Metamorphosed and ductilely deformed conodonts from Triassic limestones situated beneath ophiolite complexes: Kopaonik Mountain (Serbia) and Bükk Mountains (NE Hungary) — a preliminary comparison

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Abstract: Metamorphosed and ductilely deformed conodonts with CAI (Colour Alteration Index) values 5–7 are described and illustrated from Kopaonik Mt, Vardar Zone, Serbia and from Bükk Mts, NE Hungary. They derive from Upper Triassic cherty metalimestones, overthrust by ophiolite complexes. The metamorphism and ductile deformation of the conodont elements evidently took place simultaneously with those of the limestone host rocks, which might have been related to subduction and obduction; however, younger tectonometamorphic events could also have played a role. Unfortunately, illite "crystallinity" indices from Kopaonik Mt are too random for thermometric assessment and geochronological data are missing so far. Nevertheless, by comparison with published data about limestone textural alteration and with previously published metamorphic petrological data from NE Hungary, at least a Szendrő-type (min. 400 °C, but less then 500 °C, temperature and 300 MPa pressure) can be supposed for the regional metamorphism of conodont-bearing cherty limestone series of Kopaonik Mt.

Key words: Serbia, Vardar Zone, NE Hungary, ductile deformation, regional metamorphism, limestone textural alteration, conodont alterations.

Introduction

Conodont thermometry to reveal the thermal history of sedimentary rock sequences has been widely used since the publication of the basic works by Epstein et al. 1977 and Rejebian et al. 1987. It is based on colour alteration of conodonts (= Colour Alteration Index — CAI) caused by coalification of the small amount of organic matter they contain due to increasing temperature: the originally yellowish white, translucent (CAI = 1) conodonts become darker and darker, then black (CAI = 5). At a further increase of temperature, due to loss of organic matter, they again become lighter coloured: grey (CAI = 6), white (CAI = 7), finally crystal clear, glassy (CAI = 8). Calibration was done by heating in an electronic furnace under atmospheric conditions, and using the Arrhenius plot, was projected back to geological times up to 500 Ma. Temperature values of this experimental test are shown in Table 1. Up to the value CAI = 5, that is within the range of the diagenetic zone, correlation was also made with palynomorph colour alteration.

The investigation of conodont colour alteration seems to be a useful method to estimate temperatures of burial and contact metamorphism. Numerous papers have been published on this topic, for example Buggisch (1986), Belka (1990), Nöth (1991), Königshof (1992), Gawlick et al. (1994), Garcia-Lopez et al. (1997), Gawlick & Hopfer (1999), and many others.

However, under conditions of regional dynamothermal metamorphism, where besides temperature, lithostatic and fluid pressures also play decisive roles, the alteration of conodonts is different and above CAI = 5 is much more intense: they become progressively recrystallized and deformed, in accordance with the metamorphism and ductile deformation of their host rock. Mineral paragenesis, illite "crystallinity" and vitrinite reflectance data above the diagenetic zone indicate considerably lower temperatures, than could be deduced from simple experimental heating (Kovács & Árkai 1987; Rejebian et al. 1987). Furthermore, it was found, that different CAI indices, that should indicate different temperatures, can be found even in the same, usually fractured specimens (CAI=5 to 7, black, grey and white parts; Kovács & Árkai op. cit.).

Table 1: Temperature ranges related to different CAI of conodonts (after Epstein et al. 1977; Rejebian et al. 1987 and Königshof 1992).

CAI	Temperature °C	CAI	Temperature °C
1	<50–90	5	300–480
1.5	50–90	6	360–550
2	60–140	6.5	440–610
3	110–200	7	490–720
4	190–300	8	>600

From the experimental (hydrouos pyrolysis at 50 MPa pressure) data shown on the Arrhenius plot (Rejebian et al. 1987, Fig. 4), postulating a thermal heating of ~10 Myr duration, ~450 to 600 °C temperature values can be calculated to these high CAI (5 to 7) values. These are higher, than could be determined for regionally metamorphosed terraines in NE Hungary using illite "crystallinity" (KI — Kübler index) and b_o indices (350 to 400 °C, exceptionally 450 °C at 250 to 300 MPa or more pressure; Árkai 1983; Árkai & Kovács 1986; Kovács & Árkai 1987; see Table 2 in the present paper). Furthermore, conodont elements are supposed to disappear above 500 °C in conditions of regional dynamothermal metamorphism (Neubauer & Friedl 1997, and Neubauer, pers. commun.).

Conodonts from metamorphosed Triassic sequences of the Kopaonik Mt (Vardar Zone, Serbia) and from the Bükk Mts (Bükk Composite Terrane, NE Hungary), which are structurally beneath ophiolite complexes are presented and compared in this paper. Evidently, their alteration was not related simply to sedimentary burial and thermal effects, but to subduction and collisional processes, although subsequent nappe movements could still play a role in their alteration.

Comparison is also done with previously published metamorphosed conodonts from the Szendrő Hills and Torna *s.s.* (or Martonyi) Unit of the Rudabánya Hills, NE Hungary (Árkai & Kovács 1986; Kovács & Árkai 1987, 1989).

The preliminary results of the above mentioned investigations were already given in the abstract by Sudar & Kovács (1998).

These are the first metamorphosed conodonts described and illustrated in details from Serbia. We should add to this point that conodonts of similar preservation were shown from approximately similarly metamorphosed Triassic limestones from the Fruška Gora Mt, Northern Serbia (Đurđanović 1971; for recent description of the metamorphosed series see Čanović & Kemenci 1999 and Karamata et al. 2002) and from the Medvednica Mt near Zagreb, Croatia (Đurđanović 1973; for a recent geological description of the Medvednica Metamorphic Series see Pamić & Tomljenović 1998; Judik et al. 2004).

Rare CAI determinations of Triassic conodont elements have been performed in the territory of the former Yugoslavia, when either their numerical values have been cited (in Slovenia: Kolar-Jurkovšek 1994; Kolar-Jurkovšek & Jurkovšek 1995, 1996; Krystyn et al. 1998), or the results of the method have been used for assessing organic metamorphism (in Croatia: Palinkaš et al. 2000).

Geological setting

The geological units compared in the present study are located now in a distant position within the Neogene–Quaternary geological framework of the Pannonian area, the basement of which had been amalgamated and accreted only by the Middle Miocene, due to sizeable microplate and terrane movements (Csontos & Nagymarosy 1998; Kovács et al. 2000), the Kopaonik Mt being on the South of the Pannonian Basin, whereas the Bükk Mts were on its northern margin. Separated by the large Tisia Terrane (or Tisza Mega-unit) (Fig. 1) of quite different origin, the Bükk and neighbouring units show an undoubtedly Dinaridic Paleozoic and Mesozoic development, suggesting that they were originally parts of the same geological domain (cf. Csontos 1999; Dimitrijević et al. 2003 and Filipović et al. 2003 for latest reviews). Consequently, the tectonometamorphic evolution of the units containing the metamorphosed conodonts shown herein could be related to the same geodynamic events. However, it is not yet widely known in the international geological literature, therefore we present below the geological facts in some more detail.

The metamorphosed Triassic sequences yielding the conodonts presented herein are structurally beneath ophiolite complexes, that are eroded in most part of the Bükk Mts. Fig. 1 also shows other areas of the former Yugoslavia (Fruška Gora and Medvednica Mts), from where metamorphosed Triassic conodonts were published from a similar setting (Đurđanović 1971, 1973; for the geological setting see Čanović & Kemenci 1999 and Pamić & Tomljenović 1998).

Table 2: Average temperature (determined from illite "crystallinity" and vitrinite reflectance data) and pressure (determined from white K-mica b_o geobarometric data) of regional dynamothermal metamorphism of tectonic units in NE Hungary, as well as CAI indices of conodonts and textural alteration types of limestones recorded in them (after Árkai & Kovács 1986 and Kovács & Árkai 1987, 1989, slightly modified).

Tectonic unit	Age	Pressure (MPa)	Temperature (°C)	CAI	Recrystallization	Deformation	Carbonate texture type
Bükk Parautochthon U.	C_2–J_3	~300	~350	6–7	+	±	B–C
Szendrő U.	D_2–C_2	~300	~400	(5)6–7	+	+	C
Uppony U.	O_3–C_2	~250	~350	5	+	–	B–C
Torna U. *s.s.* (or Martonyi U.)	T_{2-3}	~700	~350	6–7	+	+	B–C
Aggtelek and Bódva Units	P_3–J_3	indeterminable (diagenetic)	< 200	1–5	–	–	A

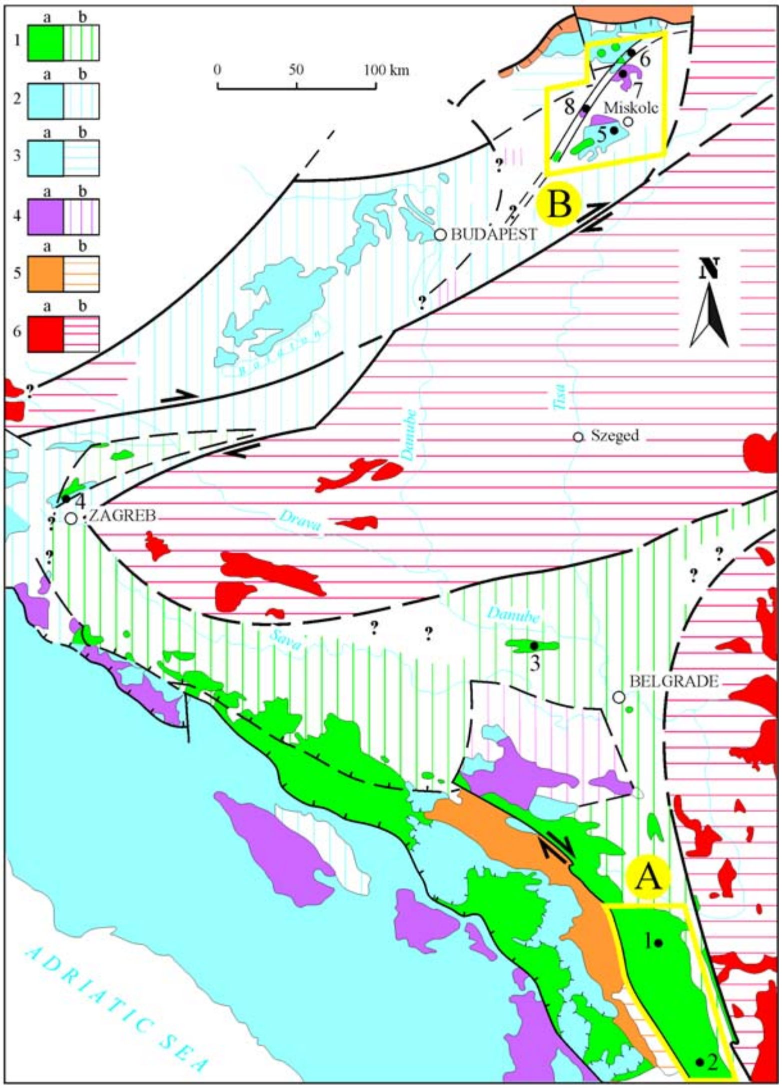

Fig. 1. Tectonic/terrane sketch map of the Dinarides+Vardar Zone and of the Pannonian area (slightly modified after Dimitrijević et al. 2003). **1** — Neotethyan ophiolite complexes (Vardar Zone, Dinaridic Ophiolite Belt, and in the Zagorje-Mid-Transdanubian and Bükk Composite Terranes); **2** — units related to the North Tethyan continental margin in the Pelsonia Composite Terrane; **3** — units related to the Adriatic/Apulian continental margin of the Neotethys in the Dinarides+Vardar Zone and in the Pelsonia Composite Terrane; **4** — areas with marine Upper Carboniferous+Permian within 3 ("Noric-Bosnian Zone" in sense of Flügel 1990); **5** — Paleozoic units without marine Upper Carboniferous and Permian in the Dinarides and Pelsonia Composite Terrane ("Betic-Serbian Zone" in sense of Flügel 1990); **6** — units related to the Variscan Median Crystalline+Moldanubian zones (in sense of Neubauer & von Raumer 1993) and to the North Tethyan (European) continental margin during the Mesozoic. **Green dots** in NE Hungary indicate drill hole occurrences of the Neotethyan Bódva Valley Ophiolite Complex, whereas the **green triangle** shows the outcrops of the Upper Jurassic (?) Telekesoldal rhyolites in the Rudabánya Mts. The area in the **full colour (a)** indicates surface occurrences, whereas those with **hachures (b)** borehole show proven ones in the pre-Tertiary basement. **A** — Kopaonik Mt area (Vardar Zone, Serbia; Fig. 2); **B** — Bükk +Aggtelek+Rudabánya Mts (Pelsonia Composite Terrane, NE Hungary; Fig. 4). **Conodont localities: 1** — Županj (Kopaonik Mt); **2** — Smrekovnica (Kopaonik Mt); **3** — Fruška Gora Mt; **4** — Medvednica Mt; **5** — Bükk PA Unit; **6** — Torna *s.s.* or Martonyi Unit; **7** — Szendrő Unit; **8** — Uppony Unit.

