consist of brecciated serpentinized ultramafics enclosed in a strongly sheared serpentinite matrix (Jaroš et al. 1981), whereas at other sites the mélange also includes other fragments of the ophiolite suite—various types of basalts, dolerites and associated oceanic sediments like Middle–Upper Triassic radiolarites and pelagic limestones, embedded in shaly matrix. We propose the term Bretka Complex for the Meliatic ophiolite-bearing mélanges (see Fig. 3), which occur at several sites (Jaklovce, Dobšiná, Bretka, Čoltovo, Hodkovce).

The *Meliata Unit s.s.*, (type locality indicated in Fig. 2), is a sedimentary unit of Jurassic deep-water deposits with olistostromes and olistoliths of various Triassic carbonates and Ladinian radiolarites, containing only little ophiolitic material (Mock et al., 1998 and references therein; Aubrecht et al. 2012). It should be noted that Jurassic radiolarites of the Meliata and Jaklovce units are distinctly different from the Triassic radiolarites. They contain a considerable amount of terrigenous admixture and are associated with flysch-type sediments instead of oceanic basalts.

After scraping off, rocks of the Meliata Unit s.s. escaped deeper burial in the accretionary wedge and presently form the structurally highest parts of the Meliatic complexes (Fig. 3) affected by very low- to low-grade (anchizonal or sub-greenschist) metamorphic transformation reaching 280–350 °C at 250–500 MPa. K–Ar ages of white mica concentrates of low-grade slates scatter between 178 and 115 Ma, with a peak at ca 145–140 Ma (Árkai et al. 2003; Kövér et al. 2009). This prograde event was coeval with retrograde mylonitic overprinting of the Bôrka blueschist phyllites. Slightly higher metamorphic pressure estimates from the overriding Turnaic nappes (Kövér et al. 2009; Kövér and Fodor 2014) might indicate out-of-sequence thrusting within the developing accretionary wedge.

The Gemeric and Meliatic units are overridden by the *Turňa Superunit* (Turnaicum or Tornaicum—cf. Vozárová and Vozár 1992; Lačný et al. 2016 and references therein). The very low-grade to low-grade Turnaic units are composed of Upper Paleozoic to Lower Triassic clastic sequences, lower Anisian platform carbonates and post-Pelsonian deep-water pelagic limestones and shales. In part they are out-of-sequence imbricated with the underlying Meliatic complexes, both belonging to the accretionary complex (Árkai et al. 2003; Kövér et al. 2009; Lačný et al. 2016).

The *Silica Superunit* (Silicicum) is represented by the classic Silica Nappe in the investigated area, whose allochthonous position was first recognized by Kozur and Mock (1973). The Silica Nappe flatly overlies the imbricated Meliatic–Turnaic units with a marked metamorphic and structural discordance (Reichwalder 1982). The base of the nappe is formed by lenses of Upper Permian to Lower Triassic evaporites followed by Lower Triassic clastics and Middle to Upper Triassic, dominantly carbonate platform complex. The thin Jurassic sequence is terminated by Upper Jurassic pelagic deposits with terrigenous admixture and carbonate olistostromes containing clasts of Middle Jurassic radiolarites (Sýkora and Ožvoldová 1996; Rakús 1996; Rakús and Sýkora 2001). Although generally considered as not metamorphosed, varying and in places fairly high conodont colour alteration indices (CAI 1.5–5.5; cf. Gawlick et al. 2002; Havrila 2011) indicate that the Silica Nappe might represent an amalgamated unit composed of several fragments that experienced different thermal overprint.

3 Methods

Analyses of all minerals including monazites were performed by Cameca SX-100 microprobe at the Department of the Electron Microanalysis, State Geological Institute of Dionýz Štúr, Bratislava. Monazite dating requires special measurement conditions since the calculated age strongly depends on the precise measurement of Pb, U, Th, and Y. For monazite analysis, beam conditions of 15 kV and 100 nA and varying counting times, depending on the measured element: Pb 150 s, Th 45 s, U 75 s, Y 45 s and all other elements 25–35 s. The elements were calibrated using synthetic or natural standards: all 14 REE elements were calibrated from synthetic phosphates, P was calibrated from apatite, Ca and Si from wollastonite, Al from corundum, Pb from galena, Th from ThO_2, and U from UO_2. Thorium, U, Pb, Y, and P were measured with LPET (large PET), and REE with LLIF (large LIF) and Si, Al with TAP analysing crystal. The beam diameter was typically 3–5 µm.

The measurement is complicated by the presence of various interferences among the X-ray lines. We used ThMα1, UMβ1, PbMα1, and YLα X-ray lines. The interferences between PbMα1–YLγ1 and UMα1–ThMβ1 were corrected by empirically measured correction coefficients. Interferences between REE X-ray lines were also corrected. The accuracy of monazite dating is therefore related to the monazite secondary standards, whose variability is constrained by SHRIMP analyses. The following monazite standards were used: granite from Veikola, Finland (1825 Ma), pegmatite from Madagascar (495 Ma), gneiss-migmatite from Dürstein/Wachau, Austria (341 Ma), granite from Aalfang, Austria (327 Ma) and monzogranite from Nakane, Japan (77 Ma). Before measuring monazites of unknown age, we first measured all standards, each at least with 20 points. The ± 5–7 Ma deviations for each monazite age standard are considered as a good precision. The statistical approach of Montel et al. (1996) was applied for the resulting age determination. The program DAMON (Konečný et al. 2004) was then used for the age recalculations, histograms, and isochron plots.

The composition of tourmaline was established with CAMECA SX-100 electron microprobe in wavelength-dispersion mode, at the State Geological Institute of Dionýz Štúr, Bratislava. The analytical conditions were: accelerating voltage 15 kV, beam current 20 nA, and beam diameter of 3 to 5 µm. The tourmaline samples were analyzed with the following standards: wollastonite (SiK_α. CaK_α), TiO_2 (TiK_α), Al_2O_3 (AlK_α), pure Cr (CrK_α), pure V (VK_α), fayalite (FeK_α), rhodonite (MnK_α), forsterite (MgK_α), willemite (ZnK_α), pure Ni (NiK_α), albite (NaK_α), orthoclase (KK_α), BaF2($FK_\alpha\alpha$) and NaCl (ClK_α). Lower detection limits of the measured elements varied between 0.01 and 0.05 wt. %; V, Cr, Mn, Zn, Ni, F, and Cl were also below their respective detection limits. The analytical data were normalized according to the PAP procedure (Pouchou and Pichoir 1985).

Procedures of separation and analyses of the heavy mineral concentrates from turbiditic sandstones of

Table 1 Summary of analysed samples

Sample no.	Locality	GPS coordinates N/E	Lithology	Unit
NAN 2	Nandráž	48°37′29.0″/20°11′47.6″	Phyllite	polygenous mélange
NAN 3	Nandráž	48°37′29.0″/20°11′47.6″	Radiolarite	polygenous mélange
NAN 5	Nandráž	48°37′29.0″/20°11′47.6″	HP metaradiolarite	polygenous mélange
NAN 6	Nandráž	48°37′29.0″/20°11′47.6″	Radiolarite	polygenous mélange
TRI 0715-1	Tri peniažky	48°37′30.1″/20°13′36.2″	Serpentinite	polygenous mélange
TRI 0715-2	Tri peniažky	48°37′30.1″/20°13′36.2″	Serpentinite	polygenous mélange
TRI 1014 B	Nandráž	48°37′33.6″/20°11′35.4″	Sandstone (matrix)	polygenous mélange
TRI 0705-11	Nandráž	48°37′17.3″/20°11′47.0″	Phyllite	polygenous mélange
VHA-3	Hačava	48°40′25.7″/20°49′47.8″	HP metabasalt	Bôrka Nappe
VHA-7	Hačava	48°40′18.2″/20°50′13.9″	HP metabasalt	Bôrka Nappe
VHA-57	Hačava	48°40′18.2″/20°50′13.9″	HP metabasalt	Bôrka Nappe
VVS-16	Brdárka	48°46′15.7″/20°19′54.1″	HP metabasalt	Bôrka Nappe
VVS-41	Kobeliarovo	48°44′13.8″/20°21′02.8″	HP metabasalt	Bôrka Nappe
VVS-173	Honce	48°39′39.1″/20°23′49.6″	HP metabasalt	Bôrka Nappe
HNC	Honce	48°39′45.8″/20°23′37.2″	HP metaradiolarite	Bôrka Nappe
OS-07-128	Honce	48°39′31.9″/20°23′49.2″	HP phyllite	Bôrka Nappe
OS-07-117	Honce	48°39′31.9″/20°23′49.2″	HP phyllite	Bôrka Nappe
OS-07-147	Dobšiná-Stirn	48°49′04.8″/20°21′09.5″	HP phyllite	Bôrka Nappe
OCH 2B	Hrádok	48°39′31.9″/20°23′49.2″	Phyllite	Bôrka Nappe
9179	Mid. Váh Val.	49°14′21.2″/18°48′53.1″	“Urgonian” lmst	Klape Unit
20444	Mid. Váh Val.	49°08′18.0″/18°26′35.0″	“Urgonian” lmst	Klape Unit

Cretaceous flysch formations are described in detail in the paper by Bellová et al. (2018).

4 Results

4.1 Composition of Meliatic polygenous mélanges

We have investigated in detail a distinctive narrow strip of Meliatic rocks that appears on the northern slopes of the Tri peniažky Hill SW of Jelšava town and at the nearby locality Nandráž (Fig. 2; Table 1), where they are squeezed between the underlying Gemeric Upper Paleozoic clastic sediments and overriding Middle–Upper Triassic carbonate formations of the Turňa Nappe. The mélange complex is characterized by a strongly imbricated to completely disintegrated structure with slivers of both non-metamorphic and HP/LT metamorphosed rocks. Variously sized, mixed slices and blocks of almost all types of Meliatic complexes described above occur together in the studied small area.

Unmetamorphosed to very low-grade rocks (Meliata Unit s.s. and/or the Jaklovce Unit) are represented by radiolarites affected only by diagenesis (Fig. 4a, b), serpentinites with preserved original peridotitic structure (pseudomorphs after pyroxene, olivine and spinel) (Fig. 4j–l), and part of light crystalline limestones with layers of green shales. Pale red radiolarites are characterized by a massive texture and irregular dense network of tiny quartz veins (Fig. 4c, d).

Rocks containing index blueschist-facies metamorphic minerals like paragonite (Pg), garnet (Grt), glaucophane (Gln), piemontite (Pmt) and chloritoid (Cld) are typical for the HP/LT Bôrka Nappe (mineral abbreviations according to Whitney et al. 2010). They include radiolarites with Grt, Gln and Pmt (Fig. 4e–i), chlorite-sericite phyllites with Pg and Cld and various lithoclasts, which represent the matrix of the polygenous mélange complex in this area (Fig. 5a–f), and crystalline limestones intercalated with thin layers and fragments of grey to black sericite–chlorite schists with relics of paragonite (Fig. 5g–l; for chemical analyses see Online resource 1).

Despite poorly exposed area, there is apparently no order in distribution of these tightly packed slices and blocks exhibiting contrasting lithologies and metamorphic overprint. Therefore, we interpret this complex as a tectonic mélange, which probably formed at the base of a developing accretionary wedge and incorporated HP/LT fragments exhumed from the subduction channel, as well as non-metamorphic to low-grade rocks, partly also unconsolidated sediments, derived from the Meliatic complexes forming the accretionary prism.

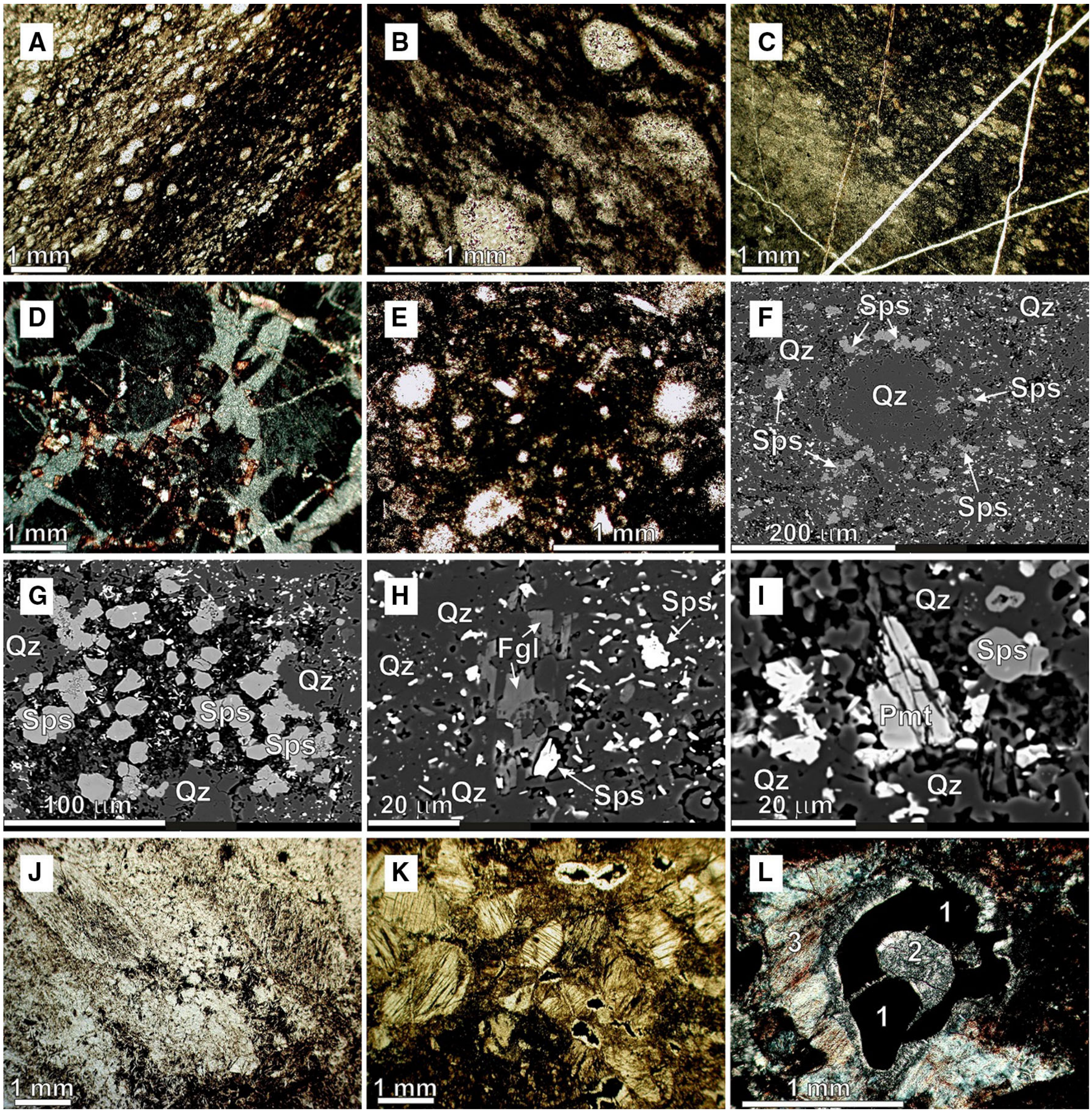


Fig. 4 Photomicrographs and backscattered electron (BSE) images of samples taken from blocks of radiolarites and serpentinites occurring in the polygenous mélange at the localities Nandráž and Tri peniažky near Jelšava town (Fig. 2). Dark brown–red radiolarites affected only by diagenetic and/or very low-grade metamorphic overprint; **a** ghosts of radiolarians, sample NAN 3, parallel pol.; **b** detail of a, parallel pol.; **c** two generations of diagenetic quartz veins in radiolarite, sample NAN 6, parallel pol.; **d** quartz veins and carbonate rhombohedrons in radiolarite, sample NAN 6. Metaradiolarite containing blueschist-facies metamorphic assemblage of spessartine garnet (Sps; see Online resource 4), ferroglaucophane (Fgl) and Mn-epidote (piemontite Pmt). Locality Nandráž, sample NAN 5. **e** Characteristic black-brown pigmentation and phantoms of radiolarians in the radiolarite, parallel pol.; **f** BSE image of radiolarite with Sps; **g** BSE image of Sps in the radiolarite; **h** BSE image of the Sps and Fgl in the radiolarite; **i** BSE image of the Sps and Pmt in the radiolarite. Serpentinites, locality Tri peniažky: **j** serpentinite with pseudomorphs after pyroxene, sample TRI 0715-1, parallel pol.; **k** serpentinite with preserved original peridotitic structure (pseudomorphs after pyroxene, olivine and spinel), sample TRI 0715-2, parallel pol.; **l** pseudomorphs after spinel (1), olivine (2) and pyroxene (3), sample TRI 0715-2, crossed pol

