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Tectonothermal history of the basement rocks within the NW Dinarides: new $^{40}Ar/^{39}Ar$ ages and synthesis

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Abstract: Very low-grade and low-grade metamorphosed basement rocks from distinct inliers of the Africa-derived northwestern Dinarides (Medvednica Mts and Paleozoic Sana-Una Unit, respectively) have been studied with the multi-grain step-heating $^{40}Ar/^{39}Ar$ technique in order to compare and reveal their tectonothermal history. $^{40}Ar/^{39}Ar$ ages from detrital white mica of the very low-grade basement rocks of the Paleozoic Sana-Una Unit gave a Variscan age of ~335 Ma. The new age is in agreement with $^{40}Ar/^{39}Ar$ ages from the very low-grade basement exposed at Petrova and Trgovska Gora of the NW Dinarides. Within low-grade metamorphic basement rocks from the Medvednica Mts, we found no Variscan ages. White mica from phyllitic basement rocks of the Medvednica Mts gives predominantly early Alpine ages ranging between 135 and 122 Ma and younger Alpine ages of ~80 Ma. The early Alpine ages of 135 and 122 Ma are interpreted as the date to the onset of ductile nappe stacking predating the formation of Gosau-type collapse basins. The late early Alpine event of ~80 Ma can be traced in the entire Cretaceous-aged orogen of the Circum-Pannonian Region and is synchronous with subsidence of the Gosau-type basins and opening and closure of the neighbouring Sava-Vardar Zone.

Key words: Cretaceous overprint, Variscan, Dinarides, basement, nappe stacking.

Introduction

Geotectonic models of the southwestern branch of the Circum-Pannonian Region largely resulted in explanation of the Early to Late Cretaceous orogeny by collision of continental units exposed after the consumption of the Maliac, Meliata and Vardar oceans throughout Jurassic, Cretaceous and Cenozoic times (e.g. Pamić et al. 1998; Neugebauer et al. 2001; Neubauer 2002; Stampfli et al. 2002; Schmid et al. 2008; Ustaszewski et al. 2009 and references therein). In those models, the Dinarides together with Apulia are predominantly regarded as a stiff backbone without considering their internal deformation. The purpose of this study is to improve our understanding of the tectonothermal evolution of the basement units within the NW Dinarides.

The Dinarides are a Mesozoic to Recent SW-vergent fold-and-thrust belt that extends from the Southern Alps in the NW to the Hellenides in the SE. The Paleozoic basement units of the Dinarides can generally be subdivided, on the basis of their internal deformation and metamorphic state, into: i) low-grade metamorphosed, and ii) very low-grade metamorphosed units (e.g. Pamić & Jurković 2002 and references therein). Low-grade metamorphosed basement units, such as the Drina-Ivanjica, Jadar, Mid-Bosnian Schist Mts, Medvednica Mts reveal widespread Alpine metamorphism (based on K/Ar mineral and whole rock ages; Milovanović 1984; Belak et al. 1995a,b; Palinkaš et al. 1996; Pamić et al. 2004; Judik et al. 2006), whereas very low-grade metamorphosed Paleozoic units of the northwestern Dinarides (Petrova and Trgovska Gora) yielded Variscan ages and an Early Permian overprint ($^{40}Ar/^{39}Ar$ ages; Borojević Šoštarić et al. 2009). What we can extract from the above mentioned literature, is that low-grade metamorphosed units underwent a single-stage Alpine metamorphism with an age range of 139–129 Ma, 121–95 Ma and 122–110 Ma in the Drina-Ivanjica, Mid-Bosnian Schist Mts and Medvednica Mts, respectively. However, Tomljenović & Csontos (2001) recognized several deformational stages in the Medvednica Mts. Here, we performed precise $^{40}Ar/^{39}Ar$ dating in order to find an appropriate age relationship between, as well as the timing of different stages of deformation.

We here report new $^{40}Ar/^{39}Ar$ ages of the (i) low-grade metamorphosed basement units of the Medvednica Mts (NW Dinaride junction, i.e. Zagorje Mid-Transdanubian Zone), and from (ii) the very low-grade metamorphosed Paleozoic Sana-Una Unit (NW Dinarides) (Fig. 1). We use an approach combining microfabric observations with the $^{40}Ar/^{39}Ar$ white mica dating. These new ages will help to resolve the stepwise, long-lasting shortening and accretion history of the Dinarides, and shed new light on the distinction between Variscan and Alpine tectonothermal events in the low-grade and very low-grade metamorphosed basement units of the Dinarides. In order to present general conclusions and models, the new data are coupled with published $^{40}Ar/^{39}Ar$ white mica ages from Borojević Šoštarić et al. (2009).

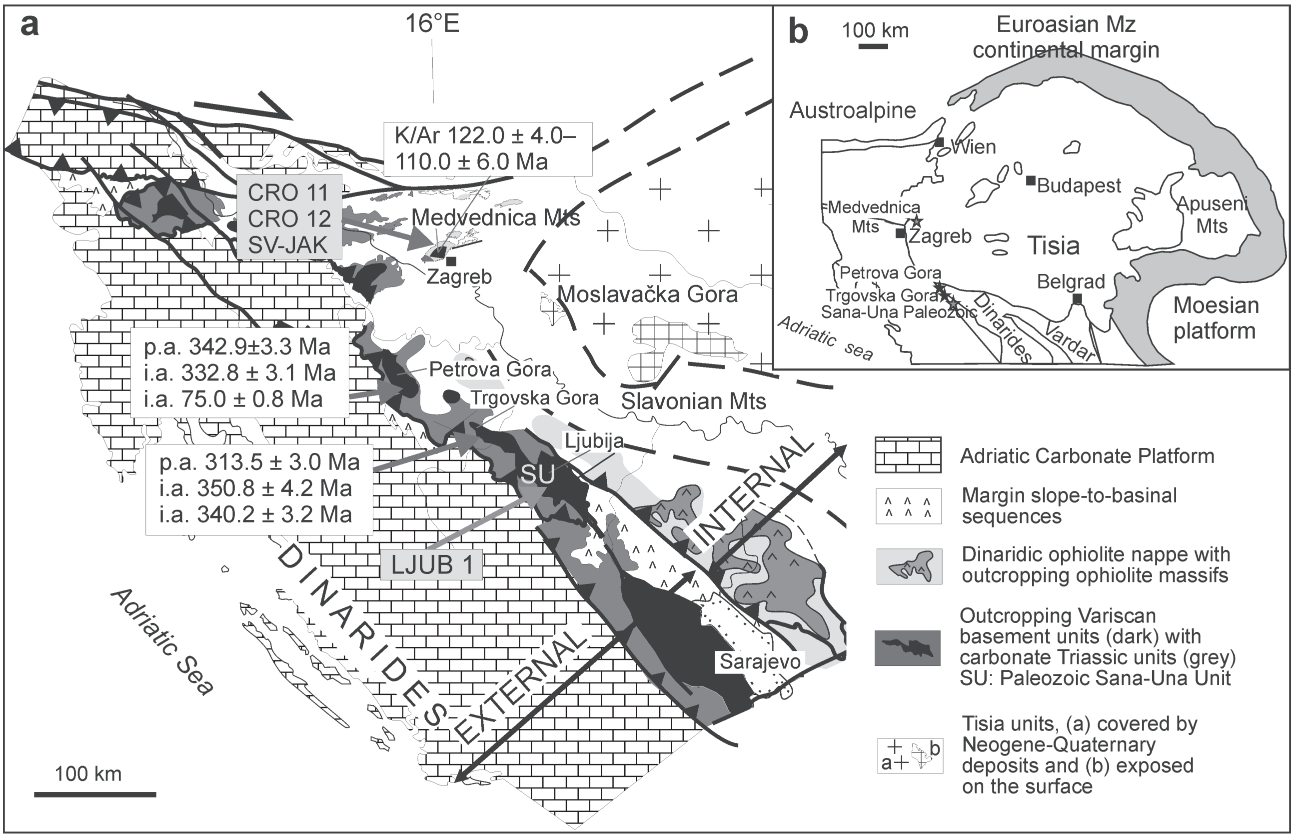

Fig. 1. a — Overview of the major tectonic units of the Alpine-Balkan-Carpathian-Dinaride orogen, with the location of the Medvednica Mts and Sana-Una basement units (grey background), and the locations of Petrova and Trgovska Gora basement units (white background). **b** — Simplified geological map of the Alpine-Carpathian-Dinaridic orogen with the positions of the investigated basement unit. Modified after Pamić et al. (1998), Schmid et al. (1998), Willingshofer (2000) and Tomljenović (2002).

Regional geological setting

The Dinarides are divided into a number of tectonic units, which include external and internal sectors and are exposed from the Adriatic Sea units towards the NE up to the adjoining Tisia Mega-tectonic Unit (the zonation follows those of reviews by Pamić et al. 1998, and Dimitrijević 1982, 1997; Fig. 1a,b). The Adriatic Carbonate Platform and its correlatives, together with the East Bosnian-Durmitor Zone constitute the External Dinarides, while the Dinaric Ophiolite nappe and the Sava-Vardar Zone represent units of the Internal Dinarides. Equally, the Internal and External Dinarides contain exposed Paleozoic basement units with various degrees of metamorphism, mainly up to greenschist, in some cases up to epidote-amphibolite facies conditions (for overview see Pamić & Jurković 2002). The Paleozoic basement units are composed of Ordovician to Carboniferous (Permian) meta-sedimentary rocks (dominantly Carboniferous turbiditic flysch sandstones and shales and Permian molasse-type deposits) and meta-volcanics overlain by a mainly Triassic carbonate-clastic cover. The degree of metamorphism increases from the northwest towards the southeast. Very low-grade metamorphism is found in the northwestermost part of the Dinarides (Petrova and Trgovska Gora) whereas low- and medium-grade metamorphism is established in the central and southeastern parts (Sana-Una, Drina-Ivanjica, Jadar, Mid-Bosnian Schist Mts; Podubsky & Pamić 1967; Podubsky 1968; Majer et al. 1991).