Geological framework of the Kopaonik Mountain area

There are two main groups of viewpoints in Serbian or Yugoslavian geological literature referring to the geological position of the Kopaonik Mt area: these terrains are considered either as parts of the Vardar Zone as a separate first-order geotectonic unit, or parts of the (Internal) Dinarides. We find it necessary to turn to the papers by M.D. Dimitrijević and S. Karamata, published during the last ten years. These papers contain the most detailed and recent geological data and facts on the composition, origin and distribution of the Kopaonik Block, as a specific part of the Vardar Zone with a long and complex evolution. These authors' viewpoints on the Vardar Zone, and on the Kopaonik area as its integral part, can be summarized as follows:

a) both authors distinguish the Vardar Zone, as a separate first-order geotectonic unit which is presently located between the Drina-Ivanjica Element/Terrane (DIE) and the Serbian-Macedonian Massif/Composite Terrane (SMCT) (Fig. 3).

b) Dimitrijević (1995, 1997, 2000, 2001) divide the Vardar Zone into three Sub-zones: External (EVSZ), Central (CVSZ), and Internal (IVSZ). The Kopaonik Block (KB), as one of its integral parts covers the whole southern part of the EVSZ (Figs. 2 and 3). Its boundaries are: the Západná Morava trough in the north, the regional tectonic zone Vrnjačka Banja-Brzeće-Podujevo-Preševo in the east, Skopje depression in the south, and as specific element, the Studenica Slice, and Kosovska Mitrovica Flysch of the DIE in the west.

c) Karamata (1995), Karamata et al. (2000), and Resimić-Šarić et al. (2000), divide the Vardar Zone into three Sub-zones as well: the Vardar Zone Western Belt (VZWB), Kopaonik Block and Ridge Unit (KBRU) including the Kopaonik block (Kb), and Main Vardar Zone (MVZ) (Fig. 3). Such division differs from that by M.D. Dimitrijević (loc. cit.) because the VZWB and the KBRU (with Kb) correspond to EVSZ, while MVZ includes both CVSZ and IVSZ. Thus, the Kopaonik block covers a smaller area, because its western boundary is in the valley of the river Ibar, and it narrows in the direction Kosovska Mitrovica-Sitnica-Lab in the south (Fig. 2). Its southern boundary is not precisely defined yet, because the deposits of the Kb are covered in this area. Besides, the Kb extends northwards to Belgrade and southwards to Priština, in the form of a narrow zone, forming the Kopaonik Block and Ridge Unit.

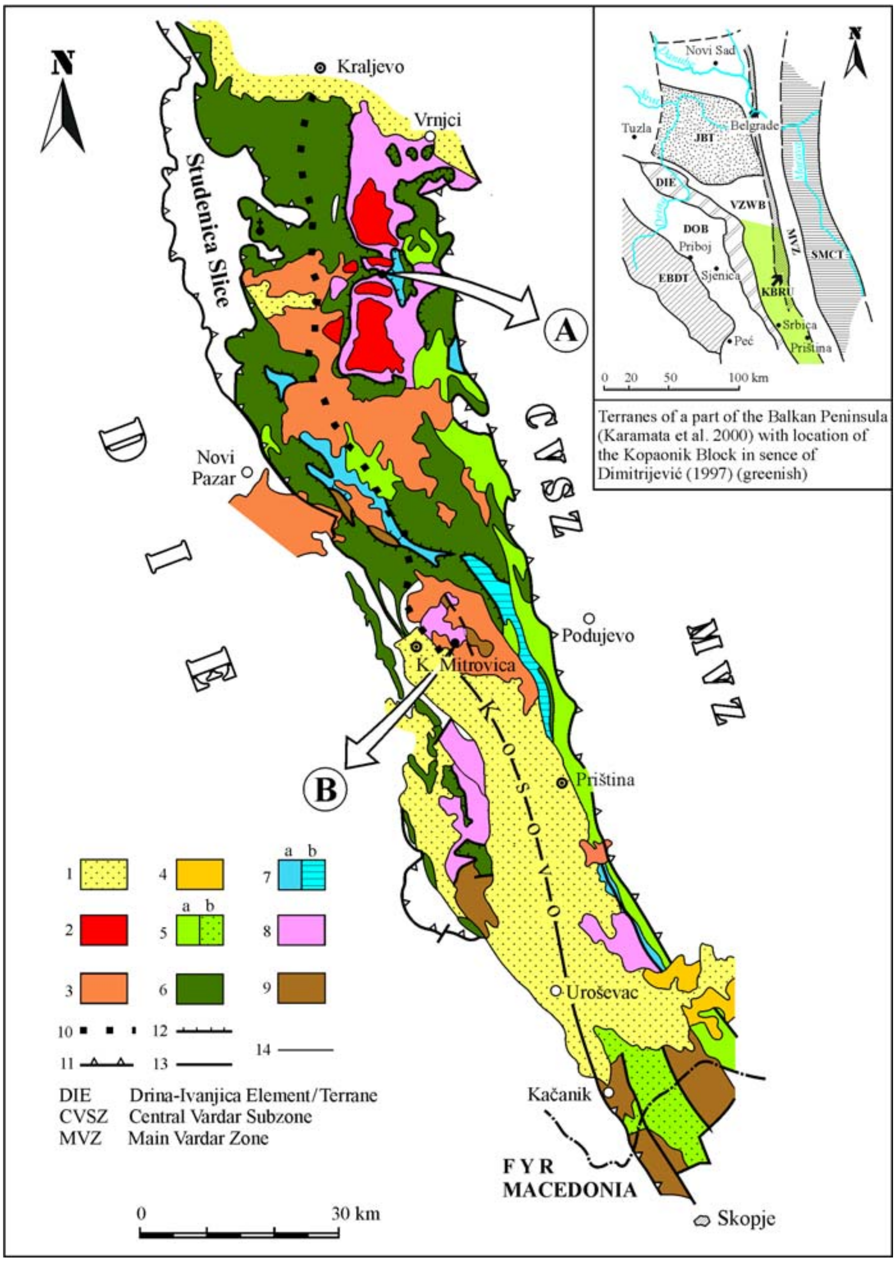

Fig. 2. Kopaonik Block of the External Vardar Subzone (simplified after Dimitrijević 1995, 1997, 2001, and modified according to Karamata 1995; Karamata et al. 2000). **1** — Miocene and Pliocene sediments; **2** — Oligocene-Miocene granodiorites; **3** — Tertiary volcanic rocks; **4** — Binačka Morava Oligocene; **5** — Cretaceous deposits (a — Upper Cretaceous deposits of the Kopaonik Block; b — Kačanik Flysch); **6** — ultramafites; **7** — ophiolitic mélange (a — unmetamorphosed mélange of the western margin of the KBRU (KB) and the VZWB; b — slightly metamorphosed mélange of the eastern margin of KB); **8** — Triassic metamorphites; **9** — Paleozoic metamorphites; **10** — western boundary of the Kb within KBRU (in sense of Karamata 1995 and Karamata et al. 2000); **11** — first order thrust faults: boundaries of the External Vardar Zone; **12** — nappe boundaries within the External Vardar Zone; **13** — normal faults; **14** — sedimentary contacts. Conodont localities: **A** — locality Županj ("Central Kopaonik Series"); **B** — locality Smrekovnica ("Metamorphic Trepča Series").

In the papers by Dimitrijević (1995, 1997, 2000) dealing with the Vardar Zone and with the Kopaonik Mt area, the registration of new facts and evolution of different models, during more than the last 50 years are quoted. In the same papers, and particularly in Dimitrijević (2001), only a rough sketch of the known facts of the evolution of the whole Vardar Zone is given, without consideration of the geological history of its segments, because there were not any and still are no sufficient paleomagnetic data. The only thing mentioned is: "Occurrence of two ophiolitic mélanges — Jurassic and Upper Cretaceous — points to a very intricate history of the ocean closing — the main at the end of the Jurassic, with subsequent opening of a back-arc basin between the main land and the Kopaonik arc." (Dimitrijević 2000, p. 12).

A more detailed discussion on the geological evolution of these areas was given by Karamata (1995), Karamata et al. (2000), and Resimić-Šarić et al. (2000).

Both authors (M.D. Dimitrijević and S. Karamata) start from the fact that the present Vardar Zone is one of the three different Mesozoic ophiolitic belts which exist in the central part of the Balkan Peninsula, and that as such, it is the relic of the main oceanic realm — the Vardar Ocean, which formed the NW part of the (Neo)Tethys. S. Karamata and co-authors are of the opinion that the Vardar Zone includes the relics of (at least) two oceanic areas: (a) the remnants of the Main Vardar (Tethys) Ocean (now the Main Vardar Zone — MVZ) in the east, and (b) formations of the western branch (i.e. scar of a marginal basin or sea) of the Vardar Ocean (now the Vardar Zone

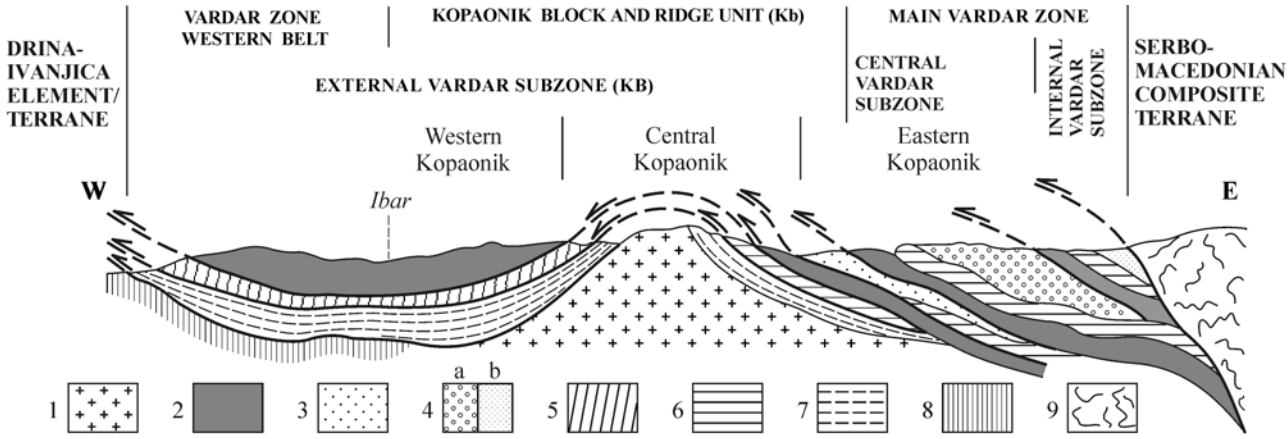

Fig. 3. Schematic tectonic cross-section of the Vardar Zone in the northern area of Kopaonik Mt (slightly modified after Grubić et al. 1995). **1** — Oligocene granodiorites; **2** — ultramafites; **3** — Upper Cretaceous deposits of the Kopaonik Block (KB) i.e. Kopaonik block (Kb); **4** — Cretaceous paraflysches/flysches: a — Lower Cretaceous paraflysch of the Central Vardar Subzone (CVSZ) i.e. Main Vardar Zone (MVZ); b — Upper Cretaceous Toplica flysch of the Internal Vardar Subzone (IVSZ) i.e. MVZ; **5** — ophiolitic mélange of the western margin of the KB i.e. Kb (Kopaonik Block and Ridge Unit (KBRU)) and the Vardar Zone Western Belt (VZWB) — unmetamorphosed; **6** — ophiolitic mélange of the eastern margin of the KB i.e. Kb (KBRU) and the MVZ — slightly metamorphosed; **7** — Triassic and Paleozoic metamorphites (+"Studenica slice"-type); **8** — deposits of the Drina–Ivanjica Element/Terrane (DIE); **9** — metamorphites of the Serbo-Macedonian Composite Terrane (SMCT). 2, 5, 6, 7. thrusts, Late Jurassic structures of Western and Central Kopaonik; 2, 3, 4, 6. Late Cretaceous structures of Eastern Kopaonik. **EVSZ** (External Vardar Subzone)**, KB, CVSZ, IVSZ —** in the sense of Dimitrijević (1997); **VZWB, KBRU**, **Kb**, **MVZ —** in the sense of Karamata et al. (2000).