4.2 Blueschist-facies metaradiolarites and associated metabasalts

In addition to the Tri peniažky locality described above (Fig. 4e–i), radiolarites metamorphosed under blueschist facies conditions have been found in the Bôrka Nappe near the villages Honce and Štítnik (Fig. 2, Table 1). They form blocks (from centimetres to several metres in diameter) in black phyllitic matrix, but they have been found also as individual blocks together with metabasalts transformed to glaucophanites. Macroscopically dark reddish-brown colour and conchoidal fractures are typical for these metaradiolarites. They are also accompanied by blocks of various types of pelagic sediments transformed to phyllites with

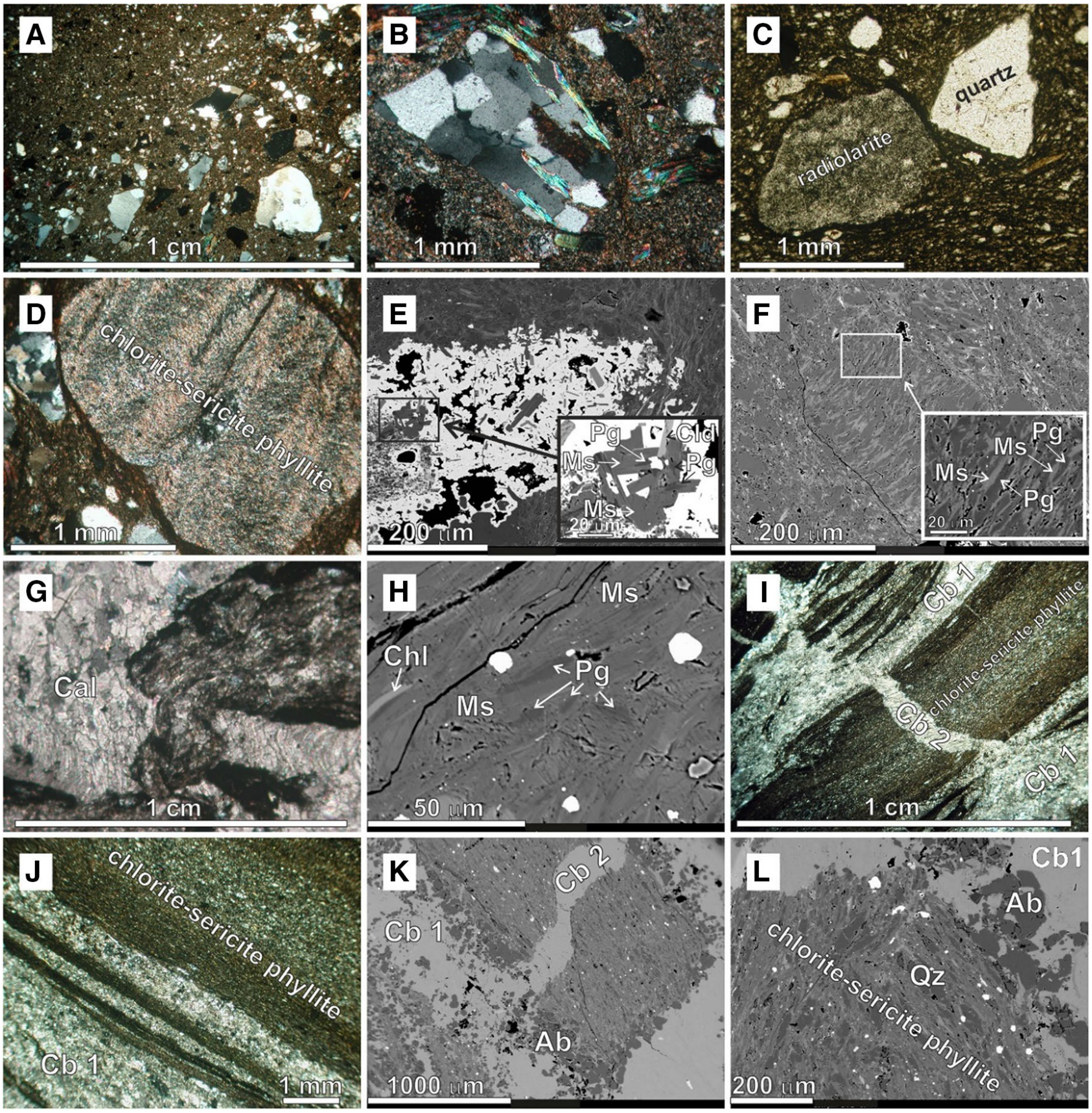


Fig. 5 Petrographically heterogeneous siliciclastic sediment with various lithoclasts forming matrix of the polygenous mélange at the locality Nandráž (Fig. 2, Table 1), sample TRI 1014 B, crossed pol.: **a** sandstone with graded bedding; **b** lithoclast of the muscovite gneiss; **c** radiolarite lithoclast; **d** lithoclast of fine-grained chlorite–sericite phyllite; **e** BSE image of the sericitic phyllite with chloritoid (Cld) and relics of older paragonite (Pg) in muscovite (Ms); **f** BSE image of the sericitic phyllite with relics of older Pg in Ms. Blocks of Triassic weakly metamorphic limestones (Cal) intercalated by thin laminas and fragments of grey to black sericite–chlorite phyllite, Locality Nandráž; **g** deformed black sericite–chlorite phyllite, sample NAN 2, crossed pol.; **h** BSE image of the deformed chlorite-sericite phyllite with relics of paragonite (Pg), sample NAN 2; **i** deformed stripe of sericite–chlorite phyllite in the crystalline limestone with primary calcite matrix (Cb 1) and remobilized calcite (Cb 2), sample TRI 0705-11, crossed pol.; **j** variably thick intercalations of the sericite–chlorite phyllite in the crystalline limestones (Cb 1), sample TRI 0705-11, crossed pol.; **k** BSE image of crystalline limestone with laminas of sericite–chlorite phyllite, sample NAN 2; **l** detail of k

paragonite and/or chloritoid and HP/LT metamorphosed basalts with well-preserved hyaloporphyric, intersertal or ophitic phantom textures, and strongly depleted N-MORB geochemical signatures. Examples of various textures of blueschist-facies metabasalts from several localities (Figs. 1, 2, Table 1) are presented in Fig. 6a–f.

Radiolarites metamorphosed under HP conditions are microscopically very fine-grained rocks with dominant quartz with dispersed Fe–Mn oxide ore pigment. Radiolarians are still discernible as oval-shaped phantoms. The presence of garnets, sodium pyroxenes and sodium amphiboles are typical features (Fig. 6g–l). Na-pyroxenes have been found only as inclusions in garnets, ca. 5 μm in size. Aegirine or manganoan aegirine are prevailing components in composition of Na-pyroxenes (Ae 62–75 mol%, Jd 5–22 mol%, Quad 15–20 mol%, Mn = up to 0.180

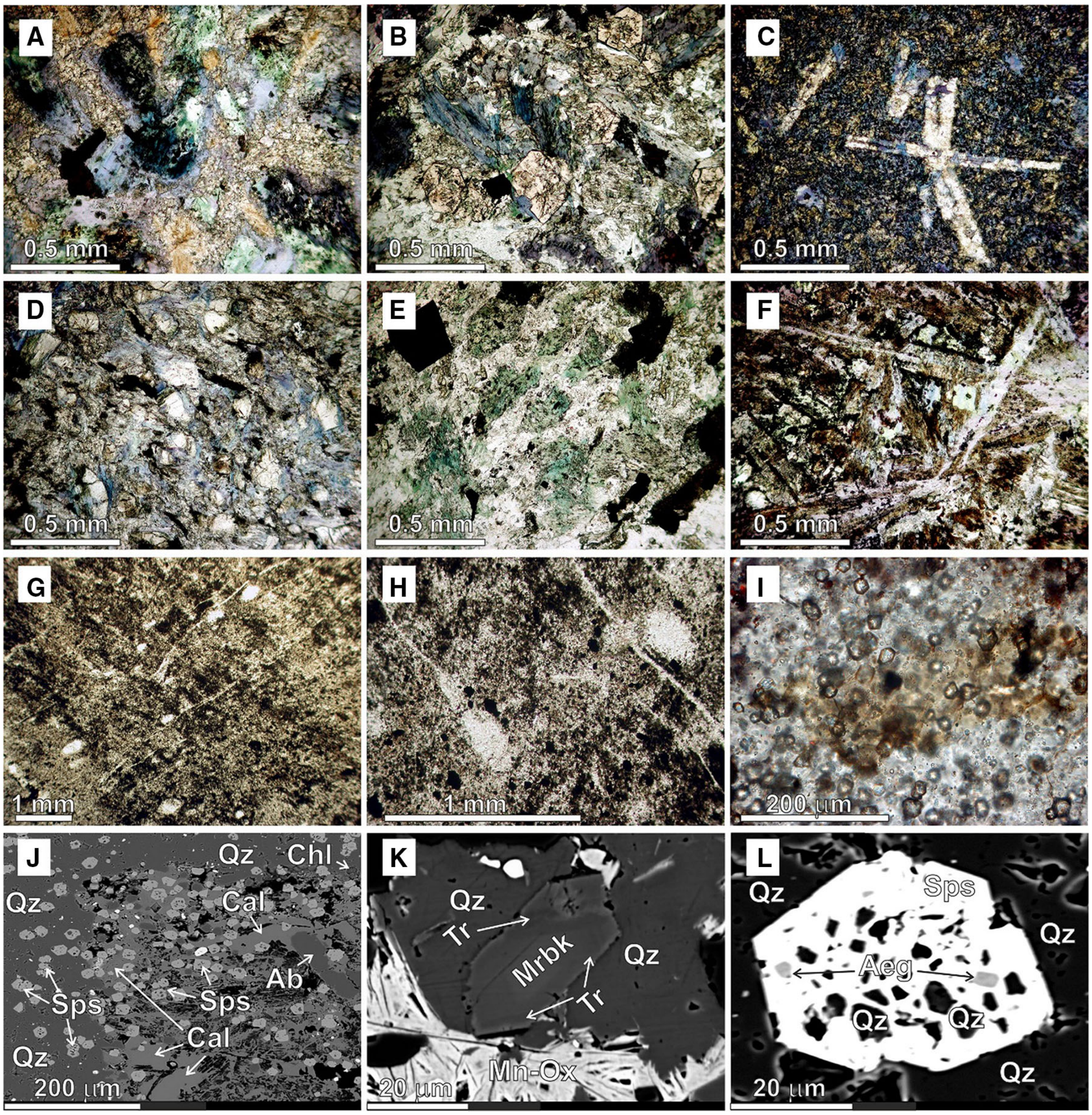


Fig. 6 Samples of some typical metabasalts of the Bôrka Nappe (localities Hačava, Brdárka, Kobeliarovo, Honce—Figs. 1 and 2, Table 1): **a** HP/LT metamorphosed basalt with relic ophitic texture composed of Na-amphibole, epidote, chlorite and leucoxenized ilmenite. Deep blue coloured glaucophane originated at the expense of older Ti–rich high-temperature Ca-amphibole. Relic fan-forming texture in former plagioclase laths indicate their transformation into prehnite preceding replacement by epidote, sample VHA-3; **b** basalt with original ophitic texture transformed into blueschist composed of glaucophane, albite, garnet, chlorite, clinozoisite and leucoxenized ilmenite, sample VHA-7; **c** basalt with original hyaloporphyric texture metamorphosed to blueschist composed of violet glaucophane, yellow epidote and fine-grained Fe–Ti oxide pigment, sample VHA-57; **d** basalt with ophitic texture experiencing metamorphic transformation and deformation in the prehnite–pumpellyite facies before alteration in blueschist facies conditions. Magmatic clinopyroxene (beige grains) partly replaced by metamorphic Na–Ca pyroxene is still preserved. Glaucophane, white mica, chlorite and leucoxenized ilmenite are also present, sample VVS-16; **e** basalt with ophitic texture previously metamorphosed to blueschist and then retrogressed in the greenschist facies conditions. Na-actinolite with sporadic relic of Na–Ca amphibole, albite, epidote, chlorite and leucoxenized ilmenite are main constituents of the rock together with magnetite octaedres. Glaucophane is present only as rare inclusions enclosed in epidote, sample VVS-41; **f** basalt with well-preserved relic ophitic texture transformed into blueschist. Na–Ca pyroxene replacing original magmatic clinopyroxene is mostly decomposed to brown pigment, pale-violet glaucophane and green chlorite. Some epidote and albite is also present. Shapes of some chlorite pseudomorphs indicate that also olivine crystals could have been present originally, sample VVS-173. Blueschist-facies radiolarites from the locality SW of Honce village, sample HNC: **g** metaradiolarite with dispersed Fe–Mn oxide ore pigment; **h** oval-shaped phantoms of radiolarians in the metaradiolarite; **i** spessartine garnets in the metaradiolarite; **i–l** BSE images of the HP/LT metaradiolarite with typical minerals: *Aeg* aegirine (for chemical analyses see Online resource 3), *Sps* spessartine garnets (for chemical analyses see Online resource 4), *Qz* quartz, *Chl* chlorite, *Cal* calcite, *Mrbk* magnesioriebeckite, *Tr* tremolite (for chemical analyses see Online resource 2)

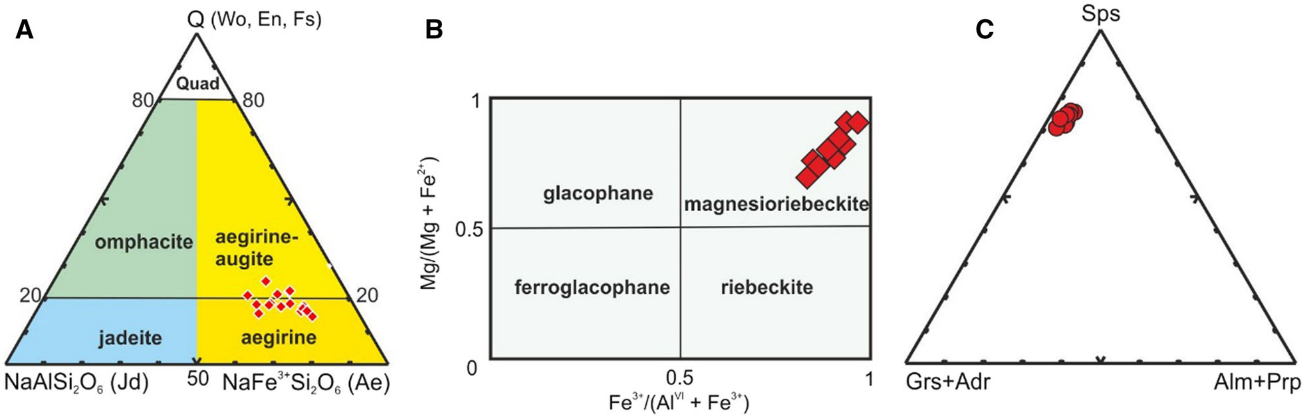


Fig. 7 Compositions of minerals from the blueschists-facies metaradiolarites, Bôrka Nappe, locality Honce village, sample HNC: **a** compositions of the Na-pyroxenes (after Morimoto et al. 1989) (for chemical analyses see Online resource 3); **b** compositions of the Na-amphiboles (after Hawthorne et al. 2012) (for chemical analyses see Online resource 2); **c** compositions of the garnets: *Sps* spessartine, *Alm* almandine, *Prp* pyrope, *Grs* grossular, *Adr* andradite (for chemical analyses see Online resource 4)