Further to the north-west, between the Periadriatic-Balaton and the Zagreb-Zemplín faults, heterogeneous units are juxtaposed, forming the NW Dinaride junction, namely the Zagorje-Mid-Transdanubian Zone (ZMTZ, according to Pamić & Tomljenović 1998) or the Sava Composite Unit (according to Haas et al. 2000). This complex zone comprises deformed blocks of the Internal and External Dinarides and of South Alpine units, and can be traced over several hundred km from the NW Dinarides to NE Hungary (Haas & Kovács 2001). The Medvednica Mts, as a part of ZMTZ, encloses low-grade and high-pressure Paleozoic metamorphic rocks (Belak & Tibljaš 1998).

Previous geochronological studies of the basement units

Various Paleozoic basement units of the northwestern Dinarides show different ages of metamorphism; Variscan (Carboniferous), eo-Alpine (Cretaceous) or Meso-Alpine (Eocene). Previous K-Ar ages from Mid-Bosnian Schist Mts show two age groups, namely 159–92 Ma and 50–37 Ma

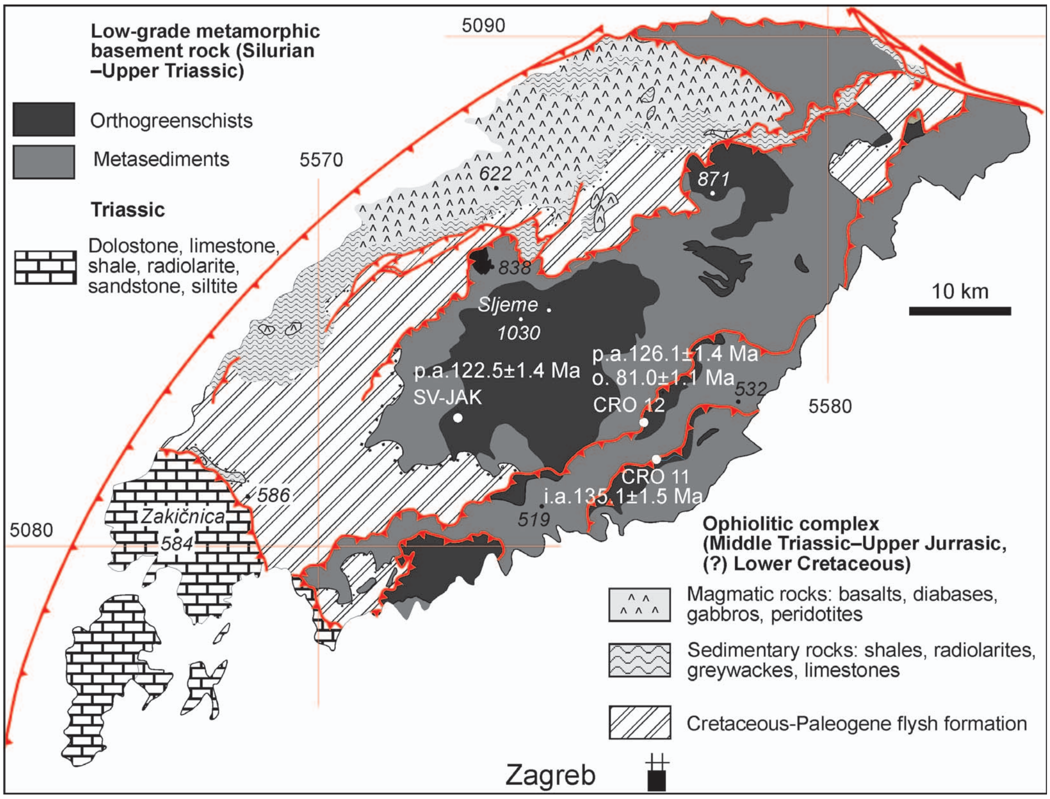

Fig. 2. Simplified tectonic map of the Medvednica Mts, showing sample localities and age of the $^{40}Ar/^{39}Ar$ dating, modified after Tomljenović (2002). Abbreviations: **i.a.** — integrated age, **p.a.** — plateau age, **o** — age of low-temperature overprint.

(Palinkaš et al. 1996; Pamić & Jurković 2002; Pamić et al. 2004). Low-grade metamorphic Paleozoic basement rocks of the Medvenica Mts show ductile deformation and an Early Cretaceous metamorphic overprint dated at 122 to 110 Ma (Belak et al. 1995a,b; Judik et al. 2006). $^{40}Ar/^{39}Ar$ dating of the Paleozoic Lim Unit (East Bosnian-Durmitor Zone, an Upper Carboniferous molasse-type foreland basin, Figs. 1, 2) gave ages at 84–78 Ma and an overprint at ca. 52 Ma, essentially showing that the older age group is younger than previously considered (Ilić et al. 2003). Ilić et al. (2005) reported detrital white mica ages from the Upper Carboniferous molasse of the Paleozoic Lim (East Bosnian-Durmitor Zone) showing the dominance of a Variscan metamorphic hinterland during the post-Variscan history. Detrital white mica from Lower Permian sandstones and Carboniferous shales adjacent to siderite-polysulphide veins of the Petrova Gora Paleozoic basement shows Variscan $^{40}Ar/^{39}Ar$ plateau ages at 342.9 ± 3.3 Ma and 332.8 ± 3.1 Ma, respectively, and are overprinted by a thermal event at ca. 265.6 ± 6.2 to 274.2 ± 3.1 Ma (Borojević Šoštarić et al. 2009). A single sample of fine-grained sericite within the tectonic breccia yielded a Late Cretaceous age (75.0 ± 0.8 Ma; Borojević Šoštarić et al. 2009). Detrital white mica from Devonian–Carboniferous flysch-like units of the Trgovska Gora Paleozoic basement shows Variscan $^{40}Ar/^{39}Ar$ ages, ranging from 353.8 ± 4.2 (?408.6 ± 3.8) to 313.5 ± 3.0 Ma. Two thermal overprints are recorded; one at 298.0 ± 4.2 Ma which is interpreted as the maximum age of hydrothermal activity, and one at 192.9 ± 7.2 Ma which is interpreted as a thermal record of Triassic advanced rifting/opening events (Borojević Šoštarić et al. 2009).

Local geological setting

Medvednica Mts, Zagorje-Mid-Transdanubian Zone

In northwestern Croatia, the Zagorje-Mid-Transdanubian Zone can be traced for about 120 km (Fig. 1a,b). The westernmost boundary of the Zagorje-Mid-Transdanubian Zone terminates within Dinaridic units and the system of Sava and Julian-Savinja nappes. Morphologically, it is characterized by a few isolated, around 1,000 m high mountains, including the Medvednica Mts, composed of pre-Neogene tectonostratigraphic units, that crop out within the Neogene and Quaternary fill of the Pannonian Basin.

The Medvednica Mts are situated in the northwestern part of the Zagorje-Mid-Transdanubian Zone (ZMTZ), as a result of Cenozoic extrusion tectonics (Pamić & Tomljenović 1998; Haas et al. 2000; Haas & Kovacs 2001; Tomljenović & Csontos 2001; Tomljenović 2002). It comprises four main tectonostratigraphic units (Fig. 2; Tomljenović 2002): (1) Paleozoic-Mesozoic magmatic-sedimentary complex metamorphosed during the Early Cretaceous; (2) Jurassic tectonized ophiolitic mélange; (3) a very low-grade Permian to Triassic sequence of the Žumberak-Medvednica nappe composed mainly of carbonate platform facies and clastites, and (4) Upper Cretaceous-Paleocene sedimentary sequences (Tomljenović 2002). The post-tectonic Upper Cretaceous-Paleogene sedimentary succession covering units (1) to (3) is considered to be similar to the Gosau formations of the Austroalpine units in the Eastern Alps.

The Paleozoic-Mesozoic magmatic-sedimentary complex is composed of siliciclastic and carbonate rocks (metagreywackes, quartz-muscovite schists, phyllites, slates, metacarbonates, marbles) interlayered with basic lava, tuffs and diabase sills. Biostratigraphic data, conodonts and graptolite assemblages of the protolith sediments indicate a Silurian to Late Triassic age (Đurđanović 1968; Šikić et al. 1979; Sremac & Mihajlović-Pavlović 1983). Meta-sediments are characterized by a syn-metamorphic foliation and lineation, generally parallel to the earlier bedding, penetrative on a micro- and macro-scale (Tomljenović 2002). K/Ar ages obtained from six muscovite fractions from para-greenschists and ortho-greenschists gave Early Cretaceous (122–110 Ma) ages, which are considered to represent an early Alpine (Cretaceous) metamorphic overprint (Belak et al. 1995a). Judik et al. (2004) distinguished a high-temperature (350–400 °C) medium-pressure (3–4 kbar) metamorphic event. The authors argue that the present tectonic framework of the Medvednica Mts can be explained by "transported metamorphism", and suggest a polyphase deformation history.