Western Belt — VZWB) in the west. The KBRU (Kb) which formed during the Upper Triassic and at the beginning of the Jurassic, had previously been an integral part of a continental margin at the side of a large Vardar (Tethys) Ocean. Uplifting of the KBRU (Kb) has been going on till present times. However, its complex evolution resulted in formation of various rock complexes such as ophiolitic mélanges, Upper Cretaceous deposits, as well as large masses of ultramafic, volcanic and granodioritic rocks. The main characteristics of the above mentioned oceanic basins are as follows:

a) The Main Vardar Ocean (MVO, present MVZ) — long continuous existence as the continuation of an Early Paleozoic (or older?) oceanic realm (e.g. of Paleotethys); closing at the end of the Jurassic; presence of Paleozoic island arc relics ("Veles Series"); prevalence of material from the higher parts of the oceanic crust (mafic i.e. basaltic rocks), cherts and lithic sandstone in the olistostrome; absence of limestone olistoplakae; and

b) Western basin of the Vardar Ocean (VOWB, present VZWB) (which originated simultaneously with the closure of the MVO, and was during Jurassic and Cretaceous, the most important oceanic realm in the central part of the Balkan Peninsula) — existence from the Late Triassic to the latest Cretaceous with very long and complex closing with formation of island arcs, obduction of ultramafic masses and development of huge masses of olistostromes. The olistostromes formed in the trench by the closure of the basin are characterized by predominance of sandstones and basalts (MORB and IAB affinity), and presence of cherts (Upper Triassic and younger), and limestone olistoliths of Middle–Late Triassic, Late Jurassic and Late Cretaceous age.

According to the data by Dimitrijević (1995, 1997, 2000, 2001), Karamata (1995), and new observations, the Kopaonik Mt region is composed of the following units (Fig. 2):

a) (low-grade) **metamorphic rocks of (Late?) Paleozoic age** composed of the clastic sediments metamorphosed to sericite-chlorite schists, metasandstones, and rare chlorite-epidote-actinolite schists, metabasalts and calcschists;

b) (very low-grade) **metamorphic rocks of Triassic age** represented by schistous and intensely folded clayish-silty or sandy rocks and deep-water grey, cherty limestones with nodules and rare beds of cherts; intraserial basaltic lava flows (now metabasalts) and small intrusive diabase bodies occur with these sediments only locally;

c) **ophiolitic mélange** representing a typical olistostromal mixture of clasts and olistoliths of different sediments and igneous rocks in a sandy to silty-clayey matrix. In this unit two facies can be distinguished:

c_1) the mélange at the eastern margin of the area, of Jurassic age, slightly metamorphosed, with plenty of basaltic fragments;

c_2) the mélange at the western margin of the Kopaonik block (in the Ibar valley), of Jurassic–Cretaceous age, where the sandstones dominate over all other sedimentary and magmatic rocks together;

d) **Cretaceous sediments**, including the Upper Cretaceous deposits of the Kopaonik Block, and the Kačanik Flysch;

e) very large bodies of **ultramafic rocks** (mostly harzburgites) thrusted over all the aforementioned formations during the Eocene–Lower Oligocene;

f) **volcanics**, of andesitic, dacitic and quartzlatitic (rhyolitic-dacitic) composition, of **Oligocene–Miocene (Tertiary)** age with associated **granodiorites** which were intruded during the same time period into the core of the Kopaonik block and formed a large contact metamorphic aureole;

g) marine Middle Oligocene at the south, the so-called **Binačka Morava Oligocene**; and

h) **Miocene and Pliocene lacustrine deposits.**

In the Kopaonik area Triassic slightly metamorphosed sediments (with rare volcanics and in this case by Dimitrijević 1995 treated as "volcanogenic-sedimentary" formation) are widely developed, especially at the Central Kopaonik and in the region of Trepča, and few "series" were distinguished, mostly locally named, as at the north the "Central Kopaonik Series" or "Suvo Rudište Series", and at the south the "Metamorphic Trepča Series", or the "Stari Trg Series", etc. All these metamorphic rocks, as well as those occurring on Željin and Goč ("Goč", "Željin" and "Banjski Kopaonik" "Series"), and those developed west of the Ibar river ("Studenica Series", "Rogozna" and "Golija" "Series" and "Radočelo" and "Čemerno" "Series"), which are also partly Paleozoic in age, are considered by Grubić (1995) and Grubić & Protić (2000) as equivalents of the Alpine "schistes lustres" of Piemont-type formed in deep-water conditions. In the above mentioned papers the problems concerning their origin, development and age are considered in detail, and interested readers can find more data in them.

S. Karamata (pers. commun.) considers all these rock series as deposits of the continental slope at the margin of the Vardar Ocean, that is the subsided margin of the intraoceanic Drina-Ivanjica carbonate platform (Dimitrijević & Dimitrijević 1991).

After the discovery of conodonts in slightly metamorphic rocks of the northern (in the "Central Kopaonik Series", Mićić et al. 1972), and the southern Kopaonik ("Metamorphic Trepča Series", Klisić et al. 1972), the Late Triassic age of some of their parts/levels was firstly documented. According to the determined conodont fauna (only platform conodonts are cited here: *Gondolella navicula*, *Neogondolella abneptis*, *Neogondolella tethydis*), and the current knowledge on their stratigraphic range, it was determined that the Carnian Stage was present in both "series". On the basis of the original material on which the above mentioned results considering the age of certain parts of the metamorphic rocks on Kopaonik Mt were based, and according to his own material, Sudar (1986) made a revision to the conodonts and their age. Thus, the new data confirmed their Carnian age, and the presence of a Norian Stage in the metamorphites was determined for the first time. Besides, biostratigraphic divisions of the sediments into conodont zones were also performed.

The specific "Central Kopaonik Series" ("CKS") occur all around the Kopaonik granodiorite massif and is composed of phyllitoids (dominantly sericite-chlorite schists), chlorite-epidote-actinolite schists, and (particularly in higher horizons) thin-bedded crystalline limestones. These grey, cherty limestones occur either as the middle horizon with interlayers of pelitic-psammitic rocks, or as interlayers within the uppermost horizon of the "series" made of terrigenous (meta)sediments. The parent rocks were shales, marls, and carbonates, subordinately sandstones, with consedimentary magmatic rocks: basalt (spilite), diabase, dolerite, and tuff.

NW of the village Županj at the right side of the river Jošanička Reka (about 2 km along the road Jošanička Banja-Biljanovac, Fig. 2) in the limestone interlayers in the higher levels of the "series", the following Carnian conodonts were found (conodont determination and zonation from Kopaonik Mt was made by M. Sudar, according to the taxonomic concept and biozonal subdivision by Budurov & Sudar 1990):

a) *Epigondolella echinata*, *Paragondolella navicula*, and *Pg. polygnathiformis* — *Paragondolella polygnathiformis* Zone (middle Cordevolian, Julian, lower Tuvalian);

b) *Pg. nodosa* and *Pg. polygnathiformis* — *Paragondolella nodosa* Zone (lower and upper Tuvalian).

The "Metamorphic Trepča Series" ("MTS") covers an area of about 30 km^2 between Trepča and Smrekovnica (vicinity of Kosovska Mitrovica, Fig. 2) and its lower part is composed of phyllitoids, argillaceous schists, cherts, gneisses, feldspathic micaschists, amphibolite and amphibole schist, and in the middle part of the unit, the Smrekovnica limestones. This metamorphic rock "series" contains abundant basaltoid sills and lava flows of spilitic character.

The following Lower and Middle Norian conodonts were found at a few places in the neighbourhood of Smrekovnica in 100–150 m thin-bedded grey cherty Smrekovnica limestones, with intercalated platy cherts in lower levels and with abundant clayey interlayers:

a) *Ancyrogondolella triangularis*, *Metapolygnathus abneptis, Mp. communisti*, *Pg. navicula*, and *Pg. steinbergensis* — *Metapolygnathus abneptis* Zone (Lacian);

b) *Ag. triangularis*, *Eg. postera*, *Mp. abneptis*, *Pg. hallstattensis*, and *Pg. steinbergensis* — *Epigondolella postera* Zone (Alaunian).

Geological framework of the Bükk Mountains and neighbouring units

Bükk nappe system (Bükk Composite Terrane)

The south-vergent nappe system of the Bükk Mts and adjacent Darnó Hill area at the NE part of the Mátra Mts are built up by the following units: the Bükk Parautochthon Unit (Bükk PA Unit) in the lowermost position and the Szarvaskő and Darnó Ophiolite Complexes emplaced onto it from the NW according to present coordinates (Figs. 4 and 5). However, taking into account the large-scale Tertiary anti-clockwise rotation (up to 90°) of the Bükk block, the original direction of nappe-stacking should have been from the NE to SW, the same as in the Dinarides (see Csontos 1999 and references therein). The subsurface continuation of the Bükk Composite Unit in the basement of the northern Pannonian Basin is bound by the Zagreb-Zemplín (or Mid-Hungarian) Lineament on the south and the Hernád fault on the east. On the west, towards the Transdanubian Range Unit the boundary is not clear, as there could also be a facies transition. Towards the north it will be discussed below at the Uppony and Szendrő Units.

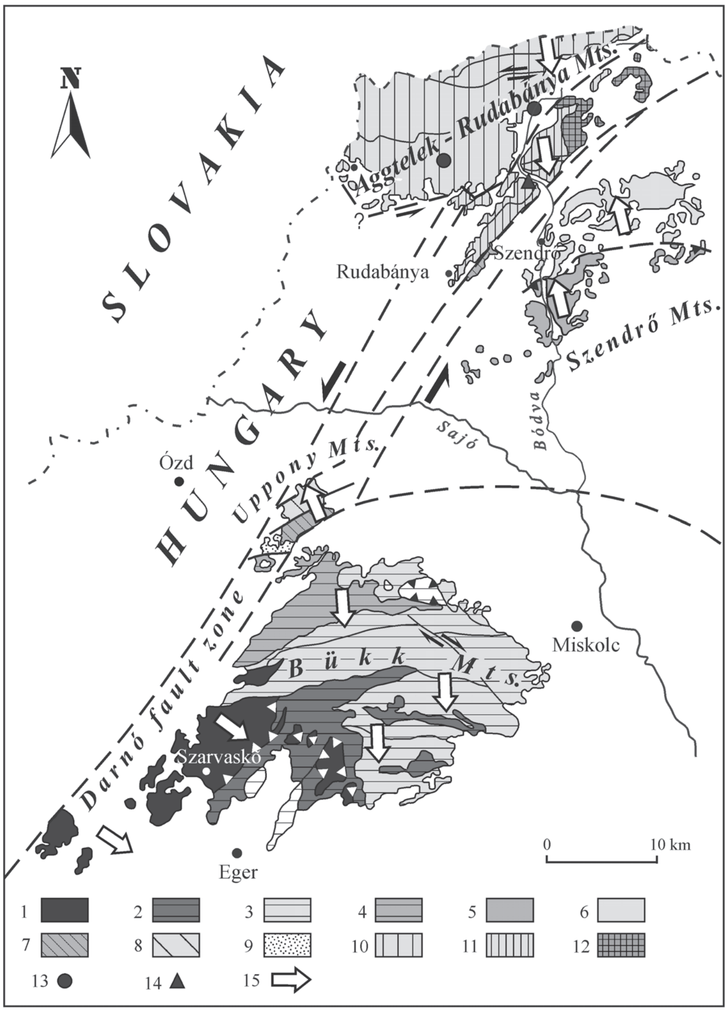

Fig. 4. Structural units in NE Hungary with vergence directions of the nappes. **1–4** — Bükk Mts and Darnó Hill: 1 — Szarvaskő and Darnó Ophiolite Complexes; 2 — Jurassic formations of the Bükk PA Unit; 3 — Triassic formations of the Bükk PA Unit; 4 — Upper Paleozoic formations of the Bükk PA Unit; **5–6** — Szendrő Unit: 5 — Abod Subunit; 6 — Rakaca Subunit; **7–9** — Uppony Unit: 7 — Tapolcsány Subunit; 8 — Lázbérc Subunit; 9 — Upper Cretaceous Gosau-type conglomerates; **10–12** — Aggtelek-Rudabánya Mts: 10 — Aggtelek Unit: *s.l.*; 11 — Bódva (+Szőlősardó Unit); 12 — Martonyi (or Torna *s.s.*) Unit; **13** — Bódva Valley Ophiolite Complex (in boreholes); **14** — Upper Jurassic (?) rhyolites; **15** — structural vergencies.