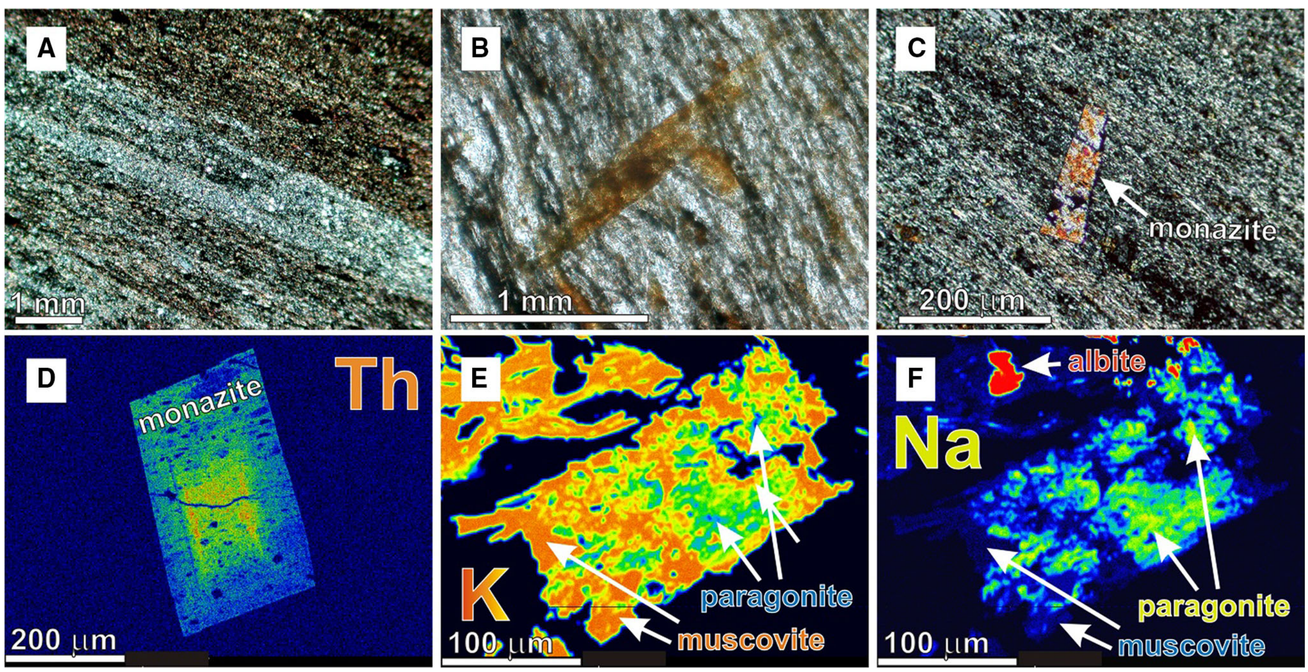


Fig. 8 Sericite–chlorite phyllite from the Bôrka Nappe (locality Honce village, sample OS-07-128): **a** photomicrograph of the sericite–chlorite phyllite, crossed pol.; **b** photomicrograph of pseudomorphs after glaucophane, parallel pol.; **c** post-tectonic idiomorphic porphyroblast of monazite, crossed pol.; **d** X-ray compositional maps of Th distribution in idiomorphic monazite porphyroblast (for chemical analyses see Online resources 7 and 8); **e** and **f** sericite–chlorite phyllite from the Bôrka Nappe (locality Honce, sample OS-07-117): X-ray compositional maps, distribution of K (**e**) and Na (**f**) shows relics of the older paragonite grains in younger muscovite/phengite. Increase in the K and Na contents is indicated by blue-green-yellow–red colours (for chemical analyses see Online resource 1)

p.f.u.) (Fig. 7a). Compositions of Na-amphiboles vary between magnesio-riebeckite and manganoan magnesio-riebeckite (Fig. 7b). The spessartine component is prevailing in the composition of garnets (75–78 mol%), andradite (15–19 mol%) and grossular (5–8 mol%) are present in smaller amount, whereas almandine (0–2 mol%) and pyrope (0–0.7%) are negligible (Fig. 7c).

Furthermore, radiolarites originally metamorphosed under the blueschist facies conditions and thereafter retrogressed at greenschist facies have been found in the Bôrka Nappe in the surroundings of Dobšiná town (Fig. 2). Besides prevailing quartz and pigment of Fe-oxides, some Na-actinolite, chlorite and epidote are present. The HP/LT metamorphic stage is detectable by locally preserved

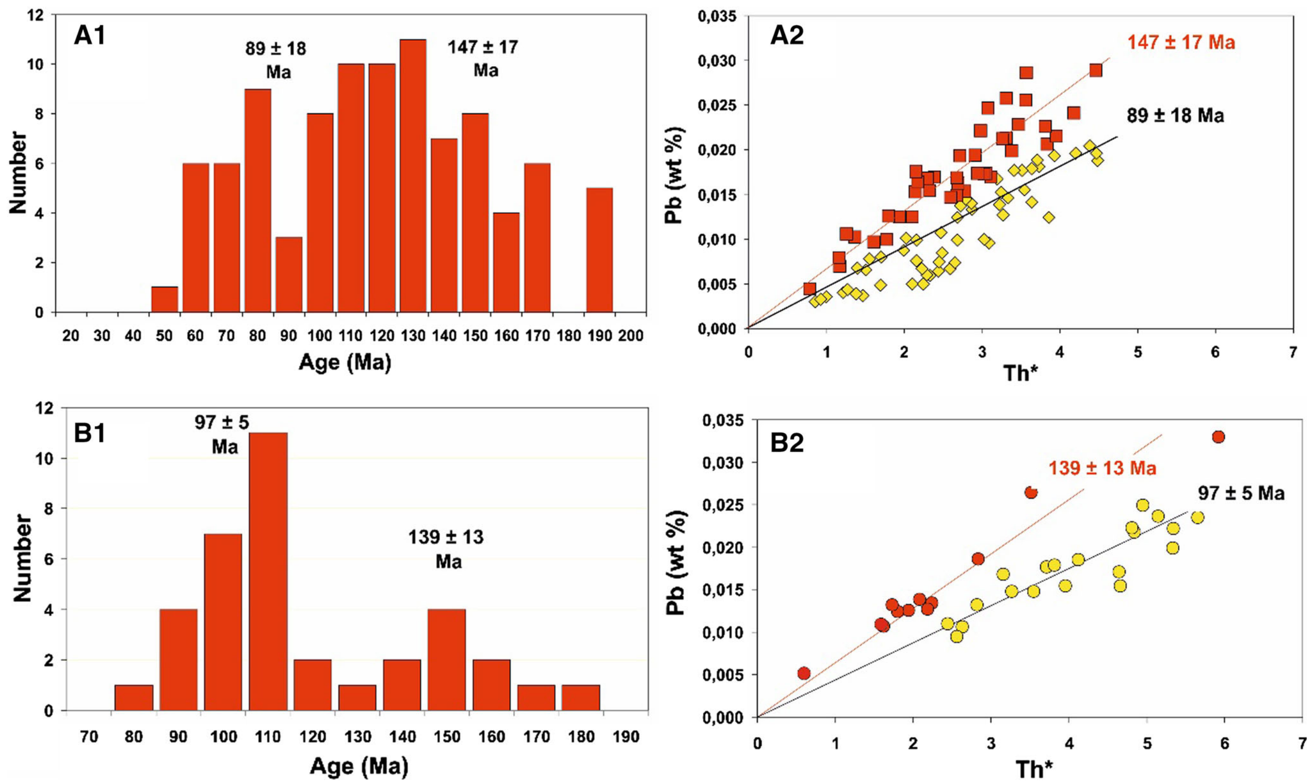


Fig. 9 Results of chemical (EMPA) U–Th–Pb dating of monazite–(Ce) from chlorite-sericite phyllites of the Bôrka Nappe; **a** locality Honce village, sample OS-07-128: **a1** Monazite age histogram; **a2** Pb vs. Th* (wt%) monazite age isochron (Th* = Th + 3.15U wt%, after Nagy et al. 2002) (for chemical analyses see Online resource 8); **b** locality Hrádok near Jelšava, sample OCH 2B: **b1** histogram of monazite ages; **b2** Pb vs. Th* (wt %) monazite age isochron (Th* = Th + 3.15U wt%, after Nagy et al. 2002) (for chemical analyses see Online resource 10)

glaucophane cores in Na-actinolite crystals or aggregates of green aegirine.

The majority of other radiolarites of the Meliatic Superunit, outside of the Bôrka Nappe and associated mélanges, do not bear any sign of HP/LT metamorphism with one exception—veinlets of magnesioriebeckite in radiolarites have been found near Jaklovce village as an indication of elevated pressure between greenschist and blueschist facies metamorphic conditions (Ivan and Méres 2009; Putiš et al. 2011a).

4.3 Dual monazite age groups from the Bôrka Nappe

The Middle–Upper Triassic up to Jurassic? fine-grained siliciclastic metasediments form the sedimentary matrix of the Bôrka Nappe in which blocks of various pelagic metasediments, metacarbonates and metabasalts are emplaced (Mello et al. 1998). The pelagic metasediments are represented by metasiltstones, albitic phyllites, sericite–chlorite phyllites (Fig. 8a–f), chloritoid schists, radiolarites with glaucophane, metasilicites with phosphates, metasilicites with basaltic volcanogenic admixture and metacarbonates. Relics of older paragonite in cores of younger muscovite/sericite are often preserved in sericitic phyllites. Numerous post-kinematic idiomorphic porphyroblasts of monazites (30–500 µm in size) were observed and analyzed in these phyllites. Monazites possess a typical oscillation zonation which is reflected in their chemical composition by relatively lower content of Ce_2O_3 (27% wt%) and higher content of Nd_2O_3 (19.2 wt%), Sm_2O_3 (3.7 wt%) and ThO_2 (4.8 wt%) in the cores of the monazite crystals. On the other hand, there are lower values of Nd_2O_3 (16 wt%), Sm_2O_3 (0.7 wt%) and ThO_2 (0.1 wt%) and increased values of Ce_2O_3 (36.6 wt%) at the crystal rims (for chemical analyses see Online resource 7).

The EMPA dating of monazites from the locality Honce near Štítnik village (sample OS-07-128) provided two age groups: (1) 147 ± 17 Ma and (2) 89 ± 18 Ma (ages calculated by the statistical method of Montel et al. 1996; Fig. 9a1, a2). We have obtained comparable monazite ages also from the chlorite-sericite phyllites at the locality Hrádok near Jelšava (sample OCH 2B; for chemical analyses see Online resources 9 and 10), which yet again fall into two statistical groups (Fig. 9b1, b2): (1) 139 ± 13 Ma and (2) 97 ± 5 Ma.

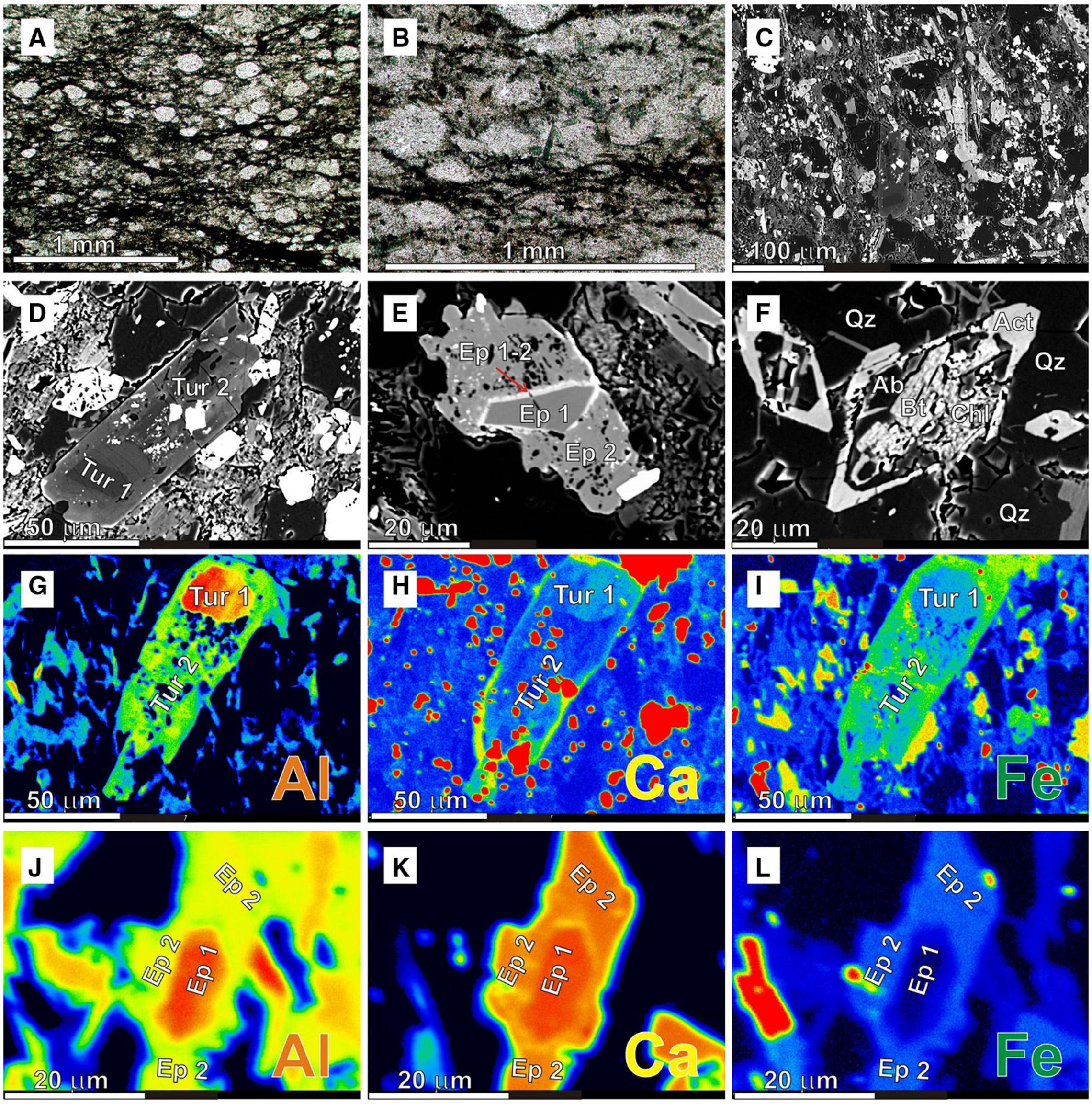


Fig. 10 Pelagic metasediment from the Bôrka Nappe (locality Dobšiná–Stirn, sample OS-07-147): **a** Photomicrograph of laminated metasilicite with alternating layers rich in elliptical phantoms (pseudomorphs) after radiolarians (lower part) and with predominating altered primary basaltic material (upper part), parallel pol.; **b** Photomicrograph of Na-actinolite pseudomorphs (blue) after glaucophane, parallel pol.; **c** BSE image of a layer rich in actinolite, epidote, chlorite and tourmaline; **d** BSE image of two types of tourmaline; **e** BSE image of two types of epidote; **f** BSE image Na-actinolite, albite, biotite and chlorite pseudomorphs after glacophane. X-ray compositional maps of Al (**g**), Ca (**h**) and Fe (**i**) in the Tur1 (dravite) and Tur2 (schorl) (for chemical analyses see Online resource 5). X-ray compositional maps of Al (**j**), Ca (**k**) and Fe (**l**) in the Ep1 (clinozoisite) and Ep2 (epidote) (for chemical analyses see Online resource 6). Increase in the Al, Ca and Fe contents is indicated by blue–green–yellow–red colours

4.4 Two types of tourmaline and epidote

Two tourmaline generations were found in metasediments of the Bôrka Nappe in the surroundings of town Dobšiná (Fig. 2; sample OS-07-147, locality Dobšiná–Stirn; Fig. 10a–l). The first generation of homogeneous tourmaline (Tur1–dravite) does not contain any inclusions. The second, younger generation (Tur2–schorl) typically comprises numerous inclusions of the greenschist facies minerals and also includes Tur1 crystals (Fig. 10d). The metamorphic origin of both types is revealed by their position in the field of tourmalines in Ca-poor metapelites and tourmaline-quartz rocks in the classification diagram of Henry and Guidotti (1985) (Fig. 11c).