The tectonized ophiolite mélange is a chaotic assemblage composed of various ophiolite members, mainly basalt, gabbro, serpentinite and diabase, greywacke, radiolarite, and exotic limestone fragments within a silty-shaly matrix (Pamić & Tomljenović 1998; Babić et al. 2002). Radiolarite biostratigraphy provides Middle to Late Triassic and Middle Jurassic ages (Halamić & Goričan 1995; Halamić et al. 1999). The Lower to Middle Jurassic shaly-silty matrix of the mélange originated in the subduction and/or accretion processes related to the closure of the Meliata and Dinaridic oceanic basins between Middle Jurassic and Early Cretaceous times (Babić et al. 2002). Pamić & Pécskay (1996) reported Late Cretaceous K/Ar ages of 94.3 and 85.4 Ma from basalt and diabase from the northwestern side of the Medvednica Mountains. The Upper Cretaceous-Paleocene flysch unit uncomformably overlies both the Paleozoic-Mesozoic metamorphic complex and the ophiolitic mélange, and was interpreted by previous researchers as a transgressive shallow water to basinal sequence. The entire succession was first described by Gorjanović-Kramberger (1908), and is considered to be similar to the Gosau-type basins of the Austroalpine domain of the Eastern Alps and Western Carpathians (e.g. Faupl et al. 1987; Willingshofer et al. 1999). The lower portion of the Medvednica Mts flysch basin is composed of conglomerates, sandstones, siltites and laminated shales grading into semi-pelagic Scaglia type micrite. All three described units are overthrusted in the southwestern part of the Medvednica Mts by the highest structural unit, the Triassic succession. The matrix of the tectonized ophiolite mélange together with the Upper Cretaceous-Paleocene flysch units underwent diagenesis and very low-grade metamorphism at temperatures of 100–240 °C based on vitrinite reflection (Judik et al. 2008).

Paleozoic Sana-Una Unit, NW Dinarides

The Banovina-Kordun (*Petrova Gora*) and Paleozoic Sana-Una (*Trgovska Gora*, *Ljubija siderite body*) Units represent the northwestern-most part of the Paleozoic formations of the south-vergent Internal Dinarides, that are paleogeographically related to Apulia and Africa. The final incorporation into the present-day position took place during the Neogene, after polyphase tectonic evolution that lasted from Late Jurassic/Early Cretaceous to Eocene times (Jurković & Pamić 2001). The lower parts of these units are composed of Lower–Middle Carboniferous flysch-type sediments (Fig. 3). During Late Carboniferous–Early Permian times, shallowing of the sedimentary basin evolved into a dry land-phase followed by deposition of fine- to coarse-grained quartz-sandstones and of quartz-conglomerates. The onset of the new sedimentation cycle is interpreted as a possible boundary between the Variscan and post-Variscan tectonic and metallogenic events (Palinkaš et al. 2008). Formations of the Paleozoic Banovina-Kordun Unit were interpreted as very low-grade sedimentary sequences (Majer 1964) while the Paleozoic Sana-Una Unit were metamorphosed under low- and very low-grade P-T metamorphic conditions (Podubsky & Pamić 1967; Podubsky 1968).

The central part of the Paleozoic Sana-Una Unit, in the Ljubija siderite open pit, consists of two sequences separated by a pronounced tectonic and erosional discordance. An older, Upper Devonian to Middle Carboniferous sequence is dominated by a paleontologically well documented Carboniferous flysch composed of metasandstones, metasiltstones, dark grey phyllite and metapelites with intercalations of limestones and metavolcanics (Podubsky & Pamić 1967; Podubsky 1968; Đurđanović 1973; Jurić 1979). Recently, Grubić et al. (2000) found remnants of trilobites and palynological material within this sequence, which is interpreted to be Carboniferous in age. Underlying Upper Devonian sequences are subordinate and consist mostly of limestone and sporadically some coarse-grained quartz-sandstone (Jurić 1979). The Devonian to Carboniferous sequence contains widespread siderite mineralizations. The overlying sequence, Late Permian to Triassic in age, starts with clastic sediments, which are composed of quartzose sandstones and conglomerates and continues to typical cavernous and weathered dolomites, such as rauhwackes. Due to the lack of any organic remains, a Late Permian age of these deposits was determined on the basis of superposition with adjoining Dinaric Paleozoic units. These deposits continue, without a break, into paleontologically well defined lowermost Scythian clastic and carbonate shallow water formations.

$^{40}Ar/^{39}Ar$ analytical techniques

The preparation of the samples before and after irradiation, $^{40}Ar/^{39}Ar$ analyses, and age calculations were carried out at the ARGONAUT Laboratory of the Division General Geology and Geodynamics at the University of Salzburg. Mineral concentrates were packed in aluminium-foil and loaded in quartz vials. For calculation of the J-values, flux-monitors

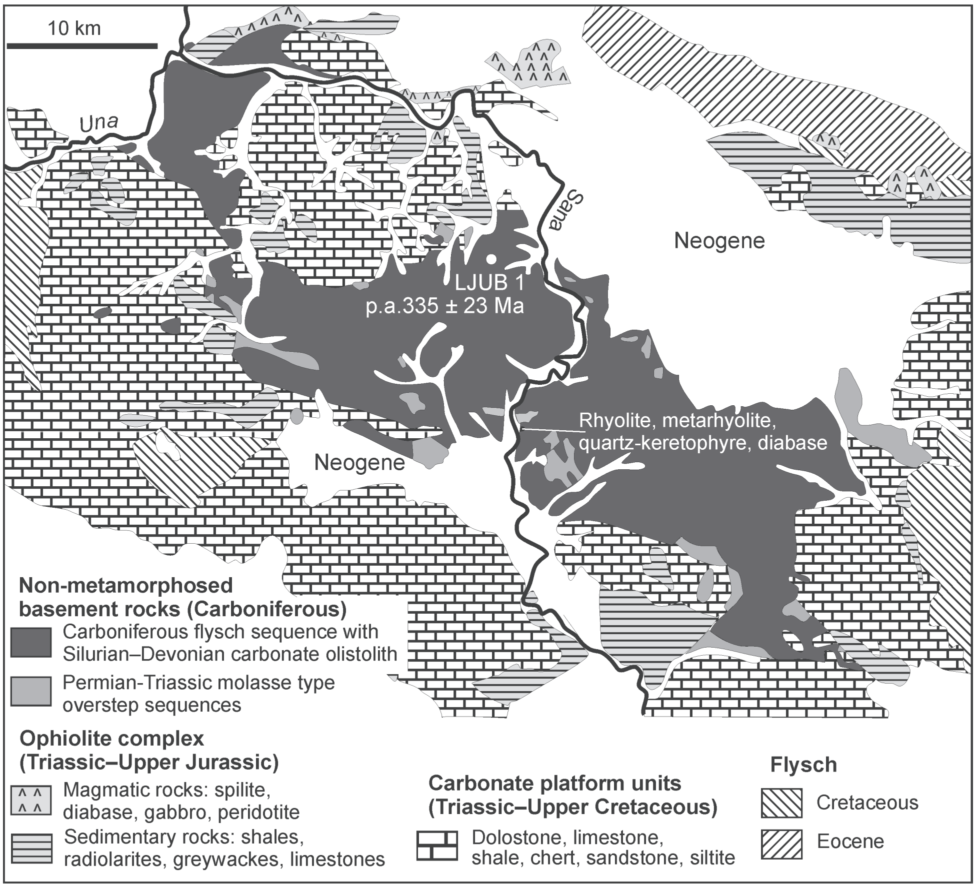

Fig. 3. Simplified tectonic map of the Paleozoic Sana-Una Unit showing sample locality for $^{40}Ar/^{39}Ar$ dating; modified after Grubić et al. (2000).

were placed between each 4–5 unknown samples, which yielded a distance of ca. 5 mm between adjacent flux-monitors. The sealed quartz vials were irradiated in the MTA KFKI reactor (Debrecen, Hungary) for 16 hours. Correction factors for interfering isotopes were calculated from 10 analyses of two Ca-glass samples and 22 analyses of two pure K-glass samples, and are: $^{36}Ar/^{37}Ar_{(Ca)}=0.00026025$, $^{39}Ar/^{37}Ar_{(Ca)}=0.00065014$, and $^{40}Ar/^{39}Ar_{(K)}=0.015466$. Variations in the flux of neutrons were monitored with the DRA 1 sanidine standard for which a $^{40}Ar/^{39}Ar$ plateau age of 25.03 ± 0.05 Ma has been reported (Wijbrans et al. 1995). After irradiation, the minerals were unpacked from the quartz vials and the aluminium-foil packets, and handpicked into 1 mm diameter holes within one-way Al-sample holders.

$^{40}Ar/^{39}Ar$ analyses were carried out using a UHV Ar-extraction line equipped with a combined MERCHANTEK^{TM} UV/IR laser ablation facility, and a VG-ISOTECH^{TM} NG3600 Mass Spectrometer. Stepwise heating analyses of samples were performed using a defocused (~1.5 mm diameter) 25 W CO_2-IR laser operating in Tem_{00} mode at wavelengths between 10.57 and 10.63 μm. The laser is controlled from a PC, and the position of the laser on the sample is monitored through a double-vacuum window on the sample chamber via a video camera in the optical axis of the laser beam on the computer screen. Gas clean-up was performed using one hot and one cold Zr-Al SAES getter. Gas admittance and pumping of the mass spectrometer and the Ar-extraction line are computer controlled using pneumatic valves. The NG3600 is a 18 cm radius 60° extended geometry instrument, equipped with a bright Nier-type source operated at 4.5 kV. Measurement was performed on an axial electron multiplier in static mode. Peak-jumping and stability of the magnet was controlled by a Hall-probe. For each increment the intensities of ^{36}Ar, ^{37}Ar, ^{38}Ar, ^{39}Ar, and ^{40}Ar are measured, the baseline readings on mass 35.5 were automatically subtracted. Intensities of the peaks are back-extrapolated over 16 measured intensities to the time of gas admittance either by a straight line or a curved fit. Intensities are corrected for system blanks, background, post-irradiation decay of ^{37}Ar, and interfering isotopes. Isotopic ratios, ages and errors for individual steps were calculated following suggestions by McDougall & Harrison (1999) and using decay factors reported by Steiger & Jäger (1977). Definition and calculation of plateau ages were carried out using ISOPLOT/EX (Ludwig 2001, 2005).