Triassic. In the course of the Late Jurassic (?)–Early Cretaceous Eohellenic tectogenesis (160–120 Ma, Árkai et al. 1995) the antiforms were formed from the areas of Late Triassic carbonate platforms, whereas the sheared-off synforms developed from the basinal carbonates (grey, cherty limestones; Felsőtárkány Limestone Formation) (Csontos 1988, 1999). The conodonts involved in the present study are from the latter. In the most complete section studied (borehole Felsőtárkány 7) the basinal carbonate sequence extends from the basal Carnian ("*Metapolygnathus*" *diebeli* Zone, together with *Gondolella polygnathiformis*) to the Rhaetian (*Neospathodus posthernsteini* Zone) (Kovács in Velledits 2000).

The emplacement of the Szarvaskő Ophiolite Complex onto the Bükk PA Unit is supposed to have taken place during the latest Jurassic and large-scale folding, resulting in the formation of the antiforms–synforms mentioned above, already affected both units together, accompanied by the first (and likely more intense) metamorphic event (Csontos op. cit.; Fig. 6 herein).

The east-west striking axis of the antiforms plunges to the west. Consequently, stratigraphically older and more metamorphosed sequences are exposed to the east, whereas younger (Jurassic) and less to non-metamorphosed ones appear to the west. The rocks exposed in the eastern and central parts of the Bükk Mts are high temperature anchizonal to epizonal metamorphosed (~350 °C and 300 MPa in average, but reaching up to 500 MPa in some zones; Árkai 1983). The degree of metamorphism and style of deformation suggest, that these processes took place at 5 to 10 km depth (Papanikolaou pers. commun. on the field in 1993). A second tectonometamorphic event (85–90 Ma) can be recognized in the NE part of the Bükk Mts. It is thought to be linked with NW-SE directed strike-slip faulting and arching of the unit (Csontos op. cit.), as well as with the emplacement of the intra-Bükkian, but non or only weakly metamorphosed Kisfennsík

The exposed part of the Bükk PA Unit is built up by four large, S-ward recumbent antiforms and strongly sheared-off synforms between them. Its known stratigraphic sequence extends from the Middle Carboniferous Variscan flysch to the Upper Jurassic Eohellenic flysch (for most the recent reviews see Haas 2001 and Filipović et al. 2003). Following the Late Paleozoic to Early Triassic marine sedimentation (with a hiatus in the Early Permian and coastal plain sediments at the beginning of the Alpine cycle in the Middle Permian), a carbonate ramp environment came into existence during the Anisian. After a significant (mostly andesitic) volcanic activity in the Ladinian, the former ramp desintegrated and platform and basin environments were differentiated during the Late

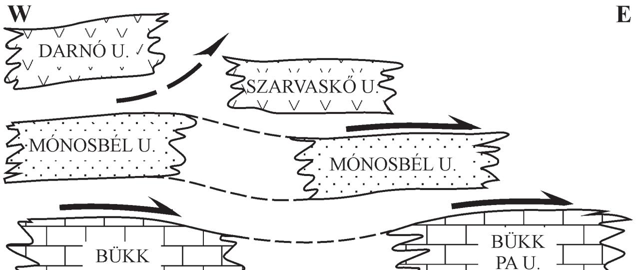

Fig. 5. Structural sketch of the Bükk Composite Terrane (after Haas & Kovács 2001, slightly modified). **U** — Unit; **Bükk PA U** — Bükk Parautochthon Unit.

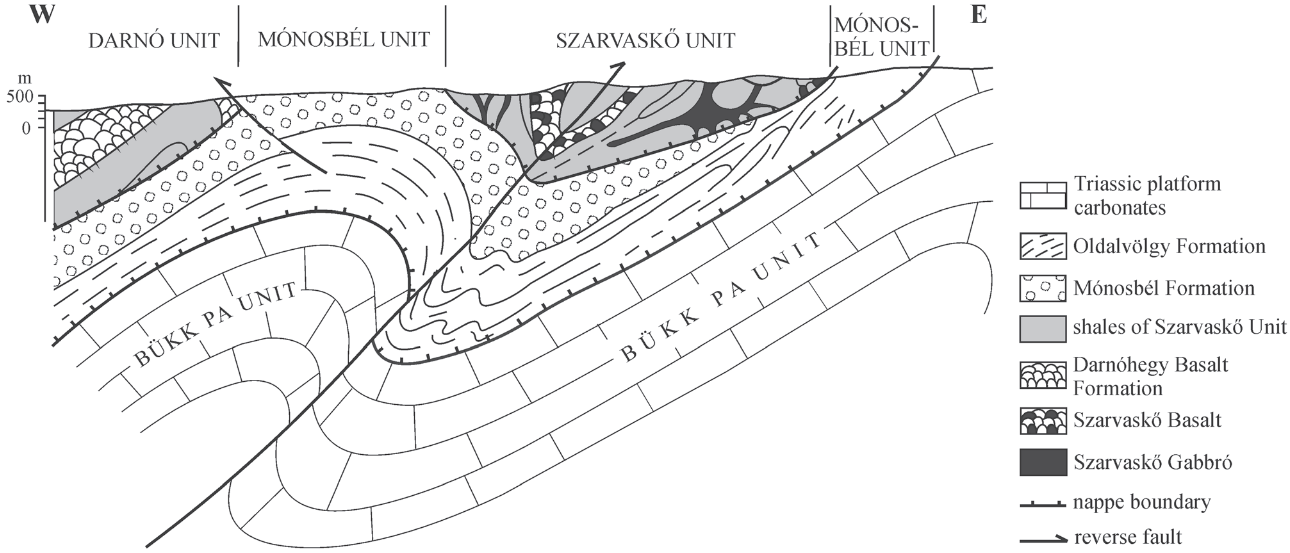

Fig. 6. Structural cross-section of the western part of Bükk Mts, through the Szarvaskő synform (after Gulácsi, in Haas 2001, slightly modified).

(Little Plateau) partial unit (Forián-Szabó & Csontos 2002). Similarly non or weakly metamorphosed intra-Bükkian Triassic occurs below the Szarvaskő Complex to the west, in the vicinity of Felsőtárkány (Velledits 2000), which likely represents the highest part of the Bükk PA Unit, not removed by erosion. The Szarvaskő Complex was affected by low temperature anchizonal (pumpellyite-prehnite facies) metamorphism (Árkai 1973, 1983; Sadek et al. 1996).

Upper Eocene shallow-marine deposits at the base of the Tertiary cover sequence postdate any metamorphic or ductile deformational event in the Bükk Mts.

Uppony and Szendrő Units

These units were previously regarded because of facial and stratigraphic links as part of the "Bükkium" (see, for example, Árkai 1983; Kovács & Péró 1983). However, they have a N-vergent structure, opposite to that of the Bükk PA Unit, therefore they can no longer be considered to form parts of the same tectonostratigraphic unit (cf. Kovács et al. 2000). They are separated from the Bükk PA Unit by the Nekézseny fault and its supposed E-ward continuation (Fig. 4).

The Uppony Unit of small surface areal extension is built almost exclusively of Paleozoic formations and is enclosed entirely within the Darnó fault zone (Fig. 4). For its stratigraphy we refer to Kovács (1992) and Ebner et al. (1998). As opposed to the Bükk PA Unit and related ophiolitic units, it has a N-vergent structure. The Paleozoic rocks were affected by a mid-Cretaceous (118 ± 14 Ma) tectonometamorphic event (Árkai et al. 1995), with metamorphic conditions reaching the boundary zone between the anchizone and epizone (350 °C, ~250 MPa; Árkai 1983). Upper Cretaceous Gosau-type sediments, covering the southern part of the unit, postdate this event.

The Szendrő Unit is built up exclusively by Paleozoic (Silurian?–Devonian–Carboniferous) formations and also has a N-vergent structure (Fig. 4). For details on its stratigraphy we refer to Kovács (1992) and Ebner et al. (1998). Facially, it appears to be linked with the Bükk Upper Paleozoic, however, their different vergencies point to a clear structural distinction (Kovács et al. 2000). The Paleozoic rocks were affected by a mid-Cretaceous (108 ± 8 Ma) tectonometamorphic event (Árkai et al. 1995) of greenschist facies, or epizonal conditions (~400 °C, ~300 MPa; Árkai 1983). It indicates the chlorite isograde, however, in some parts even the biotite isograde (min. 450 °C) was recorded (Árkai op. cit.).

Aggtelek-Rudabánya Units

The Aggtelek-Rudabánya Units include the non-metamorphosed Aggtelek and Bódva Units and the metamorphosed Torna *s.s.* or Martonyi Unit (Grill et al. 1984; Less 2000; Fig. 4 herein). They are formed by Upper Permian to Jurassic, but mainly Triassic formations (Kovács et al. 1989). The dismembered ophiolites (serpentinites, gabbros, basalts, some radiolarites and siliceous shales) do not form a distinct structural unit, but occur in the sole-thrust of the Aggtelek Unit, imbricated as isolated bodies/slices into Upper Permian evaporites (Réti 1985), as shown by borehole evidence.

The Aggtelek and Bódva Units were affected only by diagenetic alterations, whereas the Torna *s.s.* or Martonyi Unit by anchizonal to epizonal metamorphism of medium pressure (~350 °C, ~700 MPa; Árkai & Kovács 1986). The age of the tectonometamorphic event is poorly constrained, but appears to be also of Early to middle Cretaceous age (128 and 115 Ma, respectively; Balogh Kad. 1991 in Kovács et al. 2000). The ductile deformational history of the Martonyi Unit along a NNW–SSE section, with obviously southward overturned setting, was presented by Fodor & Koroknai (2000). The Aggtelek and Bódva Units show a southward thrust and folded structure, but northward backthrusts are also recognizable (Péró et al. 2002, 2003).

Metamorphosed Upper Triassic (Carnian-Norian) grey, cherty limestones of the Torna *s.s.* or Martonyi Unit, referred to as "metamorphosed Pötschen Limestone Formation" (Kovács et al. 1989), are of particular importance for our comparison, because the metamorphosed conodonts of the same age from the Kopaonik Mt presented herein, and those from other territories of the former Yugoslavia (see below) derive from similar lithologies. Such limestones in the Bükk PA Unit are called "Felsőtárkány Limestone Formation" *s.l.* (Haas 2001).

Conodont alterations

Colour alteration indices (CAI), recrystallization and ductile deformation of conodonts in the units from Serbia and NE Hungary are discussed and compared in this chapter.

Serbia

Kopaonik, metamorphosed Upper Triassic limestones

The Upper Triassic conodonts from the Kopaonik Mt included in this study come from two localities: Smrekovnica ("MTS"), in the southern part and Županj ("CKS"), in the northern part of the mountains. The illustrated ones (Figs. 7–9) are all from the former locality.

The colours of the conodonts from both localities are partly black to dark grey (CAI = 5 to 5.5), partly grey to white (CAI = 6 to 7). In some samples the former, in some others the latter predominate. However, CAI values 5–6–7 (black–grey–white) may occur not only within the same sample, but even within different parts of the same, recrystallized, usually fractured and deformed specimen (Kovács & Árkai 1987). An example concerning recrystallization is shown in Fig. 10.1–4 herein: the middle part of the carina shows CAI = 7 (Fig. 10.1,2), while the anterior part CAI = 6 (Fig. 10.3,4), without remarkable difference in the degree of recrystallization.

