

Conodont colour alteration related to a half-graben structure: an example from the Mesozoic of the Mecsek and Villány Hills area (Tisza Megaunit, Southern Hungary)

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(Manuscript received March 14, 2005; accepted in revised form December 8, 2005)

Abstract: The colour alteration of conodonts (CAI) is a good indicator of temperature increase with increasing burial depth. A characteristic example is described herein from the Mecsek and Villány Zones of the Tisza Megaunit (or Tisia Terrane), South Hungary. As well recorded by surface geological and borehole data in the area of the Mecsek and Villány Hills, Middle Triassic conodont-bearing carbonates were buried there to very different depths during the formation of a large half-graben structure from the Late Triassic to Early Cretaceous. In the Mecsek half-graben zone up to 4300 m thick sediments (Upper Triassic atypical, “grey Keuper”, Lower Liassic coal-bearing Gresten Facies, Middle Liassic to Lower Dogger “*Fleckenmergel*” or Allgäu Facies) were deposited until the end of the Bajocian. On the other hand, coeval strata on the adjacent Villány Ridge zone are missing or reach only a maximum thickness of 90 m (Upper Triassic Carpathian Keuper, Pliensbachian sandy, belemnitic limestone). The siliciclastic input ceased after the Bajocian, but the Bathonian to Albian sedimentation and magmatism (Mecsek Zone: Bathonian to Berriasian pelagic carbonates and some cherts, Berriasian to Barremian/Aptian alkaline rift-type basalts and associated volcanoclastic conglomerates with some carbonates; Villány Zone: shallow water carbonates up to Early Albian, flysch-type sediments in the Late Albian) essentially did not result in a further difference between the overburden of the two zones. The investigated conodonts of the Mecsek Zone (deriving from the depocenter of the half-graben zone) became dark grey to blackish coloured (CAI=4), whereas those of the Villány Zone preserved their original yellowish white colour (CAI=1). Neither the Early Cretaceous volcanism in the Mecsek Zone, nor the additional tectonic overburden resulting from middle–Late Cretaceous northward thrusting in the Villány Zone influenced the colour of conodonts. We also made comparison of these CAI values with previously published vitrinite reflectance data from the study area and from some other parts of Hungary. However, the few existing data from the Villány Zone would indicate an excessively high temperature related to the CAI=1 value, implying the necessity of new and more numerous measurements from this region.

Key words: Mesozoic, South Hungary, Tisza Megaunit, Mecsek and Villány Zones, half-graben, colour alteration (CAI), conodonts.

Introduction

Since the basic work of Epstein et al. (1977), the colour alteration index of conodonts (CAI) has been extensively used in many parts of the world to determine the thermal maturity of conodont-bearing (Upper Cambrian to Upper Triassic) sedimentary sequences (Table 1). This method is based on the fact, that conodont elements built of an amorphous variety of apatite (francolite; Pietzner et al. 1968) contain a minor amount of organic matter, which becomes progressively coalified with increasing temperature. In context with the coalification of the organic matter contained, the originally yellowish white or “honey coloured” (CAI=1; see below) conodont elements become darker and darker, and finally black in colour (CAI=5). This colour alteration was experimentally tested and correlated with palynomorph colour alteration and vitrinite reflectance data by Epstein et al. (op. cit.). The Colour Alteration Index (CAI) is based on the alteration of colour during laboratory testing (heating conodonts in electronic furnace un-

der atmospheric conditions) and observation of the colour of conodonts from natural collections.

At further heating the blackened conodonts become grey (CAI=6), then opaque white (CAI=7) and finally crystal clear or glassy (CAI=8). This reverse path of colour alteration is discussed in more details in Sudar & Kovács (2006).

However, Árkai & Kovács (1986) and Kovács & Árkai (1987) observed partly different colours between yellowish white (CAI=1) and black (CAI=5) in NE Hungary. Correlating with illite crystallinity (KI — Kübler index) indices and other metamorphic petrological parameters, they concluded, that all the colour changes to complete blackening (CAI=5) took place below 200 °C temperature. On the other hand, the reverse path of colour changes (from CAI=5 to 8), under conditions of regional dynamothermal metamorphism, not only changed the colour of conodonts, but they became recrystallized and usually deformed, too.