Results

Petrography

Three samples were collected from the Paleozoic-Mesozoic magmatic-sedimentary complex of the Medvednica Mountains. Samples **CRO 11** and **CRO 12**, from the Bliznec creek valley, come from the southeastern slope of the Medvednica Mts (sample locations are given at Fig. 2). Sample CRO 11 represents a fine-grained metasandstone intercalated by phyllite layers, whereas sample CRO 12 is a phyllite. The objects of the study were newly-formed metamorphic muscovites. Sample **SV-JAK** was collected from the Sv. Jakob Pb-Ag epigenetic deposit, situated on the southeastern slopes of the Medvednica Mts. The host rock is a metacarbonate (dolostone) of undetermined age, representing a part of the Lower Cretaceous low-grade metamorphic complex. Metacarbonates (dolostones) are distinctly foliated rocks, with foliation planes parallel to the original bedding. The epigenetic ore occurs as veinlets and lenses of galena and has a simple paragenesis of galena, sphalerite, pyrite, dolomite and quartz (Šinkovec et al. 1988). The vein halos are composed mainly of sericite, which was the object of our study.

Newly-grown metamorphic muscovite from three samples of the Paleozoic-Mesozoic magmatic-sedimentary complex of the Medvednica Mts have been separated. Sample locations are indicated in Fig. 2. Microfabrics of the dated rocks are presented below.

From the central part of the Paleozoic Sana-Una Unit (Ljubija open pit; sample LJUB 1; Fig. 3), a sample of phyllite from the Carboniferous flysch proximal to siderite mineralization was collected. The selected sample is tectonically disrupted by brittle microfaults, folded and characterized by lamination and foliation.

Microfabrics

The microfabrics of the low-grade metamorphosed basement rocks from the Medvednica Mts show the possible influence of a two-stage tectonothermal overprint. Representative photo micrographs are shown in Fig. 4.

Sample CRO 11 from the Medvednica Mts is a fine-grained metasandstone with clasts of a grain size of up to 0.1 mm intercalated by phyllite layers. Clasts comprise mainly quartz and subordinate plagioclase, ore minerals and tourmaline. No detrital white mica was observed in the thin section. The matrix contains well-recrystallized quartz and sericite (up to ca. 0.1 mm). The matrix as well as the clasts are affected by a secondary pressure solution foliation (Fig. 4a).

Sample CRO 12 is a laminated, banded phyllite with graphitic sericite layers and fine-grained quartz layers, which also contains lenses with large, well-recrystallized quartz and calcite (Fig. 4b). The sericite of the sericite layers is commonly between 0.02 to 0.06 mm in size and rarely contains larger grains. The quartz in fine-grained quartz layers has a grain size of 0.02 to 0.06 mm, and those of the recrystallized quartz lenses 0.1 to 0.6 mm. These large grains have straight grain boundaries and triple junctions due to perfect recrystallization. Calcite within these quartz lenses is always twinned. The foliation made up of sericite is parallel to the bedding. The foliation is folded into microfolds, and a crenulation cleavage generally affected the foliation, predominantly those defined by the sericite layers (Fig. 4b). Consequently, sericite is often kinked and folded, which commonly results in partial opening of the Ar isotopic system (Villa 1998). This could plausibly explain the decrease of ages in low-laser energy steps (see below).

The phyllite sample from the Paleozoic Sana-Una Unit (LJUB 1) consists of detrital quartz (10–20 vol. %) particles, muscovite and secondary sericite, chlorite and coalified matter of maximum 40 μm in size, within a microcrystalline sericitic matrix.

$^{40}Ar/^{39}Ar$ dating results

The results of $^{40}Ar/^{39}Ar$ dating are graphically displayed in Figs. 5–6. Most samples are fine-grained, so the actual measured white mica grains are rather at the lower limit of the given grain size.

Medvednica Mts

A fine-grained muscovite concentrate from metasandstone (CRO 11) resulted in a slightly disturbed age pattern, which yields an integrated age of ca. 135.1 ± 1.5 Ma of steps 4–8 together constituting 64.4 percent of ^{39}Ar released (Fig. 5a). High-energy release steps show a decreasing age pattern with an age of 121.3 ± 1.5 Ma.

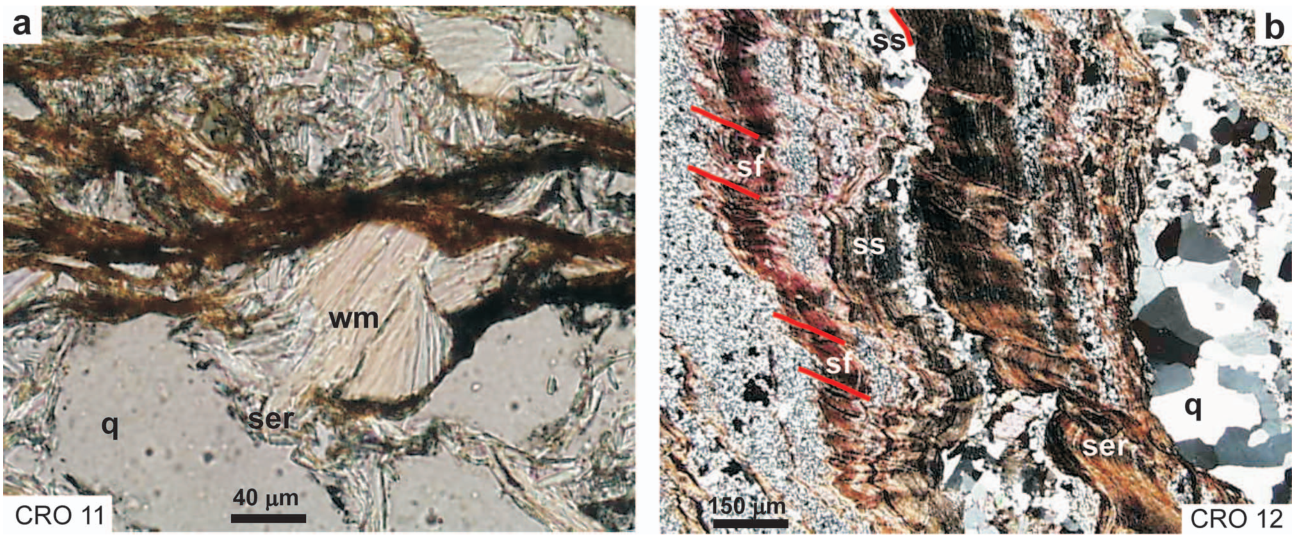

Fig. 4. Representative and critical microfabrics of dated samples. The sample number is given on the figure. **a** — New grown muscovite affected by pressure solution cleavage. Plane polarized light. **b** — Crenulation cleavage in a banded phyllite formed by affecting the metamorphic foliation during microfolding. Crossed polarizers. Legend: **q** — quartz, **wm** — white mica, **sf** — foliation, **ss** — bedding.

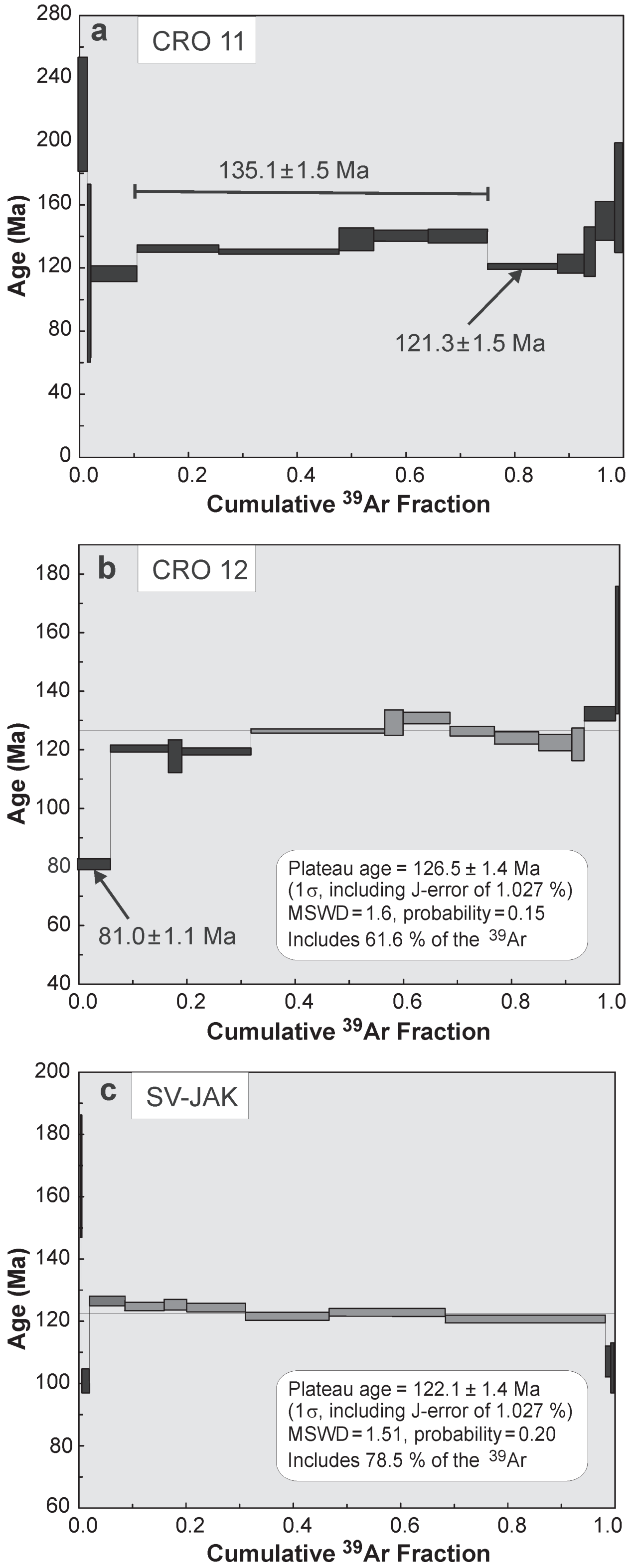

Fig. 5. ^{40}Ar/^{39}Ar apparent age spectra of the metamorphic fine-grained muscovite, ca. 10–20 grains for each sample, from: **a** — metasandstone intercalated by phyllite layers, sample CRO 11; **b** — phyllite (sample CRO 12), and **c** — metacarbonate, (sample SV-JAK) of the Medvednica Mts. Laser energy increases from left to right. Vertical width of bars represents 1 σ error. Steps used for calculation of plateau ages are delineated by bar.