All of the conodont specimens involved into the present study are considerably recrystallized and usually ruptured by minor cracks, which did not result in their complete breaking apart. The degree of recrystallization was analysed on the same parts (middle or anterior part) of the carina of selected specimens at standard SEM magnifications: 1000× and 3000× (see Figs. 10 and 12). Apatite grain size on these photos could be measured between 0.83 and 9.66 micrometers, in average 4.42 micrometers.

Many of the specimens show ductile deformation, evidently in accordance with the development of the foliation and texture with preferred orientation of their enclosing metamorphosed limestone/marble host rock. In some cases they show extreme, crook-like (Fig. 7.8–11; Fig. 9.1–3), or even accordion-like (Fig. 9.4–6) bending.

NE Hungary

Bükk Parautochthon Unit

The first report on the presence of metamorphosed, recrystallized and deformed conodonts in the NE part of the Bükk Mts was given by Kozur & Mock (1977). Detailed metamorphic petrologic study of low- to very low-grade metamorphosed rocks of the NE part of the mountains was presented by Árkai (1983) (for earlier works see references therein). Although metamorphic alteration of conodonts was compared to the metamorphic petrological parameters of other units of NE Hungary by Árkai & Kovács (1986), and Kovács & Árkai (1987, 1989), such a comparative work for the Bükk PA Unit has not been presented up to now. A number of samples were analysed for conodonts from the central and SE part of the mountains (the latter being not accessible for geological studies before 1990) by S. Kovács in collaboration with G. Nagy and P. Pelikán during the field works of the recently published geological map of the Bükk area (Less et al. 2002), which have also been unpublished so far. In the present contribution we provide a brief summary of metamorphic alterations of conodonts of Upper Triassic cherty limestones (Felsőtárkány Limestone Formation *s.l.*; for areal distribution see Less et al. 2002) and compare them with those of the Kopaonik Mt.

These cherty limestones in the NE, central and SE part of the mountains, where the structurally deeper parts of the E–W striking, W-ward plunging antiforms are exposed, are strongly schistose and folded, with even macroscopically clearly visible S_1 and locally S_2 schistosity (cf. Németh & Mádai 2003), the latter resulting in characteristic S/C structures (Koroknai pers. commun.). Conodonts here are strongly recrystallized (Fig. 12.3–6), of greyish-whitish colour (CAI = 6–7), but often of completely white colour (CAI = 7) and strongly sheared-deformed (Fig. 11). Evidently, their ductile deformation was first of all related to the development of the S_1 schistosity, although the S_2 could also contribute to their deformation. At the south-easternmost part of the mountains, however, conodonts are mostly black to dark grey coloured (CAI = 5–5.5), less recrystallized and non-deformed. In this latter area the structurally higher parts of the southernmost antiforms may be exposed. However, metamorphic petrologic investigations from this area are still missing and precise thermobarometric evaluations are not yet available.

Triassic limestones occurring in the SW Bükk Mts below Jurassic rocks (the latter belonging mostly to the "Szarvaskő-Mónosbél nappes" in the sense of Csontos 1988) show only weak or no foliation at all (cf. Velledits & Péró 1987; Velledits 2000). Conodonts from the type section of the Felsőtárkány Limestone Formation (borehole Felsőtárkány 7), extending in age from the basal Carnian to the Rhaetian (Kovács in Velledits op. cit.), are black (CAI = 5), not recrystallized and not deformed. Together with the limestone textures they would indicate the boundary interval of diagenesis and regional metamorphism or the low temperature part of the anchizone. This is in accordance with metamorphic petrologic pa-

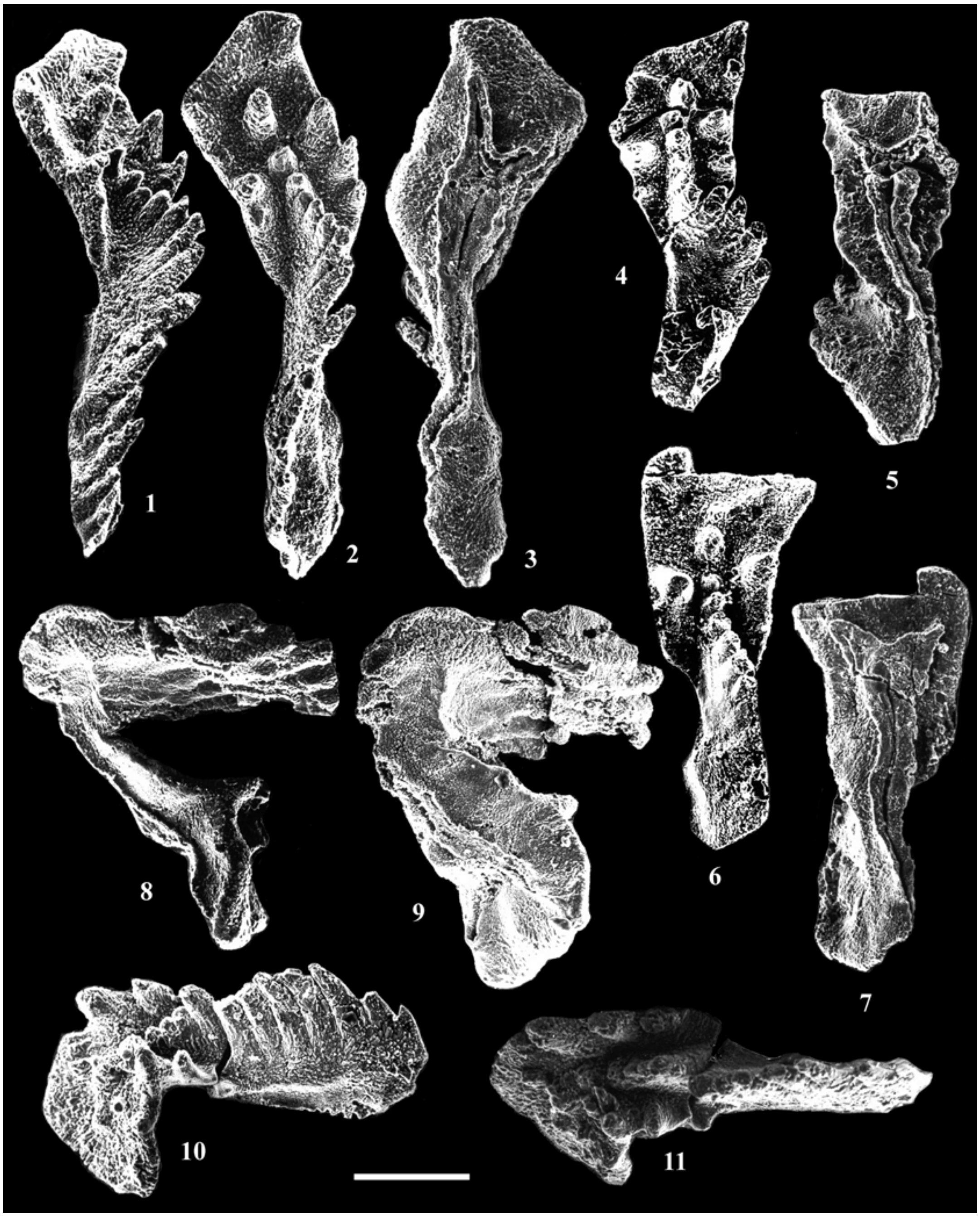

Fig. 7. Metamorphosed, recrystallized and deformed conodonts from Upper Triassic Smrekovnica Lms. (Norian, Alaunian, *Epigondolella postera* Zone) of the "Metamorphic Trepča Series", Smrekovnica, Kopaonik Mt, Vardar Zone, Serbia. **1–11** — *Metapolygnathus abneptis* (Huckriede, 1958). 1–3 — CAI 6–7, specimen with a gentle elongated and twisted free blade and slightly curved platform, No. 2/MS 884. 4–7 — CAI 6, specimens with a gentle twisted anterior part of carina, 4, 5. No. 5/MS 882, 6, 7. No. 7/MS 882. 8, 9 — CAI 6–7, extremely deformed specimen with a U-shaped carina, No. 3/MS 884. 10, 11 — CAI 6–7, specimens with a strongly curved posterior part of the platform, No. 1/MS 884. Scale bar = 100 μm (magnification: 200×).

rameters published from the Szarvaskő area slightly to the north (Árkai 1973; Sadek et al. 1996). This Triassic sequence may represent an intra-Bükkian partial unit on top of the metamorphosed antiforms, like the Kisfennsík (Little Plateau) Nappe in the NE part of the mountains (Forián-Szabó & Csontos 2002), or the structurally highest part of one of the antiforms.

Szendrő and Uppony Hills

The metamorphic petrologic parametres of the Szendrő and Uppony Paleozoic (which endured only Alpine metamorphism, with no proofs of any Variscan phase; Árkai et al. 1995) are summarized in the chapter "Geological setting"; for more details see Árkai (1977, 1983) and

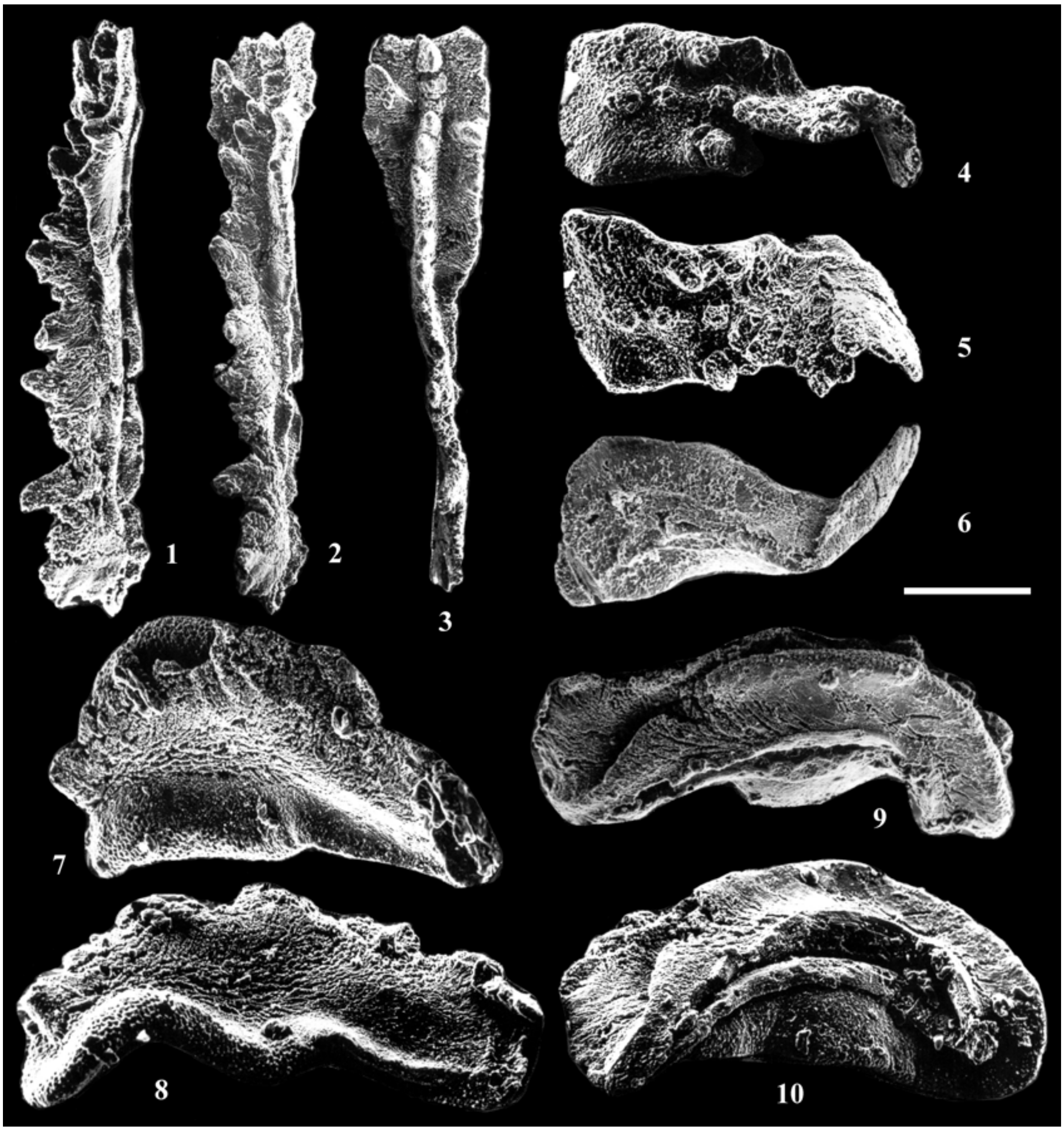

Fig. 8. Metamorphosed, recrystallized and deformed conodonts from Upper Triassic Smrekovnica Lms. (Norian, Lacian and Alaunian, *Metapolygnathus abneptis* and *Epigondolella postera* Zones) of the "Metamorphic Trepča Series", Smrekovnica, Kopaonik Mt, Vardar Zone, Serbia. **1–6** — *Metapolygnathus abneptis* (Huckriede, 1958). 1–3 — CAI 6–7, extremely elongated specimen, No. 4/MS 872, *Metapolygnathus abneptis* Zone. 4–6 — CAI 6–7, specimen with a strongly curved anterior part of carina, No. 6/MS 882, *Epigondolella postera* Zone. **7–10** — *Paragondolella hallstattensis* Mosher, 1968. CAI 6–7, double twisted specimen, No. 10/MS 880, *Metapolygnathus abneptis* Zone. Scale bar = 100 μm (magnification: 200×).