Based on microprobe analyses (Online resource 5), Tur1 differs from Tur2 (Figs. 10g–i, 11a–c) by a higher content of Al_2O_3 (33–35 wt%), and lower contents of FeO (< 8 wt%) and MgO (< 6 wt%). Weight contents of Tur2 amount to 25–27% of Al_2O_3, 10–14.5% of FeO and 6–7.5% of MgO. Differences in chemical composition of

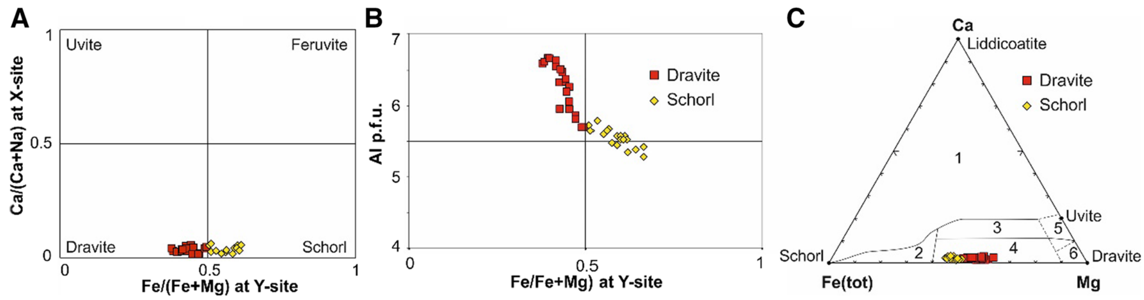
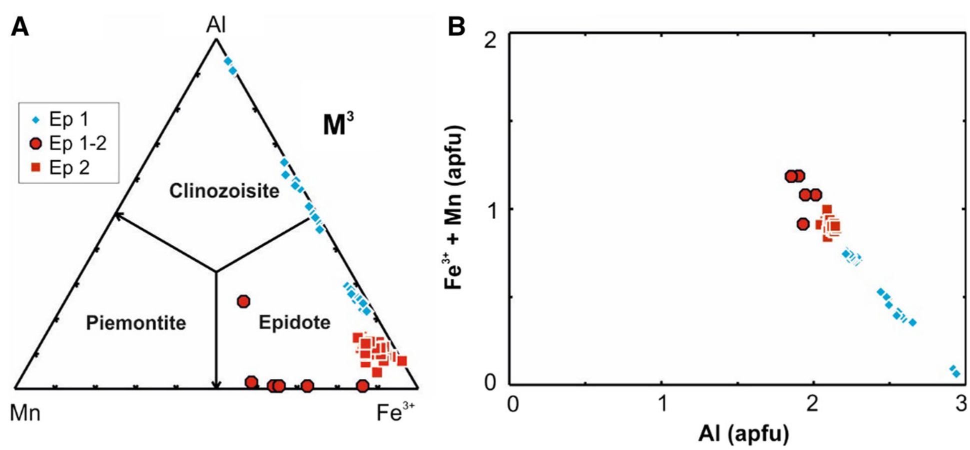


Fig. 11 Compositions of the two generations of tourmalines from pelagic metasediments of the Bôrka Nappe, locality Dobšiná–Stirn, sample OS-07-147 (nomenclature of tourmalines according to Henry et al. 2011): **a** different composition of two generations of tourmalines in the diagram Ca/(Ca + Na) at X site vs. Fe/(Fe + Mg) at Y site; **b** different composition of two tourmaline generations in the diagram Al apfu vs. Fe/(Fe + Mg) at Y site: **c** Ca–Fe(tot)–Mg diagram with the numbered fields corresponding to the following rock types (Henry and Guidotti 1985): (1) Li-rich granitoid pegmatites and aplites, (2) Li-poor granitoids and associated pegmatites and aplites, (3) Ca-rich metapelites and calc-silicate rocks, (4) Ca-poor metapelites and quartz-tourmaline rocks, (5) Metacarbonates, and (6) metaultramafics (for chemical analyses see Online resource 5)

Fig. 12 Compositions of the two epidote generations from pelagic metasediments of the Bôrka Nappe, locality Dobšiná-Stirn, sample OS-07-147: **a** Classification of the epidote EMPA data in the ternary diagram (after Armbruster et al. 2006); **b** Different composition of two epidote generations in the diagram Al apfu vs. Fe^{3+} + Mn apfu (for chemical analyses see Online resource 6)



both types of tourmaline are reflected in their structure. Compared to Tur2 tourmalines, the Tur1 generation is characterized by a higher number of vacancies and higher Mg/(Mg + Fe) ratio. The Tur2 type differs from Tur1 in the lower content of Al, Mg and vacancies. Both tourmaline types belong to the group of alkaline tourmalines and their chemical compositions vary in the range of the dravite–schorl continual series. Tur1 shows a homogeneous chemical composition and represents dravite, whilst schorl is prevailing in rims of Tur2.

In the same sample (OS-07-147), two generations of epidote group minerals—clinozoisite subgroup were identified. By its composition, Ep1 corresponds to clinozoisite to epidote and Ep2 to epidote (Fig. 12a; Armbruster et al. 2006). Epidotes of the first generation (Ep1) are homogeneous and without inclusions (Fig. 10e). The second generation (Ep2) always contains Ep1 as inclusions, together with quartz, albite, titanite, Fe-oxides. Ep1 is often surrounded by a thin (less than 3 µm) transitional zone of Ep1-2. The chemical composition of Ep1 differs from that of Ep2 by showing a higher content of Al_2O_3 (23–33 wt%) and a lower content in Fe_2O_3 (1.1–7.7 wt%) and MnO (< 0.5 wt%). Content of Al_2O_3 varies between 21–23 wt%, Fe_2O_3 between 11–16.5 wt% and MnO between 0.5 and 1.3 wt% in Ep2. Compared to Ep1, the transitional zone (Ep1-2) shows higher contents of Fe_2O_3 (7.7–11 wt%), MnO (4–6 wt%) and REE (ΣREE 7–11 wt%).

The content of Al apfu in Ep1 is higher than in Ep2, while contents of Fe apfu and Mn apfu are lower (Figs. 10j–l, 12b). Contents of Fe apfu and Mn apfu are highest and Al lowest in the transitional zone (Ep 1–2). This zone is specific also by the content of REE 0.20–0.34 apfu.

4.5 The earliest manifestation of detrital glaucophane in "Urgonian" limestones

The Cretaceous conglomerates of the Pieniny Klippen Belt contain pebbles of variable sedimentary, magmatic and metamorphic rocks (for the reviews see Mišík and Sýkora 1981; Mišík and Marschalko 1988; Mišík et al. 1980, 1981; Birkenmajer 1988). HP/LT, blueschist-facies metamorphic rocks are represented by: (1) pebbles of Upper Jurassic

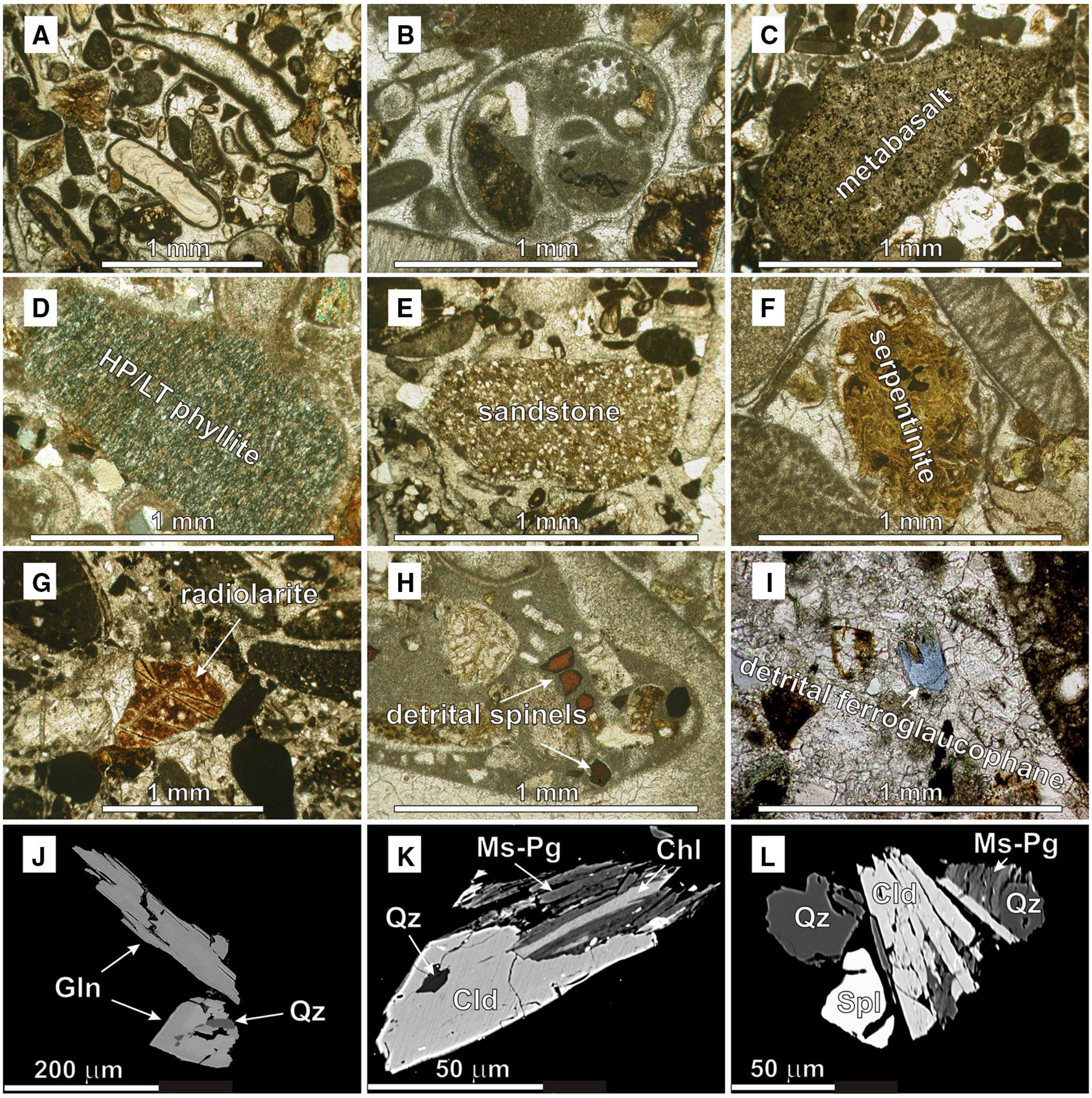


Fig. 13 "Urgonian" bioclastic limestone pebbles with terrigenous admixture. **a**, **b** Bioclastic limestone–grainstone; **c**–**g** various lithoclasts in the bioclastic limestone pebbles; **h**, **i** detrital minerals in bioclastic limestones; **j**, **k** BSE images of the HP/LT minerals and lithoclasts. *Gln* glaucophane, *Qz* quartz, *Ms* muscovite/phengite, *Pg* paragonite (for chemical analyses see Online resource 1), *Chl* chlorite, *Cld* chloritoid, *Spl* spinel. Localities in the Middle Váh River Valley (Fig. 1): **a**, **b**, **d**, **f**, **h**, **j**, **k**, **l** Nosice village; **c** Milochov village; **e** Orlové village; **g** Považská Bystrica town

glaucophanites in the Albian–Cenomanian Upohlav-type conglomerates of the Klape Unit (see below); and as (2) terrigenous clastic admixture in pebbles of Barremian–Aptian shallow-water, "Urgonian"-type bioclastic limestones that also occur in the Upohlav conglomerates. We have studied pebbles of "Urgonian" limestones with the clastic admixture from localities in the Klape and Manín units—Figs. 1, 13, Table 1.

In the "Urgonian" limestone pebbles, we have identified benthic foraminifera of genus *Orbitolina* and planktonic foraminifera of genus *Hedbergella* (Barremian–Cenomanian), as well as fragments of reef-building bivalves, echinoid particles, algae, corals and other shallow-water organisms in the limestone pebbles (Fig. 13a, b). Lithoclasts are represented by glaucophanites, serpentinites, HP/LT phyllites, amphibolites, acid and mafic volcanic rocks, sandstones, quartzites and carbonates older than Barremian. Detrital minerals include glaucophane, paragonite, muscovite, garnet, chloritoid, allanite, spinel, rutile, calcium amphibole (titanium magnesio-hastingsite), quartz, albite, tourmaline, zircon, biotite, chlorite and barite (Fig. 13c–g). Locally, the amount of blue amphiboles in the heavy mineral concentrates attains 47%. Except of rounded zircon grains, all other heavy minerals are sharp-edged.

According to their composition, the blue sodium amphiboles belong to the series glaucophane—ferro-glaucophane. The composition of detrital white micas complies with the complete substitution series of K-Na micas with the end members muscovite and paragonite. Paragonite forms centres of mica flakes replaced by muscovite in the rims. The composition of the garnets indicates their provenance from: (i) low-grade metasediments (phyllites; analyses No. 17, 22, 23 and 47 in Online resource 4); and (ii) from serpentinites (high content of andradite and grossular; analysis No. 38 in Online resource 4). The composition of spinels corresponds to the chromite—magnesio-chromite series.

The probable age range of the studied "Urgonian" limestones from pebbles of the Upohlav conglomerates is constrained by the rich orbitolinid foraminiferal microfauna. The limestones with terrigenous admixture contain numerous large-sized flat to low conical tests, which probably belong to species *Palorbitolina? lenticularis* (Blumenbach) (sample 9179; Fig. 14e–i). The precise systematic classification is not possible due to a missing embryonic apparatus of the orbitolinid tests. However, their rock-forming abundance indicates the so-called "Orbitolina episode" in development of the "Urgonian" platform during the early Aptian (Vilas et al. 1995). This could also explain a mass presence of the palorbitolinids without embryonic apparatus since the increased terrigenous influx and nutrification resulted in preference for an asexual reproduction. Therefore, the terrigenous- and orbitolinid-rich limestones could be assigned to Palorbitolina lenticularis Zone, which according to Schroeder et al. (2010) corresponds to late Barremian—early Aptian interval, i.e. around 125 Ma. This age is also indicated by the species *Dictyoconus cf. arabicus* Henson (Fig. 14j), which is mentioned from the late Barremian with presumable transition to early Aptian (Baud et al. 1994). Orbitolinid tests show a high concentration of spinel grains, which confirm a certain preferences of agglutinated foraminifera to use heavy minerals in construction of the shell material (Waśkowska 2014).

Besides detrital limestones, pebbles of the Orbitolina-bearing limestones with low content in terrigenous admixture are present as well (sample 20444). They contain a different type of orbitolinids with highly conical tests, larger protoconch and more distinctly developed subepidermal cells in marginal zone. Some axial sections of orbitolinids display a subembryonal zone and deuteroconch with alveoli, which are a typical generic feature of *Mesorbitolina* (Fig. 14a–d). Based on this type of embryonic apparatus, such orbitolinids could belong to species *Mesorbitolina texana* (Roemer) and *M. cf. parva* (Douglass). These species are considered to represent index orbitolinid taxa of the late Aptian biozones (sensu Schroeder et al. 2010). Orbitolinids are associated with other foraminiferal species, such as *Charentia cuvillieri* Neumann, *Debarina hahounerensis* Fourcade*, Melathrokerion cf. valserinensis* (Brönnimann & Conrad), *Haplophragmoides cf. globosus* Lozo, *Ammobaculites cf. subcretaceous* Cush & Alex, *Pseudochrysalidina sp*., *Bolivinopsis sp*., *Pseudocyclammina sp*. and *Conorboides sp*. Dasycladal algae are represented by species *Neomeris cretacea* Stenmann. In general, the above mentioned species *Palorbitolina? lenticularis* (Blumenbach), *Mesorbitolina texana* (Roemer) and *M. cf. parva* (Douglass) are datable for the late Barremian—Aptian age of the spinel- and glaucophane-bearing limestones.

It should be noted that these "Urgonian"-type Barremian–Aptian limestones are considerably different from other "Urgonian" limestones occurring in several Western Carpathian units (Mišík 1990; Michalík and Soták 1990; Michalík 1994). Beside differences in the fossil content and facies, it is the presence of siliciclastic admixture what is the most distinctive feature, because other common "Urgonian" limestones are devoid of it. The only exception is the Barremian–Aptian bioclastic–siliciclastic limestone formation of the Tatric cover succession in the Malé Karpaty Mts. However, these clastic limestones are characterized by the stable zircon-rutile-tourmaline (ZRT) heavy mineral association without any chrome spinels or blue amphiboles. The siliciclastic admixture was obviously derived from local sources in the Tatric crystalline basement and/or recycled from the Lower Triassic sandstones (Jablonský et al. 1993).

4.6 Detrital blue amphiboles in mid-Cretaceous synorogenic clastic formations

Amphiboles belong to the group of 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. Higher amounts of blue amphiboles in psammitic rocks then may indicate either a random local input, or limited preservation of otherwise widespread minerals.