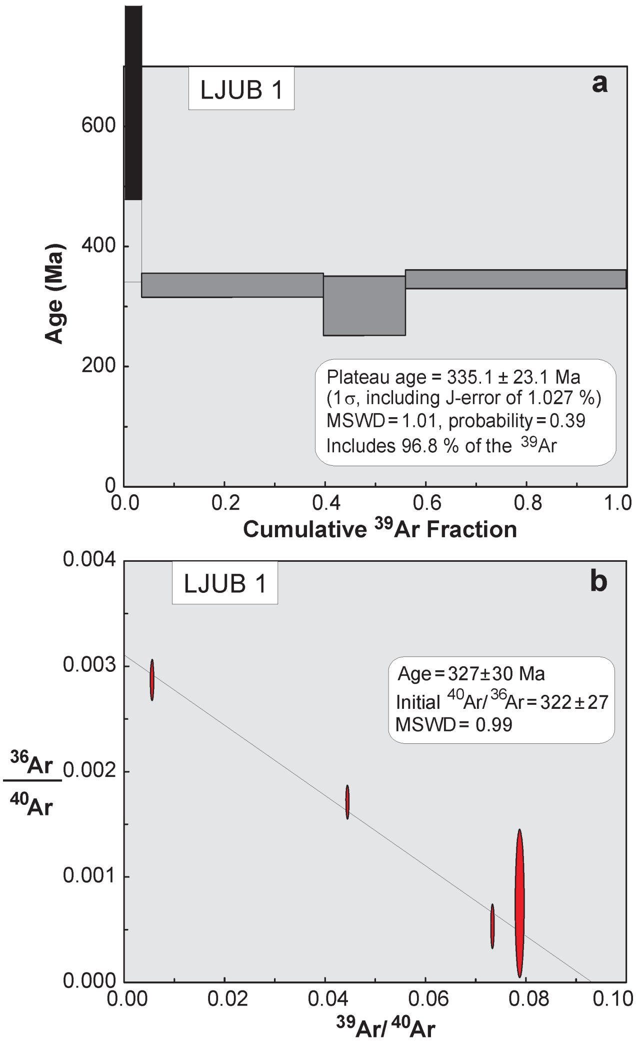

Fig. 6. ^{40}Ar/^{39}Ar apparent age spectra and inverse isochrone of the white mica (ca. 10–20 grains for each sample) from phyllite of the Ljubija open pit (Paleozoic Sana-Una Unit). Laser energy increases from left to right. Vertical width of bars represents 1 σ error. Steps used for calculation of plateau ages are delineated by bar.

A fine-grained muscovite concentrate from phyllite (CRO 12) shows a staircase pattern, which allowed the calculation of a plateau age of 126.5 ± 1.4 Ma, constituting ca. 61.6 percent of ^{39}Ar released (Fig. 5b). The first step shows a significantly younger age of 81.0 ± 1.1 Ma.

A white mica concentrate from sericitic alteration (SV-JAK) resulted in a slightly disturbed age pattern, which yielded a plateau age of 122.5 ± 1.4 Ma, with steps 3–9 together comprising 78.5 percent of ^{39}Ar released (Fig. 5c).

Paleozoic Sana-Una Unit

A white mica concentrate from the phyllite, sample LJUB 1, from the Paleozoic Sana-Una Unit yielded a plateau age of 335.1 ± 23.1 Ma comprising 96.8 percent of ^{39}Ar released (Fig. 6a). The inverse isochrone plots show a slightly disturbed initial ^{40}Ar/^{36}Ar ratio of 322 ± 27, and an age of 327 ± 30 Ma, together constituting 100 percent of ^{39}Ar released (Fig. 6b).

Discussion

The new data from very low and low-grade metamorphosed basement rocks of the northwestern Dinarides are used to confirm the existence and distribution of Variscan vs. Alpine tectonothermal events of the investigated regions including rates of erosion/uplift/cooling. The new set of $^{40}Ar/^{39}Ar$ white mica ages from Medvednica and Sana-Una basement rocks combined with microfabric observations reveal an Alpine metamorphic overprint on an earlier exclusively main-stage Variscan tectonothermal event. The data from this study are combined with published data from Borojević Šoštarić et al. (2009) in order to present general conclusions and models, which are graphically presented in Fig. 7.

Fig. 7a presents the Carboniferous development of the basement units of the northwestern Dinarides. The main process during the Carboniferous within Variscan Europe was the closure of the Paleotethys due to the progressing collision between Gondwana and Laurussia (e.g. Pamić & Jurković 2002). This process led to the exhumation and surface uplift of medium-grade metamorphic units and subsequent erosion of the Variscan orogen. The synorogenic flysch and succeeding molasse deposits filled newly formed foreland basins, Carboniferous in age. New white mica $^{40}Ar/^{36}Ar$ age data from the Sana-Una flysch-type units (~330 Ma) correspond to obtained ages from the flysch-type units of the Petrova and Trgovska Gora regions (354 to 314 Ma; Borojević Šoštarić et al. 2009). Similar ages of the detrital white mica to the stratigraphic age of their host sediments indicate rapid cooling and exhumation of the adjacent Variscides during the formation of foreland basins. Such old ages are common within the Tisia Unit (Dallmeyer et al. 1996), within the uppermost nappes of the Eastern Alps (Wiesinger et al. 2006), and are widespread within the Variscan units of the Dinarides (Ilić et al. 2005).

Fig. 7b presents the late Variscan tectonothermal event, which, within the Dinarides, developed into a rift during Early Permian times. Recorded tectonothermal overprint ranging from 298 Ma to 265 Ma, was synchronous with the formation of widespread siderite-barite-polysulphide deposits (Palinkaš et al. 2008; Borojević Šoštarić et al. 2009; Strmić Palinkaš et al. 2009) and the formation of the Dinaride evaporites. The Permian event could be related to ongoing Alpine rifting similar to that in the Southalpine and Austroalpine basement units of the Alps (e.g. Neubauer et al. 2000; Schuster et al. 2001).

Fig. 7c shows the Early Cretaceous low-grade metamorphism, recorded in the Medvednica Mts. The basement of the Medvednica Mts shows a two-stage evolution. The main stage, an early Alpine metamorphic overprint between 135 Ma and 122 Ma, is interpreted as the stage of nappe stacking predating the formation of Gosau collapse basins. The age range (135 Ma to 122 Ma) recorded in the Medvednica Mts indicates very slow regional cooling/exhumation postdating the main regional nappe stacking. A similar age range of 139–129 Ma was obtained in the Drina-Ivanjica Unit (Milovanović 1984), while ranges of 121–95 Ma and 123–116 Ma were reported for the rocks of the Mid-Bosnian Schist Mts (Palinkaš et al. 1996; Pamić et al. 2004) and Medvednica Mts (Belak et al. 1995a; Judik et al. 2006), respectively. This gives evidence for the Early Cretaceous onset of ductile nappe stacking in the entire Cretaceous-aged orogen of the Circum-Pannonian Region.

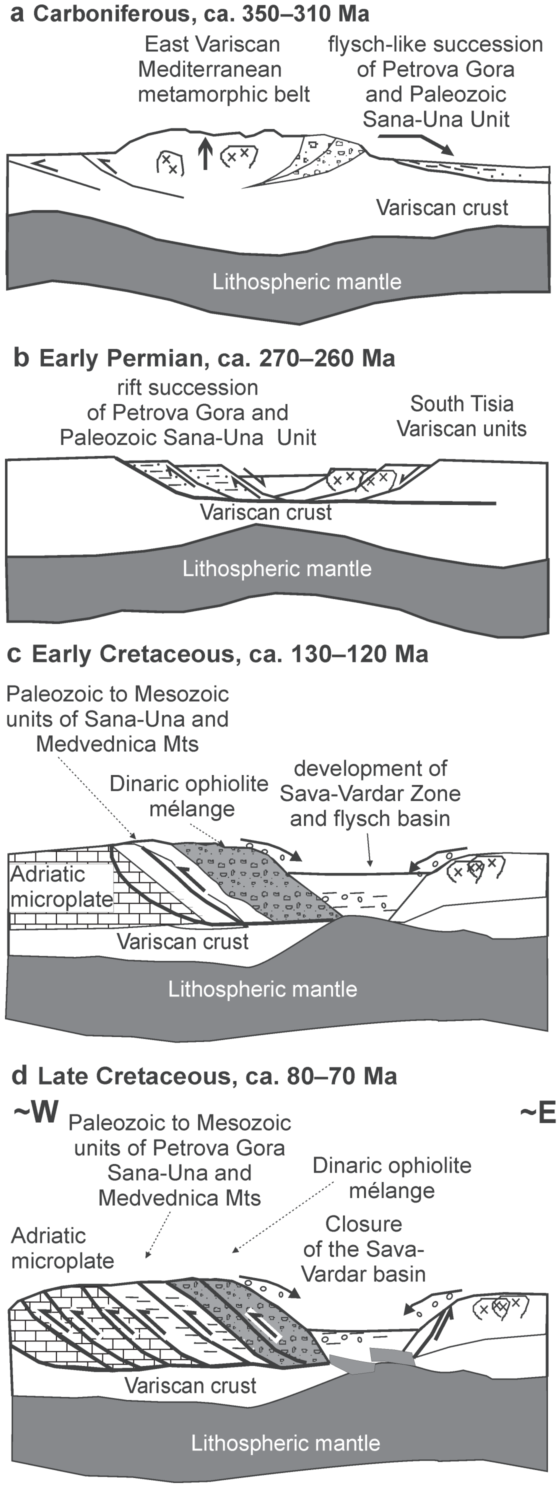

Fig. 7. Simplified tectonic models for the tectonic evolution of northwestern Dinarides.