Árkai et al. (1981). Correlation with metamorphic alteration of conodonts was briefly given in Kovács & Árkai (1987), with some specimens illustrated. This latter we just summarize here, for comparison with previously undescribed alteration of conodonts from the Kopaonik and Bükk Mts.

Conodonts of the Szendrő Paleozoic (from Middle Devonian to Middle Carboniferous, e.g. up to Early Bashkirian) are mostly light grey to white coloured (CAI = 6–7, usually within the same specimen), strongly recrystallized and often deformed. However, in some samples, especially those from the Upper Visean to Lower Bashkirian Verebeshegy Limestone Member, all the specimens were black (CAI = 5), but similarly strongly recrystallized and deformed (cf. Kovács & Árkai 1987, Pl. 13.4, Figs. 3–6; Pl. 13.5, Figs. 6–10).

Conodonts of the limestone formations of the Uppony Paleozoic (from the Upper Devonian to Middle Carboniferous, e.g. from Frasnian to Early Bashkirian) are black (CAI = 5), less recrystallized and not deformed (cf. Kovács & Árkai 1987, Pl. 13.4, Figs. 1–2). Conodonts from older limestone blocks of olistostromal formations show even higher CAI values (6–7), but they are not recrystallized and free of any deformation; because of their specific conditions of preservation they are not considered here for comparison.

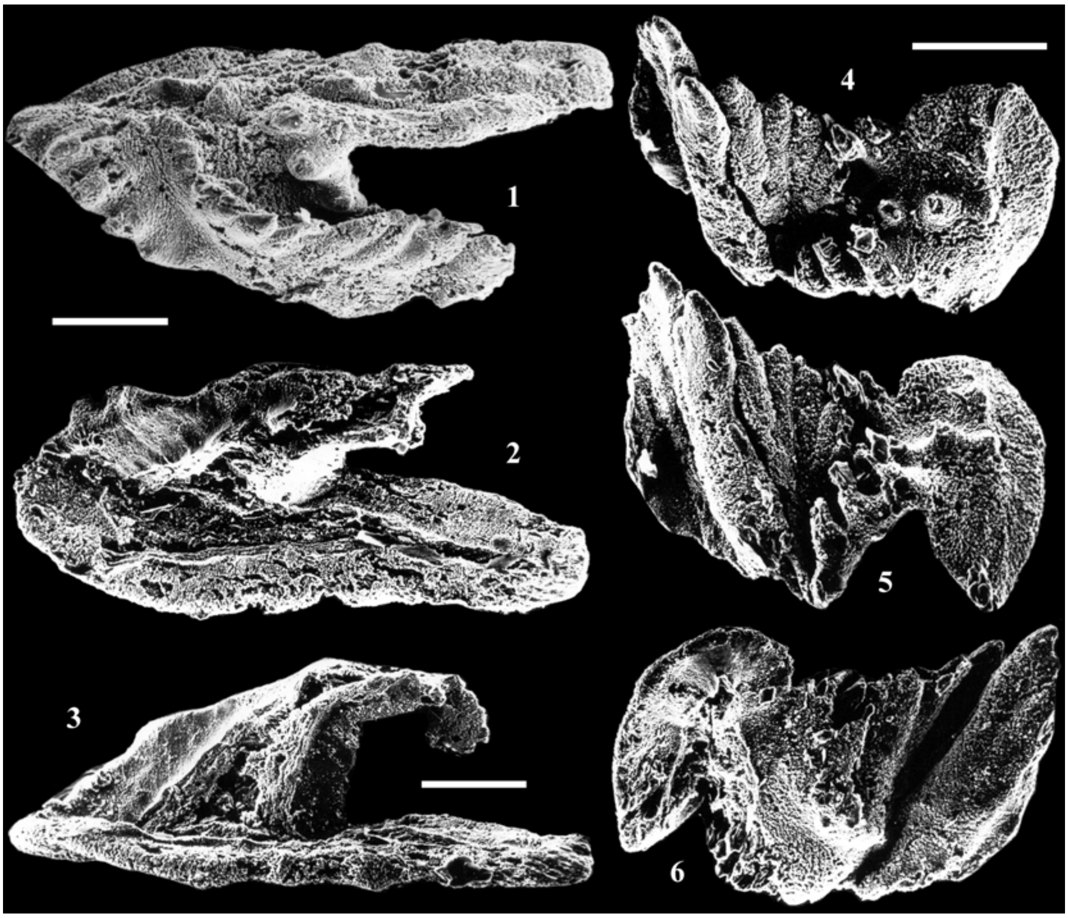

Fig. 9. Metamorphosed, recrystallized and deformed conodonts from Upper Triassic Smrekovnica Lms. (Norian, Alaunian, *Epigondolella postera* Zone) of the "Metamorphic Trepča Series", Smrekovnica, Kopaonik Mt, Vardar Zone, Serbia. **1–3** — *Ancyrogondolella triangularis* Budurov, 1972. CAI 6, extremely deformed specimen from sinistral sheared regime, No. 9/MS 885. **4–6** — *Metapolygnathus abneptis* (Huckriede, 1958). CAI 6, complexly bent specimen in a accordion-like form, almost unrecognizable, No. 8/MS 885. Scale bars for figs. 1, 2 = 100 μm (magnification: 172×); for fig. 3 = 100 μm (magnification: 156×); for figs. 4–6 = 100 μm (magnification: 200×).

Aggtelek-Rudabánya Mountains

Conodont alteration in the tectonostratigraphic units of the Aggtelek-Rudabánya Mts and their correlation with metamorphic petrologic parameters were described in detail in Árkai & Kovács (1986) and Kovács & Árkai (1987, 1989). Those of the non-metamorphosed Aggtelek and Bódva Units are of light brownish-grey to dark grey (CAI = 2 to 4, 5), exceptionally black colour (CAI = 5). They can show a corroded surface, but lack features of recrystallization or deformation. According to illite "crystallinity" indices both (except the specific Telekesoldal Subunit) were not affected by a temperarure higher than 200 °C.

Conodonts of the epizonal (Esztramos) and high temperature anchizonal (surrounding of Hidvégardó–Becskeháza–Tornaszentjakab; Becskeháza Subunit in sense of Less 2000) partial units of the Torna *s.s.* (or Martonyi) Unit, exposed in NE part of Rudabánya Mts, are light grey to white coloured (CAI = 6–7), strongly recrystallized and deformed (see Kovács 1986, Pls. 4–9 and 13; Kovács & Árkai 1987, Pl. 13.2, Figs. 5, 6 and Pl. 13.5, Figs. 1–5; Kovács & Árkai 1989, Pl. 3, Figs. 3–6, Pl. 4, Figs. 2, 4, 6, 7). Especially strongly sheared, flattened specimens are completely whitened; samples with such conodonts likely indicate zones of intense ductile shearing. These partial units endured a medium-pressure metamorphism (Árkai & Kovács 1986). However, from the region between Bódvarákó and Martonyi (Bódvarákó and Martonyi *s.s.* Subunits; Fodor & Koroknai 2000) samples collected mainly by Gy. Less yielded conodonts, which are black (CAI = 5), recrystallized, but not deformed.

Ductile deformation of limestones

Detailed studies on the ductile deformation of micritic limestones were carried out by Burkhard (1990) in the Swiss Alps. Accordingly, plastic deformation of such limestones may begin at temperatures as low as 150 °C. However, it was found, that up to the temperature 300 °C, the dominant deformational mechanism is grain boundary sliding. Crystallographic preferred orientation and features of dynamic recrystallization are missing at these temperatures; these were found to develop above 300 °C.

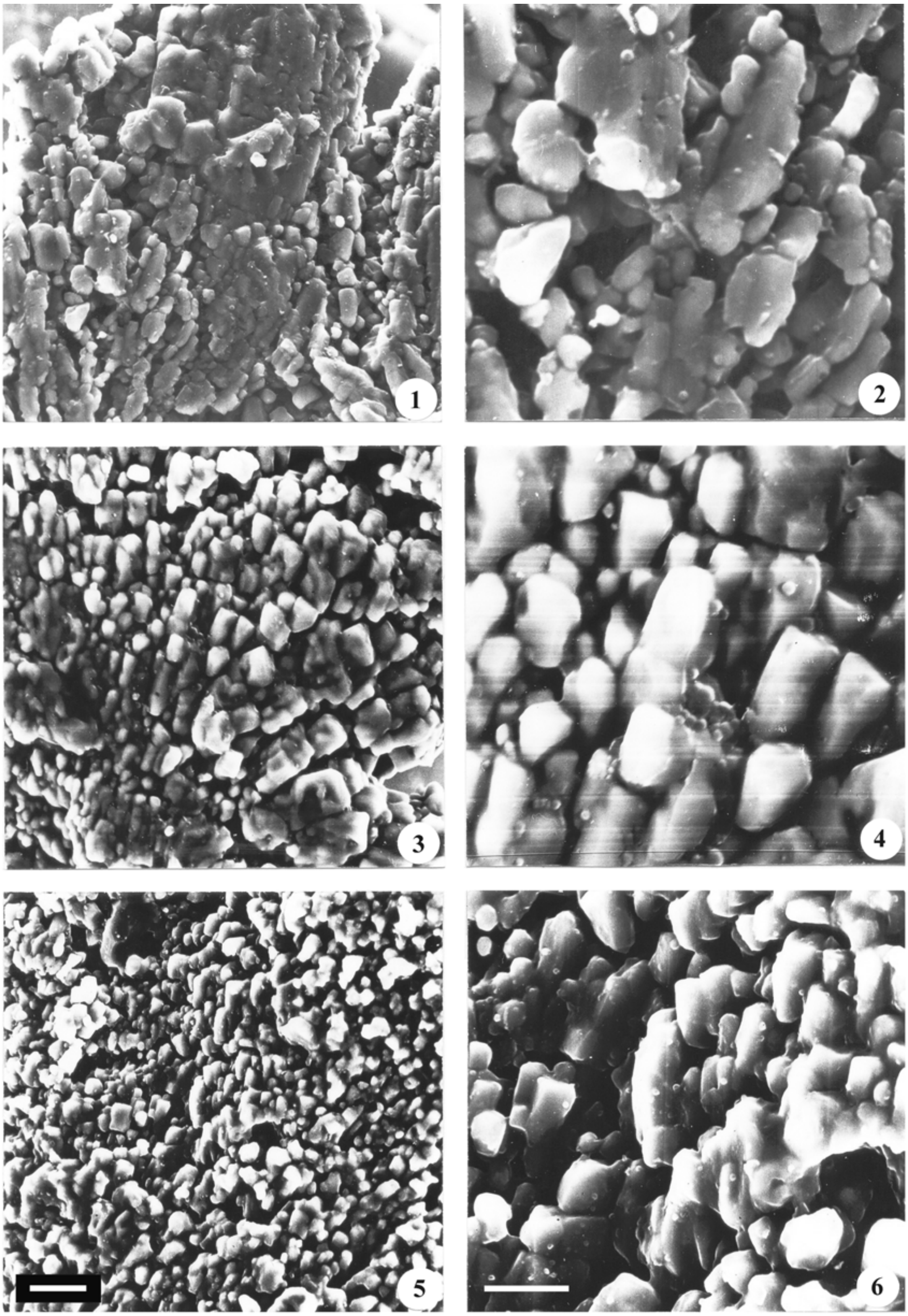

Fig. 10. Details of the surface of the metamorphosed conodonts having different CAI values. Upper Triassic Smrekovnica Lms. (Norian, Lacian and Alaunian, *Metapolygnathus abneptis* and *Epigondolella postera* Zones) of the "Metamorphic Trepča Series", Smrekovnica, Kopaonik Mt, Vardar Zone, Serbia. **1–6** — *Metapolygnathus abneptis* (Huckriede, 1958). 1, 2 — CAI 7, the surface from the middle part of the carina of the strongly recrystallized conodont. 3, 4 — CAI 6, the surface from the anterior part of the carina of the same specimen as on 1, 2. 1–4. No. 4/MS 872 (Fig. 8.1–3), *Metapolygnathus abneptis* Zone. 5, 6 — CAI 6, the surface from the anterior part of the carina of the strongly recrystallized conodont, No. 8/MS 885 (Fig. 9.4–6), *Epigondolella postera* Zone. Scale bars for figs. 1, 3, 5 (on fig. 5) = 5 μm (magnification: 2000×); for figs. 2, 4, 6. (on fig. 6) = 2.5 μm (magnification: 6000×).