Because of instability and low resistance, there are more findings of glaucophanite rock pebbles in exotics than blue-amphibole grains dispersed in the sediment (cf. Ivan and Sýkora 1993; Ivan et al. 2006; vs. Sýkora et al. 1997, von Eynatten and Gaupp 1999; Bellová et al. 2018). Blue amphiboles described from the Albian–Cenomanian flysch sandstones are represented mostly by glaucophane to ferroglaucophane. Crossite was also commonly reported as

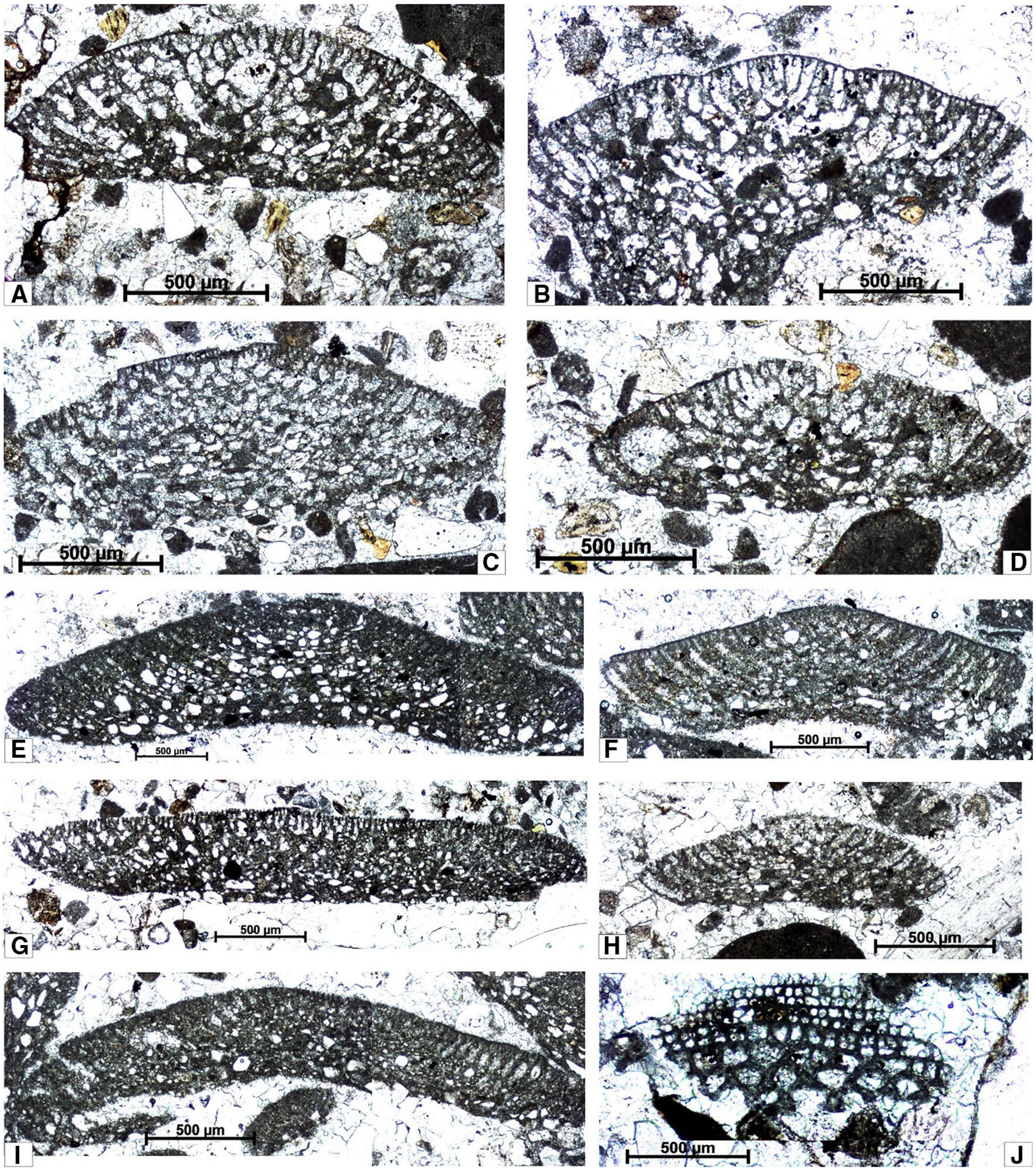


Fig. 14 Palorbitolinid and mesorbitolinid foraminifera from spinel-bearing "Urgonian" limestone (Late Barremian–Aptian): **a** *Mesorbitolina texana (*Roemer)—axial section, conical test with megalospheric embryonic apparatus; **b** *Mesorbitolina texana* (Roemer)—subaxial test with conical tests and alveolar layer of the deuteroconch; **c**, **d** *Mesorbitolina cf. parva* (Douglass)—conical tests with convex base, globular protoconch and divided peri-embryonic zone; **e**–**i** *Palorbitolina? lenticularis* (Blumenbach)—large-sized tests with low conical to flat shape and concave base without embryonic apparatuses (microspheric forms); **j** *Dictyoconus cf. arabicus* Henson—tangential section with subepidermal plates (Scale bars: 500 µm)

the blue amphibole in the exotics (e.g. Ivan and Sýkora 1993; von Eynatten and Gaupp 1999), but this amphibole name was abolished later and is no more in use (Leake et al. 1997). Formerly, the glaucophanite exotic pebbles were considered to be different from glaucophanites of the Bôrka Unit because of differences in the lawsonite content (Šímová and Šamajová 1982; Šímová 1985) and in the protolith (Faryad and Schreyer 1997; Faryad 1998). However, radiometric dating revealed the same Late Jurassic age of the blueschist pebbles (155 Ma—Dal Piaz et al. 1995) and more thorough analyses showed that the differences are minimal (e.g. Ivan et al. 2006) and hence the exotic source area was most likely formed by units derived from the Neotethyan Meliata Ocean.

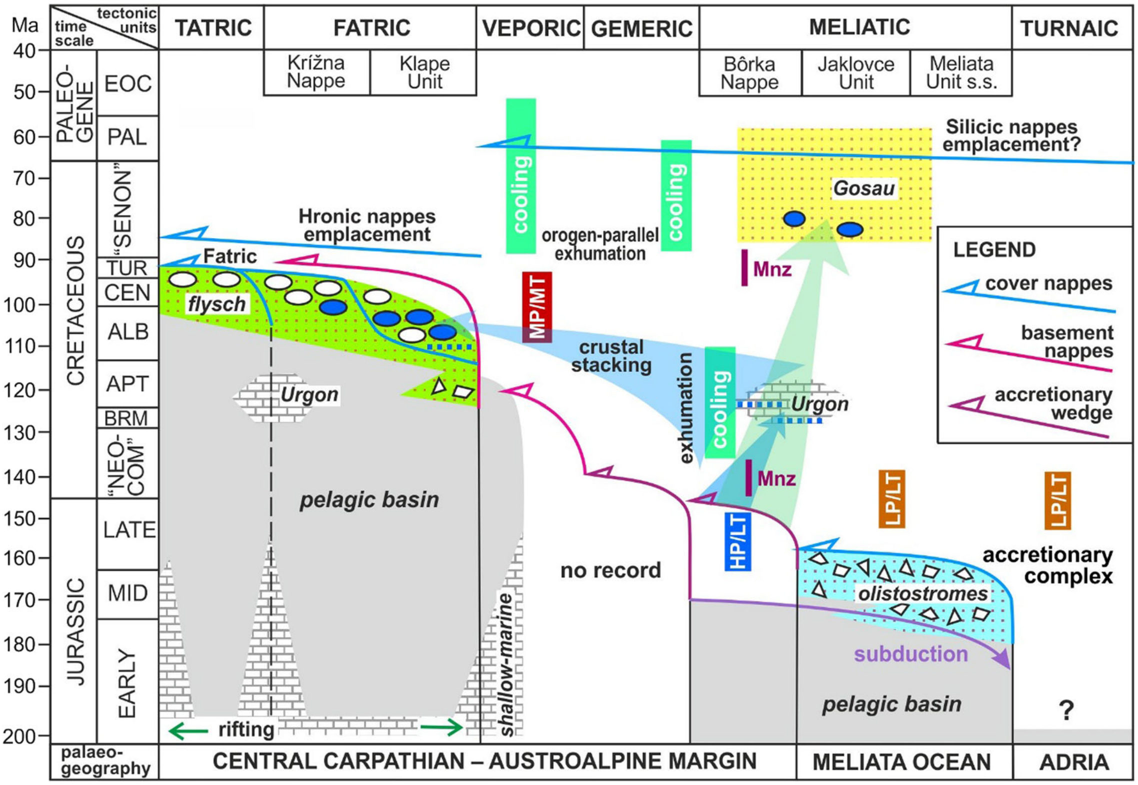


Fig. 15 Synoptic tectonostratigraphic scheme outlining the development and sedimentary dispersal of blueschist-facies rocks in the Western Carpathian units. Thick transparent arrows indicate the transport ways of blueschist detritus—pebbles (blue ellipses) and blue amphiboles found in the heavy mineral fractions (blue dots) into the Cretaceous clastic formations (green and yellow)

Recently, Bellová et al. (2018) have reported a high amount of blue amphiboles in mid-Cretaceous turbiditic sandstones of the Klape Unit in the Middle Váh River Valley of western Slovakia (Fig. 1). Besides blue amphiboles (ca 20%), the heavy mineral concentrates contain abundant chrome spinels (46%), stable ZRT association (14%), epidote (5%), apatite (5%), garnet (4%) and some monazite and kyanite grains. Amphibole composition corresponds to glaucophane and ferroglaucophane.

5 Discussion

5.1 Notes to the tectonometamorphic evolution of the Meliatic units

Based on the review of existing information, presented in the introductory chapter, and newly achieved metamorphic petrological and geochronological data, we discuss the possible scenario for the onset, course and termination of subduction of the Meliata Ocean. Our new EMPA monazite age data corroborate the time relationships of blueschist and superimposed greenschist facies metamorphism in the Bôrka Nappe. Two distinct tectonometamorphic stages postdating the HP metamorphism are indicated by older ages (1) around 145–140 Ma that were attained under greenschist-facies conditions and could indicate welding of the Meliatic and Turnaic units into a united accretionary complex that subsequently overrode the Gemeric Superunit (Fig. 15). This event is expressed by coeval upright folding and imbrication during emplacement of the Meliatic–Turnaic nappe stack over the Gemeric basement-cover complexes (Lačný et al. 2016). Consequently, the older monazite ages postdate by some 10–15 Myr the peak blueschist-facies metamorphic ages of the Bôrka Unit clustering around 155 Ma. The subsequent thrusting-related exhumation of the Meliatic units is recorded by the 135 Ma age of metamorphic perovskite and zircon (U–Th)/He cooling ages at 130–120 Ma (Putiš et al. 2014, 2015; Li et al. 2014). The resulting burial of the Gemeric complexes is revealed by low-grade metamorphism at 350–400 °C and 400–600 MPa dated to ca 140–120 Ma (Hurai et al. 2008, 2015; Vozárová et al. 2008, 2014). Subsequently, the Gemeric and overlying Meliatic complexes were affected by development of a cleavage fan related to thrusting over the foreland Veporic Superunit.

In the time interval of 130–90 Ma, the main phase of the Central Western Carpathian thick-skinned thrust stacking occurred. According to the inferred scenario of tectonometamorphic evolution of the Gemeric and Veporic units (see Jeřábek et al. 2012; Plašienka et al. 2016; Plašienka 2018 and references therein), at first the Gemeric basement sheet with passively carried Meliatic–Turnaic units was thrust over the southern Veporic zones between ca 130–120 Ma. Afterwards, the Veporic crustal-scale wedge propagated outward from the Meliata collision zone and overrode the Fatric basement attached to the foreland Tatric plate, concurrently with detachment of the Fatric sedimentary cover between 100 and 90 Ma. This process was finalized by emplacement of the detached Fatric cover nappes (Krížna and related units; e.g. Plašienka 2003, 2018; Prokešová et al. 2012) above the Tatric cover (Fig. 15). The crustal-scale shortening and thickening of the rear Veporic part of the propagating orogenic wedge was accompanied and followed by orogen-parallel unroofing and gradual exhumation of the Veporic metamorphic dome, along with the overlying Gemeric–Meliatic–Turnaic thrust pile (e.g. Vojtko et al. 2016). Consequently, the younger monazite age cluster (2) in the range 95–90 Ma might record thermal relaxation and elevated thermal gradient related to exhumation processes of the neighbouring Veporic metamorphic complex.

The distinctive poikiloblastic tourmalines (Tur2, see Sect. 3.4) are typical constituents of some rare eclogitic and eclogite-related rocks (Altherr et al. 2004; Marschall et al. 2006; Konzett et al., 2012; Broska et al. 2015), where they were interpreted as being formed in the decompression (exhumation) phase of originally high-pressure to ultra high-pressure (HP/UHP) metamorphosed rocks (Marschall et al. 2006). Considering the higher content in Mg and Al and the lower content in Fe (Fig. 10g–i), the Tur1 generation likely formed during the subduction-related HP/LT metamorphic alteration of pelagic sediments. In contrast, Tur2 might have crystallized during exhumation under greenschist facies (LP/LT) metamorphic conditions, as indicated by a comparatively higher portion of Fe and lower amounts of Mg and Al, and a number of poikiloblastic inclusions of quartz, epidote, Fe-oxides and titanite. These features point to a rapid, fluid-assisted blastesis of Tur2.

The genesis of two epidote generations is interpreted in a similar way like that of the two tourmaline generations. Tourmaline Tur 2 always includes relics of Ep2 only and the same inclusions as found in Ep2. Accordingly, the first generation (Ep1) might have originated in the blueschist-facies metamorphic conditions, whereas blastesis of the second generation (Ep 2) was connected with the superimposed metamorphosis in the greenschist facies, which affected the studied metasediments during exhumation of the Bôrka Nappe.

5.2 Distribution of erosional products of the Meliatic blueschists

The investigation of the sedimentary response to exhumation and thrusting processes offers additional hints for palaeotectonic interpretations. Therefore, the provenance studies of synorogenic clastic formations play an essential role in the reconstruction of the structure and tectonic evolution of ancient orogenic belts, because the sedimentary record may preserve information about composition, age and exhumation history of areas and units that were subsequently to a large extent, or even completely eroded and do not participate on the present erosional surface any more (e.g. Dickinson 1988).

The blueschist-facies metamorphic rocks are usually intimately related to the dismembered ophiolite suites, therefore their erosional products deposited in clastic sediments of neighbouring sedimentary basins occur jointly. This applies to both the coarse-grained material in conglomerates, as well as to heavy mineral assemblages in sandstones and siltstones. The Albian–Cenomanian conglomerates containing the exotic ophiolite- and blueschist-derived pebbles occur in several Central Western Carpathian units (Fatric, Tatric and in the largest extent in the Klape Unit in the Peri-Klippen Zone) and were thoroughly studied by a number of authors (e.g. Šímová 1982, 1985; Ivan and Sýkora 1993; Dal Piaz et al. 1995; Faryad and Schreyer 1997; Ivan et al. 2006 and references therein).

A more problematic issue concerns the recognition of blueschist-derived heavy mineral fractions in fine-grained clastic sediments. While the most indicative heavy mineral derived from ophiolitic ultramafic and mafic magmatic rocks—the chrome spinel is relatively resistant and sometimes abundant (e.g. Jablonský et al. 2001 and references therein; see also Bellová et al. 2018), the blue sodium amphiboles as the most significant evidence of blueschist-facies sources are less resistant and might be reduced or completely erased by post-sedimentary diagenetic processes like intrastratal solution. Nevertheless, they could be preserved under appropriate conditions. If so, the detrital blue amphiboles, glaucophane in particular, provide essential information about the time of the blueschists exhumation and surface erosion.

In the Western Carpathians, the first evidence of detrital chrome spinels comes from the Valanginian and Hauterivian (i.e. 135–130 Ma) siliciclastic turbidites of the Fatric Zliechov Basin located north of the developing Veporic–Gemeric–Meliatic collisional thrust stack. Turbidites with massive input of chrome spinels (up to 90% of heavy mineral concentrates—Jablonský et al. 2001) were fed from southern sources, therefore derivation of chrome spinels could be directly related to erosion of Meliatic ophiolite-bearing mélange complexes that were in a piggyback position above the Gemeric sheet thrust over the southern Veporic zones (cf. Figure 7 in Plašienka 2018). However, no blue amphiboles or other high-pressure minerals have been reported from these turbidites yet. It is worth noting that ophiolite detritus in sediments appeared considerably later here than in the Northern Calcareous Alps, where the earliest presence of detrital chrome spinels was documented from the Kimmeridgian deposits (Gawlick et al. 2015), i.e. some 20 Myr earlier than in the Carpathians. In the Transdanubian Gerecse Mts (Fig. 1), a massive input of chrome spinels into the Lower Cretaceous coarsening-upward flysch sequence started by the end of Berriasian (i.e. at 140 Ma; Császár and Árgyelán 1994; Árgyelán 1996, 1997).