Fig. 7d shows a younger, Late Cretaceous overprint (~80 Ma) contemporaneous with the subsidence of Gosau-type basins and the opening and closure in the neighbouring Sava-Vardar Zone (Neubauer et al. 1995, 2000; Dallmeyer et al. 1996; Schuster & Frank 1999; Schuster et al. 2001; Schmid et al. 2008; Ustaszewski et al. 2008). Due to a younger overprint (ca. 80 Ma), the age group 135–122 Ma from the Medvenica Mts is older than the hitherto available K-Ar white mica ages. The obtained age data of the overprint is similar to the Late Cretaceous age (75 Ma) from the fault zone of the Petrova Gora region (Borojević Šoštarić et al. 2009). Most likely, these units attained a similar geotectonical setting during the Late Cretaceous.

The new data also shows remarkable age similarities of the NW Internal Dinarides to the Eastern Alps. The similarities include all four critical time levels shown in this study: the same age as the main-stage Variscan overprint of the Austroalpine Quartzphyllite units of the Eastern Alps (Neubauer et al. 1999 and references therein), the age of Permian overprint (Schuster et al. 2001), the Early Cretaceous age of a low-grade tectonothermal overprint in some Quartzphyllite units (Dallmeyer et al. 1998; Wiesinger et al. 2006), and the Late Cretaceous deformation contemporaneous with the subsidence of Gosau-type basins (Neubauer et al. 1995, 2000; Dallmeyer et al. 1996; Schuster & Frank 1999; Schuster et al. 2001).

Cretaceous tectonic restoration

Various reconstructions of the Cretaceous and Cenozoic deformation in the Circum-Pannonian Region have been discussed by, for example, Auboin et al. (1970), Burchfiel (1980), Csontos et al. (1992), Dercourt et al. (1993), Robertson & Karamata (1994), Csontos (1995), Channell & Kozur (1997), Stampfli & Mosar (1999), Willingshofer (2000), Neugebauer et al. (2001), Ziegler & Stampfli (2001), Neubauer (2002), Stampfli et al. (2002) and Schmid et al. (2008). None of them appears to have solved all the problems, so that many open questions remain. Fig. 8 shows a tectonic reconstruction of the Cretaceous configuration that is based mainly on paleomagnetic data from Upper Cretaceous units collected by Neugebauer et al. (2001) and Stampfli et al. (2002). However, the reconstruction is considerably different from those models due to the shift of the Adriatic microplate to the East based on the restoration of the 400 km displacement along the Periadriatic fault. The reconstruction shows that the Upper Cretaceous units can be divided into: (1) the ALCAPA (ALpine-CArpathian-PAnnonian) block comprising the Austroalpine units in the Eastern Alps and Inner Western Carpathians, (2) the Tisia block extending from Moslavačka Gora in Croatia to the Apuseni Mountains, (3) the Dacia block, which includes the Eastern und Southern Carpathians and the Balkan, (4) the Rhodope block and (5) the South-Alpine Dinaric block (see Figs. 1, 2). These blocks were strongly deformed during Cenozoic time, mainly around their margins. Additionally, they were also partially rotated during their invasion into the future Alpine-Carpathian realm. The Tisia block records a 50–90° clockwise rotation mostly during the Middle Miocene (Rosu et al. 2004). A simple solution suggests that the

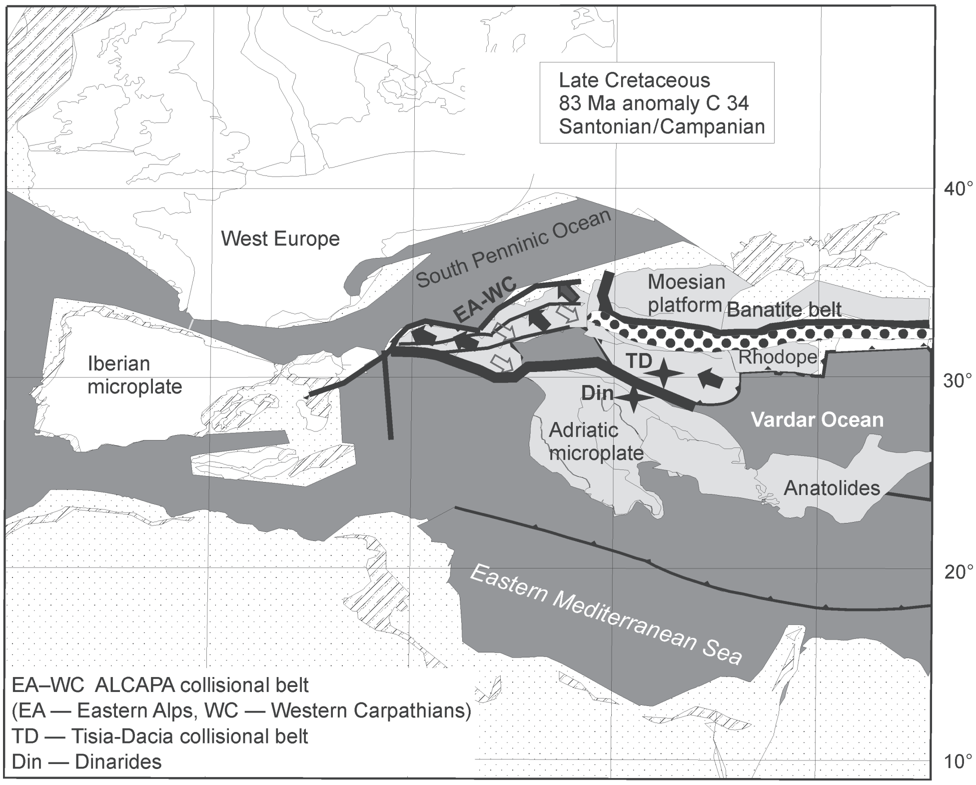

Fig. 8. Late Cretaceous tectonic reconstruction of the Circum-Pannonian Region also showing orogen polarity (modified after Neubauer 2002). Black arrows show sense of overall displacement during nappe stacking (Late–Early Cretaceous). Open arrows show sense of normal fault motion during extension (Late Cretaceous).

ALCAPA and Tisia blocks invaded the Carpathian arc during Cenozoic times, the Tisia block pushing at its front the western sectors of the Dacia block. The Moesian platform seemingly represents an indenter that is interpreted to have moved westwards during Late Cretaceous and Paleogene times due to the opening of the West Black Sea oceanic basin. The essential result of this restoration is that the ALCAPA, Tisia and Dacia blocks together formed an E–W-trending, straight orogen during the critical time at ~80 Ma when most of the so-called Banatite magmatism (e.g. Neubauer et al. 2003), which is also preserved in the Tisia microplate adjacent to NW Dinarides (Pamić et al. 2002), occurred (Fig. 8). This view is also supported by paleomagnetic data from Upper Cretaceous Banatites, which call for post-Cretaceous bending and orocline formation of the Banatite belt during its invasion into the Carpathian arc (Patrascu et al. 1992, 1994). It is reasonable to assume that the Cretaceous orogen separated a northern, South Penninic oceanic tract from the still open Tethys/Vardar ocean in the south. The South Alpine-Dinaric belt was connected to the southern ALCAPA block when an open ocean was closed in a scissor-like manner due to the convergence of the Dinarides towards the ALCAPA Tisia-Dacia-Rhodope continent. During the Late Cretaceous convergence, both the Medvednica Mts and Petrova Gora region behaved as rigid blocks. Slow regional cooling/exhumation of the Medvednica Mts throughout Cretaceous time resulted in transition from ductile deformation stage dated at 135 to 122 Ma to brittle stage dated at ~80 Ma whereas the Petrova Gora region underwent only brittle deformation stage, where new-grown muscovite from the fault zone was dated at 75 Ma (Borojević Šoštarić et al. 2009). This is synchronous with the formation of the Late Carboniferous to Paleocene Gosau-type foredeep basin along the present day northward margins of the metamorphic complex of the Medvednica Mts. The deepening of the Medvednica Mts foredeep basin, indicated by change in lithology from Santonian/Campanian fluvial-lacustrine environment to Paleocene turbiditic flysch and hemipelagic sediments (Tomljenović 1995), is a common characteristic of the Late Cretaceous Gosau type basins of the Eastern Alps and Apuseni Mts (sensu Dallmeyer et al. 1996) related to contemporaneous exhumation of the metamorphic core complexes. Both processes are a result of ongoing Cretaceous convergence (subduction/collision) of the Dinarides–Helenides and the ALCAPA Tisia-Dacia-Rhodope block.

In summary, reconstructions indicate open oceanic tracts, both to the north and south of the Upper Cretaceous orogenic belt. This belt was attached to the Moesian platform in the east, and to the Adriatic microplate in the west. This leaves open the question as to which geodynamic process occurred within this belt during the Late Cretaceous. Was there continuous subduction or collision along segments that are attached to continental blocks (Moesia/Europe) in the east, and the Adriatic block in the west? Orogenic polarity of the closure and nappe stacking was, respectively, to the N and NW rotating units back into their present-day position (e.g. Ratschbacher et al. 1989, 1993; Schmid et al. 1998, 2008 and references in these papers; Fig. 8). On the other hand, the figure shows that the Cretaceous-aged orogen could represent a double-vergent continent-continent collisional orogen. Its initial vergency is towards the Adriatic microplate during the Late Jurassic emplacement of the Dinaric ophiolite nappe; subsequently, a double-vergent orogenic wedge formed during the Early Cretaceous, but finally collapsed during the Late Cretaceous.