Fig. 11. Metamorphosed and deformed Upper Triassic (Carnian and Norian) conodonts from the Bükk Mts, NE Hungary. **1–3** — *Gondolella polygnathiformis* Budurov et Stefanov, 1965. Carnian, road between Szinva Spring to Hollóstető, sample No. SzF-Ht-18. **4** — *Metapolygnathus abneptis triangularis* (Budurov, 1972). Norian, sample Setétvölgy-3. **5** — *Metapolygnathus abneptis abneptis* (Huckriede, 1958). Norian, base of cliff Füzérkő. **6–12** — *Gondolella steinbergensis* (Mosher, 1968). Norian, sample Pazsag-1, 11, 12, isoclinally deformed, crook-like specimens. Scale bar = 100 μm (magnification: 100×).

At these higher temperatures, increase in grain size and plastic flow by twinning, strongly dependent on the grain size, as well as other intracrystalline slips together with dynamic recrystallization result in well developed crystallographic textures, such as preferred orientation.

Kovács & Árkai (1987, 1989) empirically subdivided limestone textures into three types, both for platform and basinal facies.

Type A: Intact original microfacies, without any incipient foliation or schistosity.

Type B: Incipient preferred orientation with microscopically observable foliation or schistosity (generally S_1). Allochemical components (bioclasts, such as calcified radiolarian tests or pelagic bivalve shells — "filaments") are still recognizable, although they are flattened into the plane of schistosity. The matrix is still distinct, usually only weakly recrystallized in pelagic limestones.

Type C: The original microfacies is completely obliterated by recrystallization, the matrix or cement cannot be distinguished from formerly existing bioclasts or intraclasts. A homogeneous microsparitic or sparitic texture (= metasparite or marble) is formed, with well-expressed preferred orientation. Only large grains (such as echinoderm fragments) are still distinct, showing intense twinning.

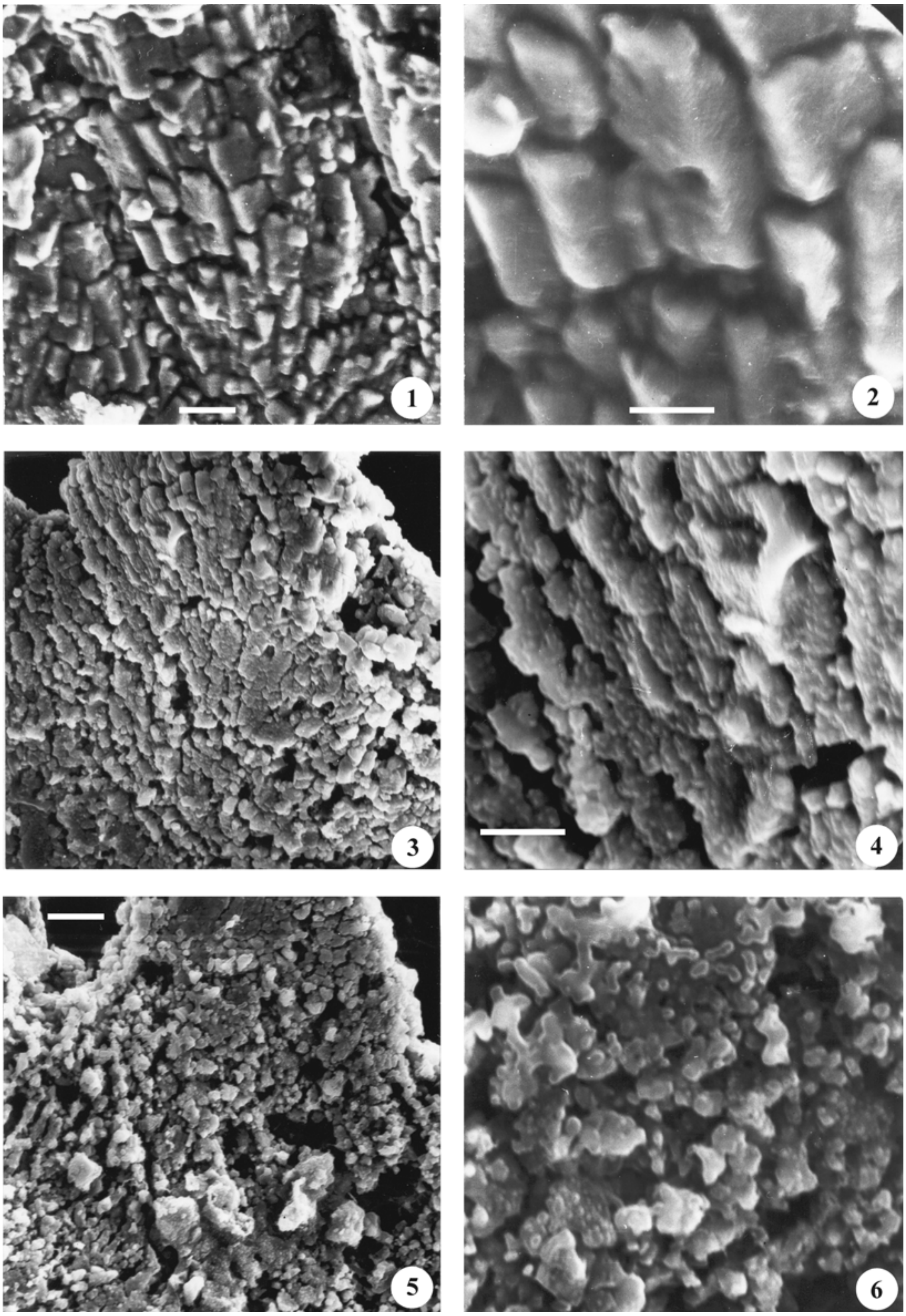

Fig. 12. Details of the surface of the metamorphosed conodonts having different CAI values. **1, 2** — *Metapolygnathus abneptis* (Huckriede, 1958). CAI 6–7, the surface from the anterior part of the carina of the strongly recrystallized conodont, No. 1/MS 884 (Fig. 7.10), Upper Triassic Smrekovnica Lms. (Norian, Alaunian, *Epigondolella postera* Zone) of the "Metamorphic Trepča Series", Smrekovnica, Kopaonik Mt, Vardar Zone, Serbia. **3, 4** — *Gondolella polygnathiformis* Budurov et Stefanov, 1972. CAI 5.5, the surface from the anterior part of the carina of the strongly recrystallized conodont, Upper Triassic (Carnian), sample No. SzF-HT-18, road between Szinva Spring to Hollóstető, Bükk Mts, NE Hungary. **5, 6** — *Gondolella steinbergensis* (Mosher, 1968). CAI 7, the surface from the anterior part of the carina of the strongly recrystallized conodont (shown on Fig. 11.9), Upper Triassic (Norian), sample Pazsag-1, Bükk Mts, NE Hungary. Scale bars for fig. 1 = 5 μm (magnification: 2000×); for fig. 2 = 2.5 μm (magnification: 6000×); for figs. 3, 5 (on fig. 5) = 10 μm (magnification: 1000×); for figs. 4, 6 (on fig. 4) = 5 μm (magnification: 3000×).

This "type C" texture obviously corresponds to the one, which forms at temperatures above 300 °C in deformed limestones according to Burkhard (1990).

Evidently, the recrystallization and ductile deformation of conodonts took place in definite interaction with those of the limestone host rock, that is above the 300 °C minimal temperature boundary.

For the investigations of the ductile deformation and illite "crystallinity" of limestones from the Kopaonik Mt, samples were taken only from the Županj ("CKS"), because the deposits of the Smrekovnica ("MTS") in the southern Kopaonik Mt are located in the territory of Kosovo, where geological investigations have not been possible during the last ten years.

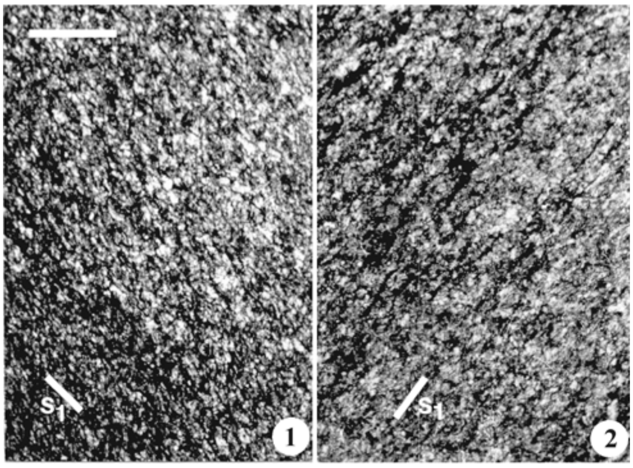

Fig. 13. Textures of metamorphosed Upper Triassic grey, cherty limestones/marbles from the Kopaonik Mt, Serbia. Samples were taken along the road leading from Brzeće to Kopaonik Sky Center, near the eastern gate of Kopaonik National Park. **1** — Marble with faint developed S_1 foliation, sample MS 1851. **2** — Marble with well developed S_1 foliation, sample MS 1852. Scale bar = 1 mm (magnification: 17.5×).

From the Kopaonik Mt, thin sections were made only from the "CKS" Upper Triassic grey cherty limestones which outcrop on the eastern slope of the main ridge (on the first curve of the road Brzeće–Kopaonik Sky Center (Suvo Rudište) after the eastern gate of the Kopaonik National Park). They show strong, rather xenotopic recrystallization with well-expressed preferred orientation (foliation/S_1 schistosity) and correspond to a higher degree of type C metasparites/marbles (see Fig. 13).

The Upper Triassic grey cherty limestones of the anchi- to epizonal metamorphosed Bükk PA Unit show both B and C type textures, independently from the degree of deformation of conodonts: strongly deformed and recrystallized specimens may occur in both textures. Similar limestone textures and deformed/recrystallized conodonts characterize the anchi- to epizonal metamorphosed Torna *s.s.* (or Martonyi) Unit of the Aggtelek-Rudabánya Mts (for details see Árkai & Kovács 1986; Kovács 1986 and Kovács & Árkai 1989) (see Fig. 14).