The manifestation of detrital chrome spinel and blue amphibole in pebbles of the "Urgonian"-type shallow-marine organogenic limestones with siliciclastic admixture was first documented by Mišík (1979—up to 47% of blue amphiboles in the heavy mineral fraction) and Mišík et al. (1980). However, these atypical "Urgonian" limestones do not occur in a primary position, but only as pebbles in the mid-Cretaceous wildflysch conglomerates of the Tatric and Fatric units, including the Peri-Klippen Klape Unit (Figs. 1, 15). In the hundreds of metres thick Albian–Cenomanian Klape flysch complex they occur in association with various blueschist-facies pebbles. Most probably, the "Urgonian" pebbles were derived from ephemeral biohermal build-ups fringing the emerged parts of Meliatic units. Considering their late Barremian—early Aptian age, the exhumation to the surface and first erosion of the Meliatic HP metamorphic rocks is dated to around 125 Ma, which coincides with the above reported thrusting-related exhumation and cooling ages (Putiš et al. 2014). The "Urgonian" limestone pebbles with detrital chrome spinels and serpentinite fragments, but lacking blue amphiboles, occur in the Albian flysch conglomerates of the Tatric sedimentary cover succession and Fatric Krížna Nappe (Mišík et al. 1980, 1981), as well as in the Transdanubian Gerecse Mts (Császár and Árgyelán 1994; Császár 1997). Wagreich et al. (1995) studied analogous clasts of "Urgonian"-type limestones with ophiolite detritus from the Upper Cretaceous Gosau conglomerates of the Northern Calcareous Alps. They found a few blue amphibole grains in two samples.

Always in association with detrital chrome spinel and locally with chloritoid, the blue amphiboles occasionally occur in the mid-Cretaceous (Albian–Cenomanian; i.e. from ca 110 Ma onward) synorogenic flysch formations of the Klape Unit in the Peri-Klippen Zone in western Slovakia (Mišík et al. 1980; Mišík and Sýkora 1981; Jablonský et al. 2001). Nevertheless, there are at least two localities, where the content of blue amphiboles in the heavy mineral concentrates is extraordinary—39% (Sýkora et al. 1997) and 20% (Bellová et al. 2018)—asterisks (1) and (2) in Fig. 1, respectively. The substantial enrichment at these two localities can be explained either by a transient exposure of the parental blueschists in the source area, or by the syn- or post-sedimentary impoverishment in majority of the host turbiditic sandstone beds, or both. The sporadic occurrence of blue amphiboles was described also from the Upper Cretaceous Gosau-type sandstones in the Peri-Klippen Zone (Wagreich and Marschalko 1995). It seems probable that these were recycled from older mid-Cretaceous sandstones of the Klape Unit (Plašienka and Soták 2015). Occurrences of chrome spinels and blue amphiboles in Cretaceous clastic formations of the Eastern Alps were reviewed and discussed e.g. by Winkler (1996).

Of special importance is "mosaic" (poikiloblastic) tourmaline revealed in the exotics-bearing psammites (Bellová et al. 2018), but also in tourmalinite pebbles occurring in the Cretaceous exotic conglomerates (Bačík et al. 2008). They were so far not detected in pre-Cretaceous Mesozoic clastic sediments of the Western Carpathians (Aubrecht and Kristín 1995; Aubrecht 2001). Nevertheless, they were registered also in the Meliatic glaucophanite-bearing complexes (see Sect. 3.4 above). Consequently, the appearance of these tourmalines provide a clue to their provenance and due to their better preservation potential, they are an important complementary indicator of presence of HP/UHP metamorphics in the source areas.

In addition to clasts of dismembered, but apparently complete ophiolite suite, pebbles of blueschist-facies metabasalts were encountered also in the Upper Cretaceous Gosau-type conglomerates (Hovorka et al. 1990). They occur in a narrow slice separating two partial structures of the Silicic Stratená Nappe, close to the present northernmost surface exposures of allochthonous Meliatic units (Fig. 1).

In this contribution, all findings of ophiolite- and blueschist-derived clastic material in the Cretaceous flysch deposits are regarded as having been derived from the Meliatic complexes in the southern Western Carpathian zones. Argumentation in support of this opinion was presented by Plašienka (1995a, 1997, 1998, 2012, 2018; Plašienka and Soták 2015) and the possible mechanism how it could have happened was proposed by Plašienka (1995b, 2018), Kissová et al. (2005) and Prokešová et al. (2012). Nevertheless, this view has not been accepted unambiguously. Instead, the concept of the exotic Pieniny cordillera that prevailed for many decades is still maintained by some authors (e.g. Aubrecht in Bellová et al. 2018). The puzzling concept of an exotic ridge was based on the massive occurrence of extremely variable pebble material, part of them of unknown provenance (summarized e.g. by Mišík and Marschalko 1988), which were designated as exotic. With the introduction of the plate tectonic theory, the source area was interpreted as a temporarily elevated compressional ridge at an active continental margin, variously explained as a subduction mélange complex or imbricated outer edge of an accretionary prism (e.g. Mišík, 1979; Mišík and Sýkora 1981), or else as the magmatic arc (Birkenmajer 1988). The ridge should have been located at the outer Tatric, i.e. Austroalpine margin facing the Triassic–Jurassic oceanic realm subducted during the Late Jurassic, but the exotic pebble material appeared as late as in mid-Cretaceous synorogenic wildflysch formations, diminished during the latest Cretaceous and then the exotic ridge was fully eliminated by underthrusting beneath the Central Carpathian thrust wedge. However, this scenario resembles a "deus ex machina" solution, since it is in a severe contradiction with the tectonostratigraphic evolution of the outer Tatric (i.e. Austroalpine) margin, and the Western Carpathians as a whole (e.g. Plašienka 1995a). Although the exotic pebble material was not re-evaluated comprehensively after the detailed analyses of Mišík and his co-authors from 1970 and 1980-ties, occasional studies in last two decades, such as presented and quoted in this contribution (e.g. Kissová et al. 2005; Ivan et al. 2006), are bringing still new arguments supporting derivation of this material from the southern Carpathian zones, without the need of an enigmatic exotic cordillera.

6 Conclusions

The paper presents a collection of new results concerning composition of variegated mélanges related to the subduction–accretion–collision processes of the Meliata oceanic domain and its continental margins, provides data about the atypical blueschist-facies radiolarites as components in these mélanges, presents the new EMPA monazite ages of HP rocks of the Bôrka Nappe that cluster in two peaks, describes two distinct types of tourmalines and epidotes occurring in the Bôrka blueschists, and reviews and interprets occurrences of the blueschist- and associated ophiolite-derived detritus in Cretaceous clastic sediments of especially the Klape Unit. From our interpretation of gathered data, the following conclusions can be drawn:

1. The Western Carpathian Meliata Superunit (Meliaticum) consists of three subunits that show in part independent characteristics concerning their composition and metamorphic evolution, but on the other hand they share the common structural position and evolution. In part they are mixed together to form polygenous mélange complexes.
2. So far not recognized blueschist-facies radiolarites, as a newly discovered component of Meliatic mélanges, are described for the first time in the Carpathians. They occur in polygenous mélange complex together with clasts of unmetamorphosed radiolarites and various other rocks, thus they register mixing processes during the mélange formation.
3. Two measured EMPA monazite age clusters from the Bôrka Unit culminate at around 145–140 Ma and 95–90 Ma. The first set coincides with the peak of K–Ar age spectra of fine-grained white micas from the very low-grade Meliata Unit s.s., therefore it could have been related to the additional burial of Meliatic units below the Turnaic nappes in the final phase of formation of the Meliata accretionary complex, and during its ensuing thrusting over the Gemeric foreland. The second age group might be tentatively ascribed to the thermal relaxation related to the initial stages of exhumation of the adjacent Veporic metamorphic dome associated with increased heat and metamorphic fluid flux.
4. Peculiar shallow-marine "Urgonian" limestones (Barremian–Aptian) contain sometimes high amounts of siliciclastic material including detrital chrome spinel and blue amphibole and thus provide evidence of the earliest recognized erosion of the Meliatic blueschists. These limestones are only present as pebbles in mid-Cretaceous flysch conglomerates. Nevertheless, they are associated with pebbles of glaucophanites and other blueschist-facies rocks implying their common provenance.
5. Scattered, but locally high concentrations of detrital blue amphiboles in the heavy mineral fractions from mid-Cretaceous turbiditic sandstones are always associated with the ophiolitic detritus dominated by chrome spinels. At the same time, the synorogenic turbiditic sequences, especially of the Klape Unit, contain huge bodies of unsorted conglomerates that contain pebbles of various HP/LT metamorphosed rocks which exhibit many common characteristics with the in situ appearances of blueschist-facies rocks in the Meliatic units, first of all the identical Upper Jurassic metamorphic age. Moreover, pebbles and detrital grains of unusual poikiloblastic tourmalines from the Cretaceous conglomerates and sandstones of the Peri-Klippen Klape Unit show the same characteristic as tourmalines from the Meliatic blueschists occurring in situ.

Summing up, the Meliatic provenance of the blueschist erosional products in the mid-Cretaceous synorogenic clastic formations appears to be the most plausible solution of the long-term discussed problem of source areas of this "exotic" material.

Acknowledgements The authors appreciate the financial support from the Grant Agency for Science, Slovakia (projects VEGA 1/0085/17 and 2/0034/16) and from the Slovak Research and Development Agency (projects APVV-0212-12 and APVV-17-0170). The authors are indebted to László Fodor and an anonymous reviewer for their valuable comments and suggestions that helped to improve the scientific content a readability of the earlier version of the manuscript. The same applies to the editorial comments of Edwin Gnos and Stefan Schmid. The analyzed samples are stored at the Department of Geology and Palaeontology and Department of Geochemistry, Faculty of Natural Sciences, Comenius University in Bratislava, and at the Earth Science Institute of the Slovak Academy of Sciences in Banská Bystrica.

References

Altherr, R., Topuz, G., Marschall, H., Zack, T., & Ludwig, T. (2004). Evolution of a tourmaline-bearing lawsonite eclogite from the Elekdağ area (Central Pontides, N Turkey): Evidence for infiltration of slab-derived B-rich fluids during exhumation. *Contributions to Mineralogy and Petrology, 148,* 409–425.

Andrusov, D. (1968). *Grundriss der Tektonik der nördlichen Karpaten*. Bratislava: Verlag Slovak. Akad. Wissensch.

Árgyelán, G. B. (1996). Geochemical investigations of detrital chrome spinels as a tool to detect an ophiolitic source area (Gerecse Mountains, Hungary). *Acta Geologica Hungarica, 39,* 341–368.

Árgyelán, G. B. (1997). Ophiolitic detritus in the Lower Cretaceous sandstones of Gerecse Mountains, Hungary: Petrography, detrital modes, provenance. *Mineralia Slovaca, 29,* 262–263.

Árkai, P., Faryad, S. W., Vidal, O., & Balogh, K. (2003). Very low-grade metamorphism of sedimentary rocks of the Meliata unit, Western Carpathians, Slovakia: Implications of phyllosilicate characteristics. *International Journal of Earth Sciences, 92,* 68–85.

Armbruster, T., Bonazzi, P., Akasaka, M., Bermanec, V., Chopin, Ch., Gieré, R., et al. (2006). Recommended nomenclature of epidote-group minerals. *European Journal of Mineralogy, 18,* 551–567.

Aubrecht, R. (2001). Jurassic heavy mineral distribution provinces of the Western Carpathians. *Mineralia Slovaca, 33*(5), 473–486.

Aubrecht, R., Gawlick, H.-J., Missoni, S., & Plašienka, D. (2012). Meliata type locality revisited: Evidence for the need of reinvestigation of the Meliata Unit and redefinition of the Meliata Mélange. *Mineralia Slovaca, 44,* 71.

Aubrecht, R., & Krištín, J. (1995). Provenance of detrital tourmaline in the Lower Jurassic of the Malé Karpaty Mts. *Mineralia Slovaca, 27*(1), 37–44.

Bačík, P., Uher, P., Sýkora, M., & Lipka, J. (2008). Low-Al tourmalines of the schorl–dravite–povondraite series in redeposited tourmalinites from the Western Carpathians, Slovakia. *The Canadian Mineralogist, 46,* 1117–1129.

Baud, A., Cherchi, A., & Schroeder, R. (1994). *Dictyoconus arabicus* Henson (Foraminiferida) from the Late Barremian of the Lhasa block (central Tibet). *Rivista Italiana di Paleontologia e Stratigafia, 100,* 383–394.

Bellová, S., Aubrecht, R., & Mikuš, T. (2018). 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. *Acta Geologica Slovaca, 10,* 45–64.

Birkenmajer, K. (1988). Exotic Andrusov Ridge: Its role in plate-tectonic evolution of the West Carpathian foldbelt. *Studia Geologica Polonica, 41,* 7–37.

Broska, I., Janák, M., Bačík, P., & Kumar, S. (2015). Tourmaline from the eclogite hosting gneisses in the Tso Morari UHP metamorphic terrane (Ladakh, India): Characteristics and evolution. *Periodico di Mineralogia, ECMS, 2015,* 37–38.

Channell, J. E. T., & Kozur, H. (1997). How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine paleogeography. *Geology, 25*(2), 183–186.

Császár, G. (1997). Sedimentary environments of the Urgonian formations of Hungary. *Mineralia Slovaca, 29,* 265–266.

Császár, G., & Árgyelán, G. B. (1994). Stratigraphic and micromineralogic investigations on Cretaceous formations of the Gerecse Mountains, Hungary and their palaeogeographic implications. *Cretaceous Research, 15,* 417–434.

Csontos, L., & Vörös, A. (2004). Mesozoic plate-tectonic reconstruction of the Carpathian region. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *210*, 1–56.

Dal Piaz, G. V., Martin, S., Villa, I. M., Gosso, G., & Marschalko, R. (1995). Late Jurassic blueschist facies pebbles from the Western Carpathian orogenic wedge and paleostructural implications for Western Tethys evolution. *Tectonics, 14,* 874–885.

Dallmeyer, R. D., Neubauer, F., & Fritz, H. (2008). The Meliata suture in the Carpathians: Regional significance and implications for the evolution of high-pressure wedges within collisional orogens. In S. Siegesmund, B. Fügenschuh, & N. Froitzheim (Eds.), *Tectonic aspects of the Alpine–Dinaride–Carpathian system* (Vol. 298, pp. 101–115). Geological Society London: Special Publication.

Dallmeyer, R. D., Neubauer, F., Handler, R., Fritz, H., Müller, W., Pana, D., et al. (1996). Tectonothermal evolution of the internal Alps and Carpathians: Evidence from $^{40}Ar/^{39}Ar$ mineral and whole-rock data. *Eclogae Geologicae Helvetiae, 89,* 203–227.

Dickinson, R. W. (1988). Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins. In K. L. Kleinspeh & C. Paola (Eds.), *New perspectives in basin analysis* (pp. 3–25). New York: Springer.

Ernst, W. G. (1988). Tectonic history of subduction zones inferred from retrograde blueschist *P–T* paths. *Geology, 16,* 1081–1084.

Faryad, S. W. (1988). Glaucophanized amphibolites and gneisses near Rudník (Gemericum). *Geologický zborník – Geologica Carpathica, 39, 6,* 747–763.

Faryad, S. W. (1995a). Phase petrology and *P–T* conditions of mafic blueschists from the Meliata unit, West Carpathians, Slovakia. *Journal of Metamorphic Geology, 13,* 701–714.

Faryad, S. W. (1995b). Petrology and phase relations of low-grade high-pressure metasediments of the Meliata Unit, Western Carpathians, Slovakia. *European Journal of Mineralogy, 7,* 71–87.

Faryad, S. W. (1998). High-pressure metamorphic rocks of the Meliata unit vs. Bôrka nappe: Their correlation with blueschist pebbles in conglomerates from the Klape unit of the Klippen Belt. *Mineralia Slovaca, 30,* 235–240. **(in Slovak with English summary)**.

Faryad, S. W. (1999). Exhumation of the Meliata high-pressure rocks (Western Carpathians): Petrological and structural records in blueschists. *Acta Montanistica Slovaca, 4,* 137–144.

Faryad, S. W., & Frank, W. (2011). Textural and age relations of polymetamorphic rocks in the HP Meliata Unit (Western Carpathians). *Journal of Asian Earth Sciences, 42,* 111–122.

Faryad, S. W., & Henjes-Kunst, F. (1997). Petrological and K–Ar and ^{40}Ar–^{39}Ar age constraints for the tectonothermal evolution of the high-pressure Meliata unit, Western Carpathians (Slovakia). *Tectonophysics, 280,* 141–156.

Faryad, S. W., & Hoinkes, G. (1999). Two contrasting mineral assemblages in the Meliata blueschists, Western Carpathians, Slovakia. *Mineralogical Magazine, 63,* 489–501.