Conclusions

The very low-grade metamorphosed basement rocks from the Paleozoic Sana-Una Unit show the main-stage Variscan tectonothermal event, synchronous with the Petrova and Trgovska Gora region (354 to 314 Ma; Borojević Šoštarić et al. 2009). Low-grade metamorphosed basement rocks from the Medvednica Mts show two stages of Alpine tectonothermal events and no evidence of Variscan tectonism: (i) The main stage of early Alpine overprint between 135 and 122 Ma, interpreted as the onset of ductile nappe stacking, predates the formation of Gosau collapse basins. The age gradient indicates very slow regional cooling/exhumation postdating the main regional nappe stacking. Similar ages can be traced in the entire Cretaceous-aged orogen of the Circum-Pannonian Region namely the Tisia Unit, uppermost nappes of the Eastern Alps and Variscan units of the Dinarides. (ii) A later, early Alpine event at ~80 Ma found in the area of the Medvednica Mts is contemporaneous with the subsidence of Gosau-type basins and the opening and closure in the neighbouring Sava–Vardar Zone.

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References

Auboin J., Blanchet R., Cadet J.P., Celet P., Charvet J., Chorowicz J., Cousin J. & Rampnoux J. 1970: Essai sur la géologie des Dinarides. *Bull. Soc. Geol. France* 7, 12, 1060–1095.

Babić L., Hochuli P.A. & Zupanič J. 2002: The Jurassic ophiolitic mélange in the NE Dinarides: dating, internal structure and geotectonic implications. *Eclogae Geol. Helv.* 95, 263–275.

Belak M. & Tibljaš D. 1998: Discovery of blueschists in the Medvednica mountain (Northern Croatia) and their significance for the interpretation of the geotectonic evolution of the area. *Geol. Croatica* 51, 27–32.

Belak M., Pamić J., Kolar-Jurkovšek T., Pécskay Z. & Karan D. 1995a: Alpine regional metamorphic complex of the Mt. Medvednica. *Proc. 1st Croat. Geol. Congr.* Opatija, Zagreb, 567–570 (in Croatian with English summary).

Belak M., Jamičić D., Crnko J. & Sremac J. 1995b: Low-metamorphic rocks from the lower part of Bliznec creek. In: Šikić K. (Ed.): Geological guide of Mts. Medvednica. *Naftaplin*, Zagreb, 97–102 (in Croatian).

Borojević Šoštarić S., Palinkaš A.L., Strmić Palinkaš S., Bermenec V., Neubauer F., Spangenberg J. & Prochaska W. 2009: Origin of siderite mineralisation in Petrova and Trgovska Gora Mts., NW Dinarides. *Miner. Petrology* 97, 111–128.

Burchfiel B.C. 1980: Eastern European alpine system and the Carpathian orocline as an example of collision tectonics. *Tectonophysics* 63, 31–61.

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

Csontos L. 1995: Tertiary tectonic evolution of the Intra-Carpathian area: a review. *Acta Vulcanol.* 7, 1–13.

Csontos L., Nagymaroshi A., Horvath F. & Kovac M. 1992: Tertiary evolution of the Intra-Carpathian arc: a model. *Tectonophysics* 208, 221–241.

Dallmeyer R.D., Neubauer F., Handler R., Fritz H., Müller W., Pana D. & Putiš M. 1996: Tectonothermal evolution of the internal Alps and Carpathians: Evidence from $^{40}Ar/^{39}Ar$ mineral and whole rock data. *Eclogae Geol. Helv.* 89, 203–227.

Dallmeyer R.D., Handler R., Neubauer F. & Fritz H. 1998: Sequence of thrusting within a thick-skinned tectonic wedge: Evidence from $^{40}Ar/^{39}Ar$ ages from the Austroalpine nappe complex of the Eastern Alps. *J. Geol.* 106, 71–86.

Dercourt J., Ricou L.E. & Vrielinck B. 1993: Atlas Tethys, paleoenvironmental maps. *Gauthier-Vilars*, Paris, 1–307.

Dimitrijević M.D. 1982: Dinarides: An outline of the tectonics. *Earth Evol. Sci.* Berlin 2, 1, 4–23.

Dimitrijević M.D. 1997: Geology of Yugoslavia. *Geol. Surv. GEMINI*, Belgrade, 1–187.

Đurđanović Ž. 1968: Conodonten des unteren Devons des Gebirges Medvednica (Zagrebačka gora). *Geol. Vjes.* 21, 93–102 (in Croatian with German summary).

Đurđanović Ž. 1973: Conodonten des Unterdevons und Unterkarbons westlich von Dvor na Uni (Kroatien–Jugoslawien). *Geol. Vjes.* 25, 29–45 (in Croatian with German summary).

Faupl P., Pober E. & Wagreich M. 1987: Facies development of the Gosau Group of the eastern parts of the Northern Calcareous Alps during Cretaceous and Paleogene. In: Flügel H.W. & Faupl P. (Eds.): Geodynamics of the Eastern Alps. *Deucticke*, Wien, 142–155.

Gorjanović-Kramberger D. 1908: Geological map and explanatory notes scheet Zagreb (Zona 22, COL. XIV). *Naklada Kr. Zemaljske Vlade*, 1–75 (in Croatian).

Grubić A., Protić L., Filipović I. & Jovanović D. 2000: New data on the Paleozoic of the Sana-Una Area. *Proceedings of the International Symposium of the Dinarides and the Vardar Zone. The Acad. Sci. Arts of the Republic of Srpska*, Banja Luka — Sarajevo 1, 49–54.

Haas J. & Kovacs S. 2001: The Dinaridic-Alpine connection — as seen from Hungary. *Acta Geol. Hung.* 44, 345–362.

Haas J., Mioč P., Pamić J., Tomljenović B., Árkai P., Berczi-Makk A., Koroknai B., Kovacs S. & Felganhauer E. 2000: Complex structural pattern of the Alpine-Dinaric-Pannonian triple junction. *Int. J. Earth Sci. (Geol. Rundsch.)* 89, 377–389.

Halamić J. & Goričan Š. 1995: Triassic radiolarites from Mts. Kalnik and Medvednica (Northwestern Croatia). *Geol. Croatica* 48, 2, 129–146.

Halamić J., Goričan G., Slovenec D. & Kolar-Jurkovšek T. 1999: Middle Jurassic Radiolarite-Clastic Succession from the Medvednica Mt. (NW Croatia). *Geol. Croatica* 52, 1, 29–57.

Ilić A., Neubauer F. & Handler R. 2003: Cretaceous collision and Tertiary oblique convergence in Central Dinarides. *Geophys. Res. Abstracts*, 5-0056.

Ilić A., Neubauer F. & Handler R. 2005: Late Paleozoic-Mesozoic tectonics of Dinarides revisited: implications from $^{40}Ar/^{39}Ar$ dating of detrital white micas. *Geology* 33, 3, 233–236.

Judik K., Árkai P., Horváth P., Dobosi G., Tibljaš D., Dražen B., Tomljenović B. & Pamić J. 2004: Diagenesis and low-temperature metamorphism of Mt. Medvednica, Croatia: mineral assemblages and phyllosilicate characteristics. *Acta Geol. Hung.* 47, 2, 151–176.

Judik K., Balogh K., Tibljaš D. & Árkai P. 2006: New age data on the low-temperature regional metamorphism of Mt. Medvednica (Croatia). *Acta Geol. Hung.* 49, 3, 207–221.

Judik K., Rantitsch G., Rainer T.M., Árkai P. & Tomljenović B. 2008: Alpine metamorphism of organic matter in metasedimentary rocks from Mt. Medvednica (Croatia). *Swiss. J. Geosci.* 101, 605–616.

Jurić M. 1979: Geology of the Sana-Una Paleozoic within northwestern Bosnia. *Unpubl. PhD Thesis*, *University of Sarajevo*, Sarajevo, 1–175 (in Croatian).

Jurković I. & Pamić J. 2001: Geodynamics and metallogeny of Variscan complexes of the Dinarides and South Tisia as related to plate tectonics. *Nafta*, Zagreb 52, 9, 267–284.

Ludwig K.R. 2001: Using Isoplot/Ex, Version 2.01: a geochronological toolkit for Microsoft Excel. *Berkeley Geochronology Center, Spec. Publ. 1a*, Berkeley, 1–47.

Ludwig K.R. 2005: Isoplot/EX rev. 3.32: A geochronological toolkit for Microsoft Excel. *Berkeley Geochronology Center, Spec. Publ. 4*, Berkeley, *USG Open File Repository*.

Majer V. 1964: Petrography of Paleozoic sediments from the northeastern part of Trgovska gora Mts. *Geol. Vjes.* 17, 79–92 (in Croatian with German summary).

Majer V., Lugović B. & Trubelja F. 1991: Metamorphism of the Bosnian Schist Mountains (Preliminary investigation). *Rad. Akad. Nauka Umjet BiH*, Sarajevo 13, 141–158 (in Croatian with German summary).

McDougall I. & Harrison M.T. 1999: Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ Method. *Oxford University Press Sec. Ed.,* Oxford, 1–269.

Milovanović D. 1984: Petrology of low-metamophic rocks from the central part of the Drina-Ivanjica Paleozoic. *Glasnik Prir. Muzeja,* Belgrade A39, 13–139 (in Serbian with English summary).