Illite "crystallinity"

Altogether 7 samples from crystalline cherty limestones with metaclastic intercalations were analysed by X-ray powder diffractometry in the Institute of Geochemical Research of the Hungarian Academy of Sciences, by P. Árkai and K. Judik. They derive partly from the eastern slope, partly from the western slope of the Kopaonik Mt, from the "CKS" outcrops along the road Brzeće–Kopaonik Sky Center–Jošanička Banja. Unfortunately, the illite "crystallinity" indices (KI — Kübler index) obtained are too ran-

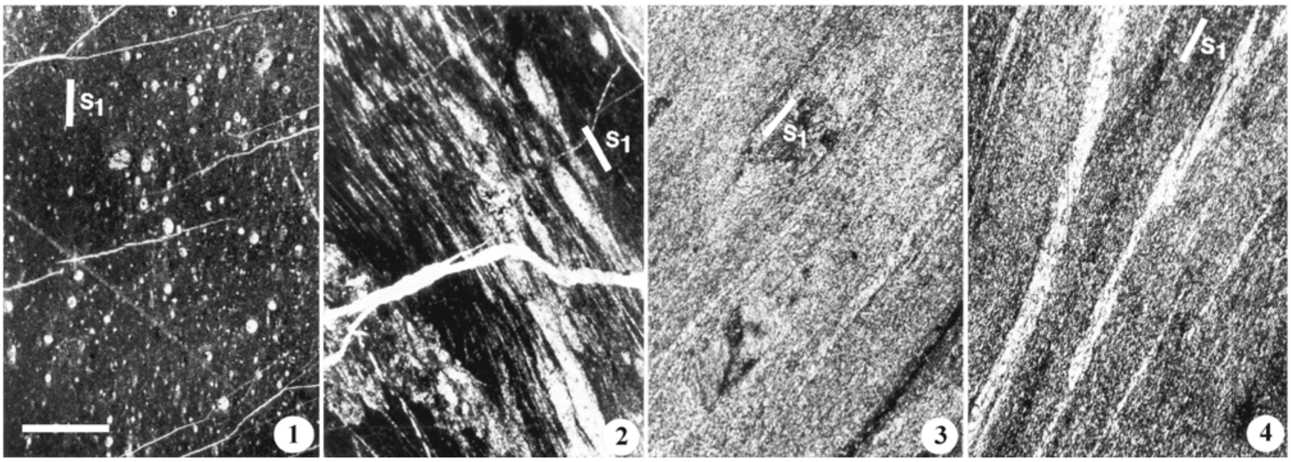

Fig. 14. Textures of metamorphosed limestones from the Bükk Mts (1 and 2) and Szendrő Mts (3 and 4), NE Hungary. **1** — Grey, cherty limestone (Lower Norian) from borehole Felsőtárkány 7, 83.0 m; radiolarian biomicrite with slight, incipient S_1 foliation. (Courtesy of F. Velledits.) **2** — Grey, cherty limestone with well developed S_1 foliation; note the radiolarians strongly flattened into the plane of schistosity. Road cut along the road leading from Eger to Miskolc, between Hollós-tető and Lusta-völgy, sample B-1/1975. **3** — Upper Visean Verebeshegy Limestone, western slope of Bátori-völgy; marble with well developed S_1 foliation and with crinoid fragments, sample Szrő-68. **4** — Upper Visean Verebeshegy Limestone, road curve SE of Rakacaszend; marble with well developed S_1 foliation, sample Szrő-62. Scale bar = 1 mm (magnification: 17.5×).

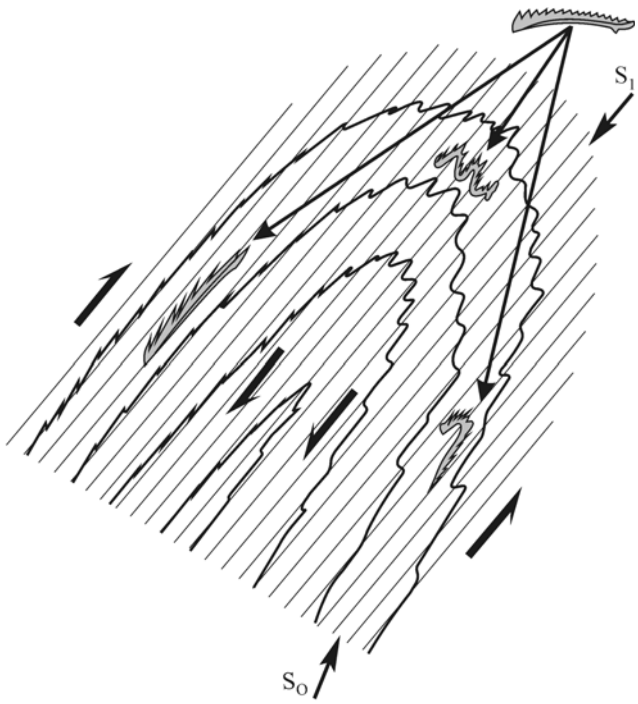

Fig. 15. Possible types of ductile deformation of conodonts in different parts of a fold during the development of axial-plane schistosity (S_1): flattened and elongated (left limb), crook-like (right limb) or accordion-like (hinge zone).

domly scattered for thermometric evaluation, which can be explained by two reasons (Árkai pers. commun.):

a) the samples were too much weathered;

b) the KI indices were partly resetted due to the Oligocene granodiorite intrusion.

Regarding the regional geological setting of the investigated rocks (see Fig. 3), the second case could even be more responsible for the random KI indices.

For correlation of conodont alterations with metamorphic petrologic data (illite "crystallinity", vitrinite and b_o reflectances, mineral parageneses) from NE Hungary the reader is referred to the papers by Árkai & Kovács (1986), and Kovács & Árkai (1987, 1989).

Conclusions

1 — Contemporaneously with the dynamic recrystallization and development of foliation/schistosity of the limestone host rocks, the recrystallization and ductile deformation of conodonts also took place (cf. Fig. 15).

2 — In a dynamic system, in which besides increasing temperature, fluid pressure and oriented/tectonic pressure (stress) also played a significant role, the colour alteration of conodonts took place differently from what could be deduced from laboratory experiments (hydrous pyrolysis at 50 MPa pressure, Rejebian et al. 1987). Due to increasing fluid and tectonic pressure, the lightening

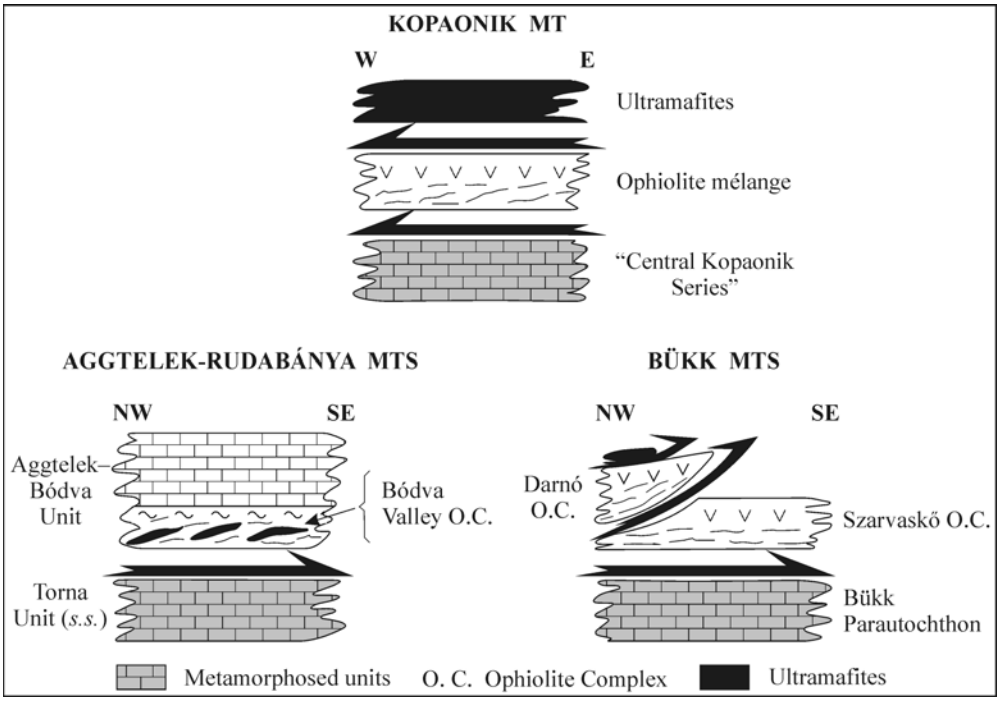

Fig. 16. Structural cartoon of the Kopaonik Mt (Vardar Zone, Serbia) and of the Aggtelek-Rudabánya and Bükk Mts (NE Hungary), illustrating the setting of metamorphosed Triassic carbonates containing the conodonts described herein and in Kovács & Árkai (1987, 1989). These units are situated beneath obducted ophiolite complexes, that were reworked in the Aggtelek-Rudabánya Mts during the emplacement of the non-metamorphosed Aggtelek–Bódva Units (cf. Péró et al. 2002, 2003). Note: the Tertiary 70–90° counter-clockwise rotation recorded in the eastern part of the Pelso Megaunit (=Pelso Composite Terrane) (Márton in Csontos 1999 and Less 2000) implies, that the emplacement of ophiolitic units was originally from the NE to SW, the same, as in the present Dinarides.

(CAI = 6–7 in our case) of the previously blackened (CAI = 5) conodonts could be accelerated. Tectonic shearing could also accelerate this process. Consequently, different colours (black, grey and white) could develop even within the same specimen (cf. also Kovács & Árkai 1987). This makes temperature estimates solely based on the colour of conodonts, even if always the same part of the elements is considered, highly problematic.

3 — The metamorphism and ductile deformation of the conodonts presented here evidently took place contemporaneously with those of the limestone host rocks. The general structural setting (being situated below overthrust ophiolitic nappes; see Fig. 16) suggests that this tectonometamorphic event could be related to subduction and obduction processes (160 to 120 Ma in the Bükk Mts; Árkai et al. 1995). However, subsequent nappe movements could also play a role in the metamorphism and ductile deformation of the limestones and of the conodonts contained in them.

4 — Compared with other methods (illite "crystallinity", mineral paragenesis), at CAI values ≥5 the lowest temperature values given by Rejebian et al. (1987) on the basis of experimental testing seem to be the most realistic approximation to the ones obtained by those methods for conditions of regional dynamothermal metamorphism.

5 — Compared with thermobarometric data of very low to low grade metamorphosed units of NE Hungary containing recrystallized and deformed conodonts with CAI values 5–6–7 (Torna Unit *s.s.*, Szendrő Unit, Bükk PA Unit), at least a Szendrő-type metamorphism (which was of ~400 °C temperature and of ~300 MPa pressure; cf. Árkai 1983) can be assumed for the metamorphosed Upper Triassic limestones of the Smrekovnica ("MTS"). If the apatite grain size illustrated here (Fig. 10.1–6; Fig. 12.1,2) is also compared with those illustrated by Kovács & Árkai (1987) from epizonal metamorphosed units from NE Hungary (Esztramos, Torna Unit *s.s.*: Pl. 13.3, Figs. 5, 6, and Szendrő Unit: Pl. 13.4, Figs. 3, 4 therein), a Szendrő-type metamorphism can also be assumed for the "MTS", e.g the lower part of the greenschist facies, at minimal pressure of the boundary of low and medium pressure domains. The same can also be postulated by comparing the texture and calcite grain size of the recrystallized limestones/marbles; cf. Fig. 13.1,2 and 14.3,4 herein. We should add to this point, that P. Horváth, also at the Institute of Geochemical Research of HAS, Budapest, investigated two metabasite samples from the Županj ("CKS"), collected by the second author, which yielded considerably higher data: 530–550 °C and 500 MPa, as well as 620–630 °C and 500 MPa, respectively (P. Horváth, pers. commun. and unpubl. manuscript).

6 — It is worth noting, that in the high temperature anchimetamorphosed Uppony Unit (at ~350 °C and ~250 MPa; Árkai et al. 1981; Árkai 1983) conodonts are black (CAI = 5), but less recrystallized (Kovács & Árkai op. cit., Pl. 13.4, Figs. 1, 2) and not deformed. It implies, that at temperature ~400 °C and ~300 MPa (e.g. at the Szendrő-type metamorphism) there should be a remarkable increase in metamorphism and deformation of conodonts, that is about at the boundary of the anchizone and epizone, and at the boundary of low and medium pressure domains, respectively. It also underlines, that the metamorphism of "MTS" was at least of Szendrő-type.

7 — As the colour of conodonts under the conditions of regional dynamothermal metamorphism is also influenced by the factors mentioned above, the apatite grain size could probably be a more trustworthy indicator of the temperature of metamorphism. However, detailed studies are needed on the statistic evaluation of the average grain size and its correlation with other metamorphic petrologic methods (illite "crystallinity", chlorite "crystallinity", etc.).

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