Faryad, S. W., & Schreyer, W. (1997). Petrology and geological significance of high-pressure metamorphic rocks occurring as pebbles in the Cretaceous conglomerates of the Klippen Belt (West Carpathians, Slovakia). *European Journal of Mineralogy, 9,* 547–562.

Faryad, S. W., Spišiak, J., Horváth, P., Hovorka, D., Dianiška, I., & Józsa, S. (2005). Petrological and geochemical features of the Meliata mafic rocks from the sutured Triassic oceanic basin, Western Carpathians. *Ofioliti, 30,* 27–35.

Faupl, P., & Wagreich, M. (2000). Late Jurassic to Eocene palaeogeography and geodynamic evolution of the Eastern Alps. *Mitteilungen der Österreichischen Geologischen Gesellschaft, 92*(1999), 79–94.

Frank, W., & Schlager, W. (2006). Jurassic strike-slip versus subduction in the Eastern Alps. *International Journal of Earth Sciences, 95,* 431–450.

Frisch, W., & Gawlick, H.-J. (2003). The nappe structure of the Northern Calcareous Alps and its disintegration during Miocene tectonic extrusion—A contribution to understanding the orogenic evolution of the Eastern Alps. *International Journal of Earth Sciences, 92,* 712–727.

Froitzheim, N., Plašienka, D., & Schuster, R. (2008). Alpine tectonics of the Alps and Western Carpathians. In T. McCann (Ed.), *The Geology of Central Europe* (Vol. 2, pp. 1141–1232)., Mesozoic and Cenozoic London: Geological Society Publishing House.

Froitzheim, N., Schmid, S. M., & Frey, M. (1996). Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: A working hypothesis. *Eclogae Geologicae Helvetiae, 89,* 81–110.

Gawlick, H.-J., Aubrecht, R., Schlagintweit, F., Missoni, S., & Plašienka, D. (2015). Ophiolitic detritus in Kimmeridgian resedimented limestones and its provenance from an eroded obducted ophiolitic nappe stack south of the Northern Calcareous Alps (Austria). *Geologica Carpathica, 66,* 473–487.

Gawlick, H.-J., Frisch, W., Vecsei, A., Steiger, A., & Böhm, F. (1999). The change from rifting to thrusting in the Northern Calcareous Alps as recorded in Jurassic sediments. *Geologische Rundschau, 87,* 644–657.

Gawlick, H.-J., Havrila, M., Krystyn, L., Lein, R., & Mello, J. (2002). Conodont colour alteration indices (CAI) in the Central Western Carpathians and the Northern Calcareous Alps—A comparison. *Geologica Carpathica, 53,* 15–17.

Haas, J., Kovács, S., Krystyn, L., & Lein, R. (1995). Significance of Late Permian–Triassic facies zones in terrane reconstruction in the Alpine–North Pannonian domain. *Tectonophysics, 242,* 19–40.

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E., & Bernoulli, D. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews, 102,* 121–158.

Havrila, M. (2011). Hronicum: Palaeogeography and stratigraphy (late Pelsonian–Tuvalian), deformation and structure. *Geologické práce, Správy, 117,* 7–103. **(in Slovak with English summary)**.

Hawthorne, F. C., Oberti, R., Harlow, G. E., Maresch, W. V., Martin, R. F., Schumacher, J. C., et al. (2012). Nomenclature of the amphibole supergroup. *American Mineralogist, 97,* 2031–2048.

Henry, D. J., & Guidotti, C. V. (1985). Tourmaline as a petrogenetic indicator mineral: An example from the staurolite-grade metapelites of NW Maine. *American Mineralogist, 70,* 1–15.

Henry, D. J., Novák, M., Hawthorne, F. C., Ertl, A., Dutrow, B., Uher, P., et al. (2011). Nomenclature of the tourmaline supergroup minerals. *American Mineralogist, 96,* 895–913.

Hók, J., Kováč, P., & Rakús, M. (1995). Structural investigations of the Inner Carpathians—Results and interpretation. *Mineralia Slovaca, 27,* 231–235. **(in Slovak with English summary)**.

Hók, J., Šujan, M., & Šipka, F. (2014). Tectonic division of the Western Carpathians: An overview and a new approach. *Acta Geologica Slovaca, 6,* 135–143. **(in Slovak with English summary)**.

Hovorka, D., Ivan, P., Mock, R., Rozložník, L., & Spišiak, J. (1990). Sediments of Gosau type near the Dobšiná Ice Cave: Ideas for their non-traditional interpretation. *Mineralia Slovaca, 22,* 519–525. **(in Slovak with English summary)**.

Hurai, V., Lexa, O., Schulmann, K., Montigny, R., Prochaska, W., Frank, W., et al. (2008). Mobilization of ore fluids during Alpine metamorphism: Evidence from hydrothermal veins in the Variscan basement of Western Carpathians, Slovakia. *Geofluids, 8,* 181–207.

Hurai, V., Paquette, J.-L., Lexa, O., Konečný, P., & Dianiška, I. (2015). U–Pb–Th geochronology of monazite and zircon in albitite metasomatites of the Rožňava–Nadabula ore field (Western Carpathians, Slovakia): Implications for the origin of hydrothermal polymetallic siderite veins. *Mineralogy and Petrology, 109,* 519–530.

Ivan, P. (2002a). Relics of the Meliata Ocean crust: Geodynamic implications of mineralogical, petrological and geochemical proxies. *Geologica Carpathica, 53,* 245–256.

Ivan, P. (2002b). Relict magmatic minerals and textures in the HP/LT metamorphosed oceanic rocks of the Triassic–Jurassic Meliata Ocean (Inner Western Carpathians). *Slovak Geological Magazine, 8,* 109–122.

Ivan, P. (2007). Lithostratigraphic units of Bôrka Nappe: Their brief characteristics and possible evolution. In Ľ. Jurkovič (Ed.), *Cambelove dni 2007. Geochémia v súčasných geologických vedách* (pp. 42–48). Bratislava: Comenius University. **(in Slovak with English abstract)**.

Ivan, P., & Méres, Š. (2009). Blueschist enclave in the Dobšiná serpentinite quarry: The evidence of the relation of the ultrabasic body to the Hačava Fm. of the Bôrka nappe (Meliatic Unit, Slovakia). *Mineralia Slovaca, 41,* 409–418. **(in Slovak with English summary)**.

Ivan, P., Méres, Š., & Sýkora, M. (2009). Magnesioriebeckite in red cherts and basalts (Jaklovce Fm. of the Meliatic Unit, Western Carpathians): An indicator of initial stage of the high-pressure subduction metamorphism. *Mineralia Slovaca, 41,* 419–432. **(in Slovak with English summary)**.

Ivan, P., & Sýkora, M. (1993). Finding of glaucophane-bearing rocks in Cretaceous conglomerates from Jasenov (Krížna nappe, Eastern Slovakia). *Mineralia Slovaca, 25,* 29–33. **(in Slovak with English abstract)**.

Ivan, P., Sýkora, M., & Demko, R. (2006). Blueschists in the Cretaceous exotic conglomerates of the Klape Unit (Pieniny Klippen Belt, Western Carpathians): Their genetic types and implications for source areas. *Geologia, 32,* 47–63.

Ivanička, J., Snopko, L., Snopková, P., & Vozárová, A. (1989). Gelnica Group—Lower unit of Spišsko-gemerské rudohorie Mts. *Geologický zborník – Geologica Carpathica, 40,* 483–501.

Jablonský, J., Michalík, J., Plašienka, D., & Soták, J. (1993). Sedimentary environments of the Solírov Formation and correlation with Lower Cretaceous turbidites in Central West Carpathians, Slovakia. *Cretaceous Research, 14,* 613–621.

Jablonský, J., Sýkora, M., & Aubrecht, R. (2001). Detritic Cr-spinels in Mesozoic sedimentary rocks of the Western Carpathians (overview of the latest knowledge). *Mineralia Slovaca, 33,* 487–498. **(in Slovak with English summary)**.

Janák, M., Froitzheim, N., Lupták, B., Vrabec, M., & Ravna, E. J. K. (2004). First evidence for ultrahigh-pressure metamorphism of eclogites in Pohorje, Slovenia: Tracing deep continental subduction in the Eastern Alps. *Tectonics, 23,* TC5014.

Janák, M., Plašienka, D., Frey, M., Cosca, M., Schmidt, S Th, Lupták, B., et al. (2001). Cretaceous evolution of a metamorphic core complex, the Veporic unit, Western Carpathians (Slovakia): *P–T* conditions and in situ $^{40}Ar/^{39}Ar$ UV laser probe dating of metapelites. *Journal of Metamorphic Geology, 19,* 197–216.

Jaroš, J., Kratochvíl, M., & Zlocha, J. (1981). Mesoscopic structural analysis of serpentinite bodies in the Spišsko-gemerské rudohorie Mts. (Eastern Slovakia). *Mineralia Slovaca, 13,* 527–548. **(in Slovak with English summary)**.

Jeřábek, P., Lexa, O., Schulmann, K., & Plašienka, D. (2012). Inverse ductile thinning via lower crustal flow and fold-induced doming in the West Carpathian Eo-Alpine collisional wedge. *Tectonics, 31,* TC5002.

Kissová, D., Dunkl, I., Plašienka, D., Frisch, W., & Marschalko, R. (2005). The Pieninic exotic cordillera (Andrusov Ridge) revisited: New zircon FT ages of granite pebbles from Cretaceous conglomerates of the Pieniny Klippen Belt (Western Carpathians, Slovakia). *Slovak Geological Magazine, 11,* 17–28.

Koller, F. (1985). Petrologie und Geochemie der Ophiolite des Penninikums am Alpenostrand. *Jahrbuch der Geologischen Bundesanstalt, 128,* 83–150.

Konečný, P., Siman, P., Holický, I., Janák, M., & Kollárová, V. (2004). Methodics of monazite dating using an electron microprobe. *Mineralia Slovaca, 36,* 225–235. **(in Slovak with English summary)**.

Konzett, J., Krenn, K., Hauzenberger, Ch., Whitehouse, M., & Hoinkes, G. (2012). High-pressure tourmaline formation and fluid activity in Fe–Ti-rich eclogites from the Kreuzeck Mountains, Eastern Alps, Austria. *Journal of Petrology, 53,* 99–125.

Kovács, S., Less, Gy, Piros, O., Réti, Zs, & Róth, L. (1989). Triassic formations of the Aggtelek–Rudabánya Mountains (Northeastern Hungary). *Acta Geologica Hungarica, 32,* 31–63.

Kovács, S., Sudar, M., Grădinaru, E., Gawlick, H.-J., Karamata, S., Haas, J., et al. (2011). Triassic evolution of the tectonostratigraphic units of the Circum-Pannonian region. *Jahrbuch der Geologischen Bundesanstalt, 151,* 199–280.

Kövér, Sz, & Fodor, L. I. (2014). New constraints to the Mesozoic structural evolution of the Inner Western Carpathians achieved by metamorphic, structural and geochronological data. *Geologia Sudetica, 42,* 43–44.

Kövér, Sz, Fodor, L., Judik, K., Németh, T., Balogh, K., & Kovács, S. (2009). Deformation history and nappe stacking in Rudabánya Hills (Inner Western Carpathians) unravelled by structural geologic, metamorphic petrological and geochronological studies of Jurassic sediments. *Geodinamica Acta, 22,* 3–29.

Kövér, Sz, Fodor, L., Kovács, Z., Klötzli, U., Haas, J., Zajzon, N., et al. (2018). Late Triassic acidic volcanic clasts in different Neotethyan sedimentary mélanges: Paleogeographic and geodynamic implications. *International Journal of Earth Sciences*, *107*, 2975–2998.

Kozur, H. (1991). The evolution of the Meliata-Hallstatt ocean and its significance for the early evolution of the Eastern Alps and Western Carpathians. *Paleogeography, Palaeoclimatology, Palaeocology, 87,* 109–135.

Kozur, H., & Mock, R. (1973). Zum Alter und zur tektonischen Stellung der Meliata-Serie des Slowakischen Karstes. *Geologický Zborník – Geologica Carpathica, 24,* 365–374.

Kozur, H., & Mock, R. (1997). New paleogeographic and tectonic interpretations in the Slovakian Carpathians and their implications for correlations with the Eastern Alps and other parts of the Western Tethys. Part II: Inner Western Carpathians. *Mineralia Slovaca, 29,* 164–209.

Kurz, W., Neubauer, F., & Dachs, E. (1998). Eclogite meso- and microfabrics: Implications for the burial and exhumation history of eclogites in the Tauern Window (Eastern Alps) from P–T–d paths. *Tectonophysics, 285,* 183–209.

Lačný, A., Plašienka, D., & Vojtko, R. (2016). Structural evolution of the Turňa Unit constrained by fold and cleavage analyses and its consequences for the regional tectonic models of the Western Carpathians. *Geologica Carpathica, 67,* 177–193.

Leake, B. E., Wooley, A. R., Arps, C. E. S., Birch, W. D., Gilbert, M. C., Grice, J. D., et al. (1997). Nomenclature of amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. *Mineralogical Magazine, 61,* 295–321.

Leško, B., & Varga, I. (1980). Alpine elements in the West Carpathian structure and their significance. *Mineralia Slovaca, 12,* 97–130.

Less, Gy. (2000). Polyphase evolution of the structure of the Aggtelek-Rudabánya Mountains (NE Hungary), the southernmost element of the Inner Western Carpathians—A review. *Slovak Geological Magazine, 6,* 260–268.

Lexa, O., Schulmann, K., & Ježek, J. (2003). Cretaceous collision and indentation in the West Carpathians: View based on structural analysis and numerical modeling. *Tectonics, 22,* 1066.

Li, X.-H., Putiš, M., Yang, Y.-H., Koppa, M., & Dyda, M. (2014). Accretionary wedge harzburgite serpentinization and rodingitization constrained by perovskite U/Pb SIMS age, trace elements and Sm/Nd isotopes: Case study from the Western Carpathians, Slovakia. *Lithos, 205,* 1–14.

Maheľ, M. (1986). *Geological structure of the Western Carpathians. Part 1—Palaeoalpine units*. Bratislava: Veda Publ. **(in Slovak)**.

Maluski, H., Rajlich, P., & Matte, Ph. (1993). ^{40}Ar-^{39}Ar dating of the Inner Carpathian Variscan Basement and Alpine mylonitic overprinting. *Tectonophysics, 223,* 313–337.

Marschall, H., Ludwig, T., Altherr, R., Kalt, A., & Tonarini, S. (2006). Syros metasomatic tourmaline: Evidence for very high-$\delta^{11}B$ fluids in subduction zones. *Journal of Petrology, 47,* 1915–1942.

Mello, J. (ed.), Elečko, M., Pristaš, J., Reichwalder, P., Snopko, L., Vass, D., Vozárová, A., et al. (1997). *Explanations to the geological map of the Slovenský kras Mts 1:50,000*. Bratislava: Vydavateľstvo Dionýza Štúra **(in Slovak with English summary)**.

Mello, J., Ivanička, J., Grecula, P., Janočko, J., Jacko, S., Elečko, M., et al. (2008). *General Geological Map of Slovak Republic (1:200 000), map sheet: 37—Košice*. Bratislava: State Geol. Inst. of Dionýz Štúr.

Mello, J., Reichwalder, P., & Vozárová, A. (1998). Bôrka nappe: High-pressure relic from the subduction–accretion prism of the Meliata ocean (Inner Western Carpathians, Slovakia). *Slovak Geological Magazine, 4,* 261–273.

Michalík, J. (1994). Lower Cretaceous carbonate platform facies, Western Carpathians. *Palaeogeography, Palaeoclimatology, Palaeoecology, 111,* 263–277.

Michalík, J., & Soták, J. (1990). Lower Cretaceous shallow marine buildups in the Western Carpathians and their relationship to pelagic facies. *Cretaceous Research, 11,* 211–227.

Mišík, M. (1979). Pieniny Klippen Belt and the global tectonics model. In M. Maheľ & P. Reichwalder (Eds.), *Czechoslovak geology and global tectonics* (pp. 89–101). Bratislava: Veda Publ.

Mišík, M. (1990). Urgonian facies in the West Carpathians. *Knihovnička Zemního plynu a nafty, 9a,* 25–54.

Mišík, M., Jablonský, J., Fejdi, P., & Sýkora, M. (1980). Chromian and ferrian spinels from Cretaceous sediments of the West Carpathians. *Mineralia Slovaca, 12,* 209–228.