Neubauer F. 2002: Contrasting Late Cretaceous to Neogene ore provinces in the Alpine-Balkan-Carpathian-Dinaride collision belt. In: Blundell D.J., Neubauer F. & von Quadt A. (Eds.): The timing and location of major ore deposits in an evolving orogen. *Geol. Soc. London, Spec. Publ.* 206, 81–102.

Neubauer F., Dallmeyer R.D., Dunkl I. & Schirnik D. 1995: Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. *Tectonophysics* 242, 79–89.

Neubauer F., Hoinkes G., Sassi F.P., Handler R., Höck V., Koller F. & Frank W. 1999: Pre-Alpine metamorphism of the Eastern Alps. *Schweiz. Mineral. Petrogr. Mitt.* 79, 1, 41–62.

Neubauer F., Genser J. & Handler R. 2000: The Eastern Alps: result of a two-stage collision process. *Mitt. Österr. Geol. Gesell.* 92, 117–134.

Neubauer F., Heinrich C.A. & GEODE ABCD Working Group 2003: Late Cretaceous and Tertiary geodynamics and ore deposit evolution of the Alpine-Balkan-Carpathian-Dinaride orogen. In: Eliopoulos D.G. et al. (Eds.): Mineral exploration and sustainable development. *Proceedings of the Seventh Biennial Society for Geology Applied to Mineral Deposits Meeting on Mineral Exploration and Sustainable Development, Athens, Greece. Millpress Science Publishers, Rotterdam*, 1133–1136. August 24–28, 2003.

Neugebauer J., Greiner B. & Appel E. 2001: Kinematics of Alpine-West Carpathian orogen and palaeogeographic implications. *J. Geol. Soc. London* 158, 97–110.

Palinkaš L., Majer V., Balogh K., Bermanec V. & Jurković I. 1996: Geochronometry and thermochronometry of the metamorphism in the Inner Dinarides, Mid-Bosnian Schist Mts. *IGCP*

No. 356, Plate tectonic aspects of the Alpine metallogeny. Poster Session, 2, 53.

Palinkaš L., Borojević Šoštarić S. & Strmić Palinkaš S. 2008: Metallogeny of the North-Western and Central Dinarides and Southern Tisia. *Ore Geol. Rev.* 34, 501–520.

Pamić J. & Jurković I. 2002: Paleozoic tectonostratigraphic units of the northwest and central Dinarides and the adjoining South Tisia. *Int. J. Earth Sci.* 91, 538–554.

Pamić J. & Pécskay Z. 1996: Geological and K/Ar ages of Tertiary volcanic formations from the southern part of the Panonian Basin in Croatia — based on surface and subsurface data. *Nafta*, Zagreb 47, 195–202.

Pamić J. & Tomljenović B. 1998: Basic geological data from the Croatian part of the Zagorje-Mid-Transdanubian Zone. *Acta Geol. Hung.* 41, 4, 389–400.

Pamić J., Gušić I. & Jelaska V. 1998: Geodynamic evolution of the Central Dinarides. *Tectonophysics* 297, 251–268.

Pamić J., Tomljenović B. & Balen D. 2002: Geodynamic and petrogenetic evolution of Alpine ophiolites from the central and NW Dinarides: an overview. *Lithos* 65, 113–142.

Pamić J., Balogh K., Hrvatović H., Balen D., Jurković I. & Palinkaš L. 2004: K-Ar and Ar-Ar dating of the Palaeozoic metamorphic complex from the Mid-Bosnian Schist Mts., Central Dinarides, Bosna and Hercegovina. *Miner. Petrology* 82, 65–79.

Patrascu S., Bleahu M., Panaiotu C. & Panaiotu C.E. 1992: The paleomagnetism of the upper Cretaceous magmatic rocks in the Banat area of the South Carpathians: tectonic implications. *Tectonophysics* 213, 341–352.

Patrascu S., Panaiotu C., Seclaman M. & Panaiotu C.E. 1994: Timing of rotational motion of Apuseni Mountains (Romania): paleomagnetic data from Tertiary magmatic rocks. *Tectonophysics* 233, 163–176.

Podubsky V. 1968: Lithology of Paleozoic formations from NW Bosnia. *Geol. Glas.,* Sarajevo 12, 73–91 (in Croatian).

Podubsky V. & Pamić J. 1967: Volcanic rocks in the Sana Paleozoic (NW Bosnia) and their position in columnar section. *Rad JAZU*, Zagreb, 45–54.

Ratschbacher L., Frisch W., Neubauer F., Schmid S.M. & Neugebauer J. 1989: Extension in compressional orogenic belts: The eastern Alps. *Geology* 17, 404–407.

Ratschbacher L., Linzer G.H., Moser F., Strusievicz R.O., Bedelean H., Har N. & Mogos P.A. 1993: Cretaceous to Miocene thrusting and wrenching along the central South Carpathians due to a corner effect during collision and orocline formation. *Tectonics* 12, 855–873.

Robertson A.H.F. & Karamata S. 1994: The role of subduction-accretion process in the tectonic evolution of the Mesozoic Tethys in Serbia. *Tectonophysics* 234, 73–94.

Rosu E., Seghedi I., Downes H., Alderton D.H.M., Szakács A., Pécskay Z., Panaiotu C., Panaiotu C.E. & Nedelcu L. 2004: Extension-related Miocene calc-alkaline magmatism in the Apuseni Mountains, Romania: Origin of magmas. *Schweiz. Mineral. Petrogr. Mitt.* 84, 153–172.

Schmid S.M., Berza T., Diaconescu N., Fügenschuh B., Schönborn O. & Kissling E. 1998: Orogen-parallel extension in the Southern Carpathians. *Tectonophysics* 15, 1036–1064.

Schmid S.M., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K. 2008: The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss J. Geosci.* 101, 139–183.

Schuster R. & Frank W. 1999: Metamorphic evolution of the Austroalpine units east of the Tauern Window: indications for Jurassic strike slip tectonics. *Mitt. Gesell. Geol. Bergbaustud. Österr.* 42, 37–58.

Schuster R., Scharbert S., Abart R. & Frank W. 2001: Permo-Triassic extension and related HAT/LP metamorphism in the Austroalpine–Southalpine realm. *Mitt. Gesell. Geol. Bergbaustud. Österr.* 45, 111–141.

Sremac J. & Mihajlović-Pavlović M. 1983: Graptolites from Mt. Medvednica. *Rad JAZU,* Zagreb 404, 19, 65–68 (in Croatian).

Stampfli G.M. & Mosar J. 1999: The making and becoming of Apulia. *Mem. Sci. Geol.,* Padova 51, 141–154.

Stampfli G.M., Borel G.D., Marchant R. & Mosar J. 2002: Western Alps geological constraints on western Tethyan reconstructions. *J. Virtual Explorer* 8, 77–106.

Steiger R.H. & Jäger E. 1977: Subcommission on geochronology: Convention on the use of decay constants in geo-and cosmochronology. *Earth Planet. Sci. Lett.* 36, 359–362.

Strmić Palinkaš S., Spangenberg J.E. & Palinkaš L. 2009: Organic and inorganic geochemistry of Ljubija siderite deposits, NW Bosnia and Herzegovina. *Min. Deposita* 44, 893–913.

Šikić K., Basch O. & Šimunić A. 1979: Explanatory notes for the geological map 1 : 100,000, sheet Zagreb. *Geol. Surv.,* Belgrade, 1–81 (in Croatian with English summary).

Šinkovec B., Palinkaš L. & Durn G. 1988: Ore deposits from Medvednica Mts. *Geol. Vjes.,* Zagreb 41, 395–405 (in Croatian with English summary).

Tomljenović B. 2002: Structural characteristics of the Mt. Medvednica and the Samoborsko gorje Mt (in Croatian). *Unpubl. PhD Thesis*, *University of Zagreb*, Zagreb, 1–208.

Tomljenović B. & Csontos L. 2001: Neogene-Quaternary structures in the border zone between Alps, Dinarides and Pannonian Basin (Hrvatsko zagorje and Karlovac Basin, Croatia). *Int. J. Earth Sci. (Geol. Rundsch.)* 90, 560–578.

Ustaszewski K., Schmid S.M., Lugović B., Schuster R., Schaltegger U., Bernoulli D., Hottinger L., Kounov A., Fügenschuh B. & Schefer S. 2009: Late Cretaceous intra-oceanic magmatism in the internal Dinarides (northern Bosnia and Herzegovina): Implications for the collision of the Adriatic and European plates. *Lithos* 108, 1–4, 106–125.

Villa I. 1998: Isotopic closure. *Terra Nova* 10, 42–47.

Wiesinger M., Neubauer F. & Handler R. 2006: Exhumation of the Saualpe eclogite unit, Eastern Alps: constraints from $^{40}Ar/^{39}Ar$ ages. *Miner. Petrology* 88, 149–180.

Wijbrans J.R., Pringle M.S., Koopers A.A.P. & Schveers R. 1995: Argon geochronology of small samples using the Vulkaan argon laserprobe. *Proc. Kon. Ned. Akad. Wetensch* 98, 2, 185–218.

Willingshofer E. 2000: Extension in collisional orogenic belts: the Late Cretaceous evolution of the Alps and Carpathians. *Unpubl. PhD Thesis*, *Vrije University,* Vrije, 1–146.

Willingshofer E., Neubauer F. & Cloetingh S. 1999: Significance of Gosau basins for the upper Cretaceous geodynamic history of the Alpine–Carpathian belt. *Phys. Chem. Earth Part A: Solid Earth Geodes.* 24, 687–695.

Ziegler P.A. & Stampfli G.M. 2001: Late Paleozoic Early Mesozoic plate boundary reorganisation: collapse of the Variscan orogen and opening of Neotethys. In: Cassinis R. (Ed.): The continental Permian of the Southern Alps and Sardinia (Italy) regional reports and general correlations. *Ann. Museo Civico Science Naturali,* Brescia 25, 17–34.