Mišík, M., Jablonský, J., Mock, R., & Sýkora, M. (1981). Konglomerate mit exotischen Material in dem Alb der Zentralen Westkarpaten—Paläogeographische und tektonische Interpretation. *Acta Geologica et Geographica Universitatis Comenianae, Geologica, 37,* 5–55.

Mišík, M., & Marschalko, R. (1988). Exotic conglomerates in flysch sequences: Examples from the West Carpathians. In M. Rakús, J.

Dercourt & A. E. M. Nairn (Eds.), *Evolution of the northern margin of Tethys. Mém. Soc. Géol. France, Nouvelle Série* (Vol. I, No. 154, pp. 95–113). Paris: Société Géologique de France.

Mišík, M., & Sýkora, M. (1981). Der pieninische exotische Rücken, rekonstruiert aus Geröllen karbonatischer Gesteine kretazischer Konglomerate der Klippenzone und der Manín-Einheit. *Západné Karpaty, sér. geológia, 7,* 7–111. **(in Slovak with German summary)**.

Missoni, S., & Gawlick, H.-J. (2011). Evidence for Jurassic subduction from the Northern Calcareous Alps (Berchtesgaden Alps; Austroalpine, Germany). *International Journal of Earth Sciences, 100,* 1605–1631.

Mock, R., Sýkora, M., Aubrecht, R., Ožvoldová, L., Kronome, B., Reichwalder, P., et al. (1998). Petrology and stratigraphy of the Meliaticum near the Meliata and Jaklovce Villages, Slovakia. *Slovak Geological Magazine, 4,* 223–260.

Montel, J. M., Foret, S., Veschambre, M., Nicollet, C., & Provost, A. (1996). Electron microprobe dating of monazite. *Chemical Geology, 131,* 37–53.

Morimoto, N., Fabries, J., Ferguson, A. K., Ginzburg, I. V., Ross, M., Seifeit, F. A., et al. (1989). Nomenclature of pyroxenes. *Canadian Mineralogist, 27,* 143–156.

Morton, A. C. (1984). Stability of heavy minerals in Tertiary sandstones from the North Sea Basin. *Clay Minerals, 19,* 287–308.

Nagel, T. J., Herwartz, D., Rexroth, S., Münker, C., Froitzheim, N., & Kurz, W. (2013). Lu–Hf dating, petrography, and tectonic implications of the youngest Alpine eclogites (Tauern Window, Austria). *Lithos, 170–171,* 179–190.

Nagy, G., Draganits, E., Demény, A., Pantó, G., & Árkai, P. (2002). Genesis and transformations of monazite, florencite and rhabdophane during medium grade metamorphism: Examples from the Sopron Hills, Eastern Alps. *Chemical Geology, 191,* 25–46.

Németh, Z., & Radvanec, M. (2014). Alpine nappe transport of the high-pressure exhumed blocks from the Meliatic oceanic realm collision zone over Gemericum (Inner Western Carpathians). *Geologia Sudetica, 42,* 65–66.

Németh, Z., Radvanec, M., Kobulský, J., Gazdačko, Ľ., Putiš, M., & Zákršmídová, B. (2012). Allochthonous position of the Meliaticum in the North-Gemeric zone (Inner Western Carpathians) as demonstrated by paleopiezometric data. *Mineralia Slovaca, 44,* 57–64.

Neubauer, F. (1994). *Kontinentkollision in den Ostalpen. Geowissenschaften, 12,* 136–140.

Neubauer, F., Genser, J., & Handler, R. (2000). The Eastern Alps: Result of a two-stage collision process. *Mitteilungen der Österreichischen Geologischen Gesellschaft, 92*(1999), 117–134.

Pettijohn, F. J. (1941). Persistence of heavy minerals and geologic age. *Journal of Geology, 49,* 610–625.

Pettijohn, F. J. (1975). *Sedimentary rocks* (3rd ed.). New York: Harper & Row Publisher.

Plašienka, D. (1991). Mesozoic tectonic evolution of the epi-Variscan continental crust of the Western Carpathians—A tentative model. *Mineralia Slovaca, 23,* 447–457.

Plašienka, D. (1995a). Passive and active margin history of the northern Tatricum (Western Carpathians, Slovakia). *Geologische Rundschau, 84,* 748–760.

Plašienka, D. (1995b). Mesozoic evolution of Tatric units in the Malé Karpaty and Považský Inovec Mts.: Implications for the position of the Klape and related units in western Slovakia. *Geologica Carpathica, 46,* 101–112.

Plašienka, D. (1997). Cretaceous tectonochronology of the Central Western Carpathians (Slovakia). *Geologica Carpathica, 48,* 99–111.

Plašienka, D. (1998). Paleotectonic evolution of the Central Western Carpathians during the Jurassic and Cretaceous. In M. Rakús (Ed.), *Geodynamic development of the Western Carpathians* (pp. 107–130). Bratislava: Geol. Surv. Slov. Rep., D. Štúr Publ.

Plašienka, D. (2003). Development of basement-involved fold and thrust structures exemplified by the Tatric–Fatric–Veporic nappe system of the Western Carpathians. *Geodinamica Acta, 16,* 21–38.

Plašienka, D. (2012). Jurassic syn-rift and Cretaceous syn-orogenic, coarse-grained deposits related to opening and closure of the Vahic (South Penninic) Ocean in the Western Carpathians—an overview. *Geological Quarterly*, *56*, 601–628.

Plašienka, D. (2018). Continuity and episodicity in the early Alpine tectonic evolution of the Western Carpathians: How large-scale processes are expressed by the orogenic architecture and rock record data. *Tectonics, 37,* 2029–2079.

Plašienka, D., Grecula, P., Putiš, M., Kováč, M., & Hovorka, D. (1997). Evolution and structure of the Western Carpathians: An overview. In P. Grecula, D. Hovorka, & M. Putiš (Eds.), *Geological evolution of the Western Carpathians* (pp. 1–24i). Monograph: Mineralia Slovaca.

Plašienka, D., Jeřábek, P., Vojtko, R., Králiková, S., Janák, M., Ivan, P., et al. (2016). *Alpine structural and metamorphic evolution during burial and exhumation of the Veporic basement and cover complexes*. Bratislava: Comenius University Press.

Plašienka, D., & Soták, J. (2015). Evolution of Late Cretaceous–Palaeogene synorogenic basins in the Pieniny Klippen Belt and adjacent zones (Western Carpathians, Slovakia): Tectonic controls over a growing orogenic wedge. *Annales Societatis Geologorum Poloniae, 85,* 43–76.

Platt, J. P. (1986). Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *Geological Society of America Bulletin, 97,* 1037–1053.

Platt, J. P. (1993). Exhumation of high-pressure rocks: A review of concepts and processes. *Terra Nova, 5,* 119–133.

Pleuger, J., Roller, S., Walter, J. M., Jansen, E., & Froitzheim, N. (2007). Structural evolution of the contact between two Penninic nappes (Zermatt-Saas zone and Combin zone, Western Alps) and implications for the exhumation mechanism and palaeogeography. *International Journal of Earth Sciences, 96,* 229–252.

Pouchou, J. L., & Pichoir, F. (1985). "PAP" (φpZ) procedure for improved quantitative microanalysis. In J. T. Armstrong (Ed.), *Microbeam analysis* (pp. 104–106). San Francisco: San Francisco Press.

Prokešová, R., Plašienka, D., & Milovský, R. (2012). Structural pattern and emplacement mechanisms of the Krížna cover nappe (Western Carpathians, Slovakia). *Geologica Carpathica, 63,* 13–32.

Putiš, M., Danišík, M., Ružička, P., & Schmiedt, I. (2014). Constraining exhumation pathway in accretionary wedge by (U–Th)/He thermochronology—Case study on Meliatic nappes in the Western Carpathians. *Journal of Geodynamics, 81,* 80–90.

Putiš, M., Radvanec, M., Sergeev, S., Koller, F., Michálek, M., Snárska, B., et al. (2011a). Metamorphosed succession of cherty shales with basalt and diastrophic breccia in olistolith of the Meliatic Jurassic accretion wedge near Jaklovce (Slovakia), dated on zircon (U–Pb SIMS SHRIMP). *Mineralia Slovaca, 43,* 1–18. **(in Slovak with English summary)**.

Putiš, M., Radvanec, M., Sergeev, S., Koller, F., Michálek, M., Snárska, B., et al. (2011b). The blueschist-associated perovskite–andradite-bearing serpentinized harzburgite from Dobšiná (the Meliata Unit), Slovakia. *Journal of Geosciences, 57,* 221–240.

Putiš, M., Yang, Y.-H., Koppa, M., Dyda, M., & Šmál, P. (2015). U/Pb LA–ICP–MS age of metamorphic-metasomatic perovskite from serpentinized harzburgite in the Meliata Unit at Dobšiná, Slovakia: Time constraints of fluid–rock interaction in an accretionary wedge. *Acta Geologica Slovaca, 7,* 63–71.

Rakús, M. (1996). Jurassic of the innermost Western Carpathians zones—Its importance and influence on the geodynamic evolution of the area. *Slovak Geological Magazine, 3–4*(96), 311–317.

Rakús, M., & Sýkora, M. (2001). Jurassic of Silicicum. *Slovak Geological Magazine, 7,* 53–84.

Ratschbacher, L., Behrmann, J. H., & Pahr, A. (1990). Penninic windows at the eastern end of the Alps and their relation to the intra-Carpathian basins. *Tectonophysics, 172,* 91–105.

Reichwalder, P. (1970). Some notes on occurrences of glaucophanite rocks near Hačava. *Geologické práce, Správy, 53,* 157–165. **(in Slovak with English summary)**.

Reichwalder, P. (1982). Structural characteristic of root zones of some nappes in innermost parts of West Carpathians. In M. Mahel' (Ed.), *Alpine structural elements: Carpathian–Balkan–Caucasus–Pamir orogene zone* (pp. 43–56). Bratislava: Veda Publ.

Schmid, S. M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., et al. (2008). The Alpine–Carpathian–Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss Journal of Geosciences, 101,* 139–183.

Schmid, S. M., Fügenschuh, B., Kissling, E., & Schuster, R. (2004). Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae, 97,* 93–117.

Schroeder, R., van Buchem, F. S. P., Cherchi, A., Baghbani, D., Vincent, B., Immenhauser, A., et al. (2010). Revised orbitolinid biostratigraphic zonation for the Barremian—Aptian of the eastern Arabian Plate and implications for regional stratigraphic correlations. *GeoArabia Special Publication, 4*(1), 49–96.

Šímová, M. (1982). Eclogitoid rock in pebbles of Cretaceous conglomerates of Klippen Belt. *Geologické práce, Správy, 77,* 55–74. **(in Slovak with English summary)**.

Šímová, M. (1985). Magmatogene Gesteine kretazischer Konglomerate des westlichen Teiles der Klippen- und Manín-Zone der Westkarpaten. *Západné Karpaty, sér. Mineralógia, petrografia, geochémia, metalogenéza, 10,* 9–110. **(in Slovak with German summary)**.

Šímová, M., & Šamajová, E. (1982). Lawsonite from rock pebbles in the Cretaceous conglomerate of the Pieniny Klippen Belt. *Mineralia Slovaca, 14,* 431–441. **(in Slovak with English summary)**.

Stampfli, G. M., & Borel, G. D. (2002). A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restores synthetic oceanic isochrones. *Earth and Planetary Science Letters, 196,* 17–33.

Stampfli, G., & Hochard, C. (2009). Plate tectonics of the Alpine realm. In J. B. Murphy, J. D. Keppie, & A. J. Hynes (Eds.), *Ancient orogens and modern analogues* (Vol. 327, pp. 89–111)., Special Publication London: Geological Society.

Stampfli, G., & Kozur, H. (2006). Europe from the Variscan to the Alpine cycles. In D. G. Gee & R. A. Stephenson (Eds.), *European lithosphere dynamics* (Vol. 32, pp. 57–82)., Memoirs London: Geological Society.

Stüwe, K., & Schuster, R. (2010). Initiation of subduction in the Alps: Continent or ocean? *Geology, 38,* 175–178.

Sýkora, M., Halásová, E., & Boorová, D. (1997). Blue amphiboles and microfossils from the Mesozoic basement of the Vienna Basin (borehole Smolinské 27), Slovakia. *Mineralia Slovaca, 29,* 227–233.

Sýkora, M., & Ožvoldová, L. (1996). Lithoclasts of Middle Jurassic radiolarites in debris flow sediments from Silica Nappe (locality Bleskový prameň, Slovak Karst, Western Carpathians. *Mineralia Slovaca, 28,* 21–25.

Thöni, M., & Jagoutz, E. (1993). Isotopic constraints for eo-Alpine high-P metamorphism in the Austroalpine nappes of the Eastern Alps: Bearing on Alpine orogenesis. *Schweizerische Mineralogische und Petrographische Mitteilungen, 73,* 177–189.

Vilas, L., Masse, J. P., & Arias, C. (1995). *Orbitolina* episodes in carbonate platform evolution: The early Aptian model from SE Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology, 119,* 35–45.

Vojtko, R., Králiková, S., Jeřábek, P., Schuster, R., Danišík, M., Fügenschuh, B., et al. (2016). Geochronological evidence for the Alpine tectono-thermal evolution of the Veporic Unit (Western Carpathians, Slovakia). *Tectonophysics, 666,* 48–65.

Von Eynatten, H., & Gaupp, R. (1999). Provenance of Cretaceous synorogenic sandstones in the Eastern Alps: Constraints from framework petrography, heavy mineral analysis and mineral chemistry. *Sedimentary Geology, 124,* 81–111.

Vozárová, A. (1996). Tectono-sedimentary evolution of late Paleozoic basins based on interpretation of lithostratigraphic data (Western Carpathians, Slovakia). *Slovak Geological Magazine, 3–4*(96), 251–271.

Vozárová, A., Konečný, P., Šarinová, K., & Vozár, J. (2014). Ordovician and Cretaceous tectonothermal history of the Southern Gemericum Unit from microprobe monazite geochronology (Western Carpathians, Slovakia). *International Journal of Earth Sciences, 103,* 1005–1022.

Vozárová, A., Konečný, P., Vozár, J., & Šmelko, M. (2008). Upper Jurassic–Lower Cretaceous tectonothermal events in the Southern Gemeric Permian rocks deduced from electron microprobe dating of monazite (Western Carpathians, Slovakia). *Geologica Carpathica, 59*(2), 89–102.

Vozárová, A., Šmelko, M., Paderin, I., & Larionov, A. (2012). Permian volcanics in the Northern Gemericum and Bôrka Nappe system: U–Pb zircon dating and the implications for geodynamic evolution (Western Carpathians, Slovakia). *Geologica Carpathica, 63,* 191–200.

Vozárová, A., & Vozár, J. (1988). *Late Paleozoic in West Carpathians*. Bratislava: Geol. Inst. D. Štúr.

Vozárová, A., & Vozár, J. (1992). Tornaicum and Meliaticum in borehole Brusník BRU-1, Southern Slovakia. *Acta Geologica Hungarica*, *35*(2), 97–116.

Wagreich, M., Faupl, P., & Schlagintweit, F. (1995). Heavy minerals from Urgonian pebbles of the Northern Calcareous Alps (Austria, Bavaria): Further evidence for an intra-Austroalpine suture zone. *Geologica Carpathica, 46,* 197–204.

Wagreich, M., & Marschalko, R. (1995). Late Cretaceous to Early Tertiary palaeogeography of the Western Carpathians (Slovakia) and the Eastern Alps (Austria): Implications from heavy mineral data. *Geologische Rundschau, 84,* 187–199.

Waśkowska, A. (2014). Selective agglutination of tourmaline grains by foraminifera in a deep-water flysch environment (Eocene Hieroglyphic Beds, Silesian Nappe, Polish Outer Carpathians). *Geological Quarterly, 58,* 337–352.

Weber, S., Sandmann, S., Miladinova, I., Fonseca, R. O. C., Froitzheim, N., Münker, C., et al. (2015). Dating the initiation of Piemonte-Liguria Ocean subduction: Lu–Hf garnet chronometry of eclogites from the Theodul Glacier Unit (Zermatt-Saas zone, Switzerland). *Swiss Journal of Geosciences, 108,* 183–199.

Whitney, D. L., Bernard, W., & Evans, B. W. (2010). Abbreviations for names of rock-forming minerals. *American Mineralogist, 95,* 185–187.

Winkler, W. (1996). The tectono-metamorphic evolution of the Cretaceous northern Adriatic margin as recorded by sedimentary series (western part of the Eastern Alps). *Eclogae Geologicae Helvetiae, 89,* 527–551.