Nevertheless, the usefulness of conodonts for temperature estimations in case of burial and contact metamor-

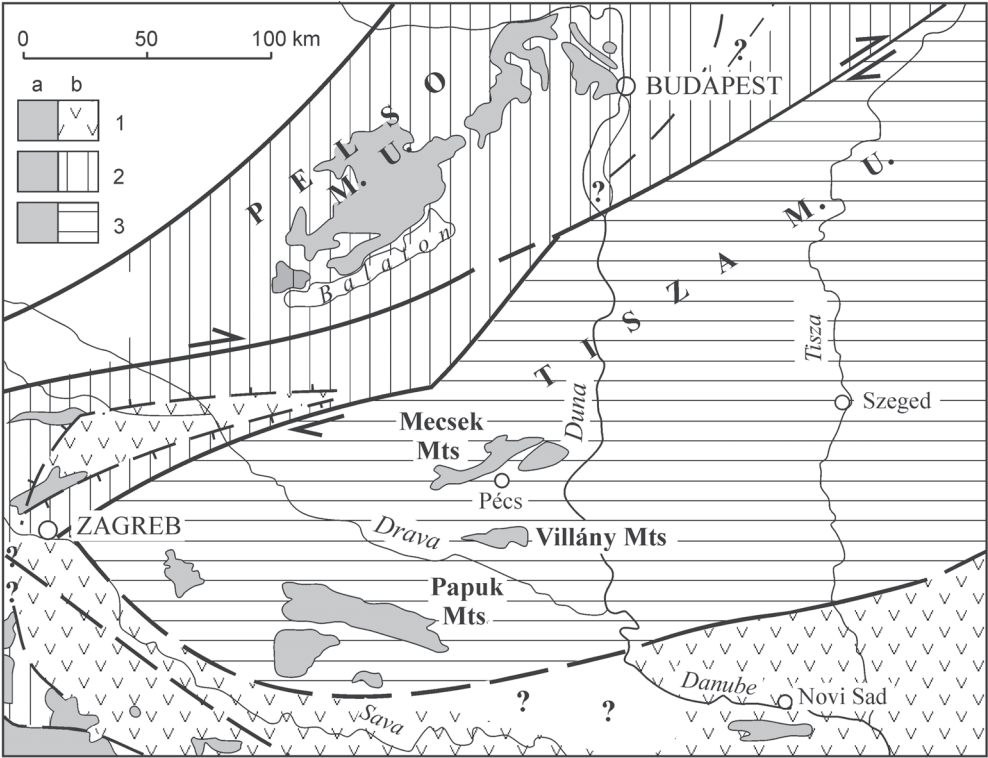


Fig. 1. Location of the Mecsek and Villány Hills, South Hungary, in the major tectonic framework of the SW part of the Pannonian area. **1** — Ophiolitic complexes representing the continuation of the Vardar Zone; **2** — Units related the southern (Apulian) margin of Neotethys; **3** — Units related to the northern (European) margin of Neotethys. Shaded areas indicate surface outcrops.

phism has been proven by numerous papers (see, for example, Armstrong & Strens 1987; Nowlan & Barnes 1987; Belka 1990; Nöth 1991; Königshof 1992; Pondrelli 2000 for some more detailed studies).

In this contribution we present conodont colour alteration data from a Mesozoic half graben zone (Mecsek Unit), in which conodonts became dark grey to blackish (CAI=4), whereas on the adjacent ridge zone (Villány Unit) they remained unaltered (CAI=1). We attempted to

correlate these CAI values with published vitrinite reflectance data from both units (Laczó 1982, 1984; Horváth et al. 1982), as was done by Epstein et al. (1977) and Königshof (1992). Comparisons from some other parts of Hungary, where both CAI and published vitrinite reflectance data are available, are also included.

Geological setting

The Mecsek and Villány Hills in SE Transdanubia (Southern Hungary, western vicinity of the Danube River; Figs. 1, 2) form surface outcrops of the northern zones of the Tisza Megaunit (or Tisia Terrane): of the Mecsek (— Northern Great Plain) Zone in the most external position and of the Villány (— Bihor) Zone. East of the Danube River they are known only from boreholes in the pre-Neogene basement of the Great Plain, the latter having much larger surface exposures in the Bihor Unit of the Northern Apuseni Mts, Romania (Bleahu et al. 1994).

The Mesozoic formations of the Mecsek and Villány zones were laid down on a Variscan basement composed mainly of synkinematic granitoids and associated medium grade metamorphics, showing close correlation with the Moldanubian Zone of the European Variscides (Buda 1996; Buda et al. 2004; Klötzli et al. 2004). In the area of the Mecsek and Villány Hills, a fault-controlled basin came into existence in late Variscan time, in which up to 3500 m thick Upper Carboniferous to Upper Permian

Table 1: Conodont CAI (Colour Alteration Index) values and corresponding temperatures as calibrated by experimental testing, and their correlation with vitrinite reflectance data and burial depth in the Appalachian Basin, USA (compiled after Epstein et al. 1977).

			CAI isograds and Middle -Ordovician-Permian isopachs in Appalachian Basin	
CAI	Temperature °C	Vitrinite reflectance (R)	Overburden	
			(in m)	(in feet)
1	<50–80°	<0.7	<1220	4000
1 1/2	50–90°	0.7–0.85	1220–2440	4000–8000
2	60–140°	0.85–1.4	2440–3660	8000–12000
3	110–200°	1.4–1.95	3660–5490	12000–18000
4	190–300°	1.95–3.6	5490–7625	18000–25000
5	300–400°	>3.6	>7625–9156	>25000–30000

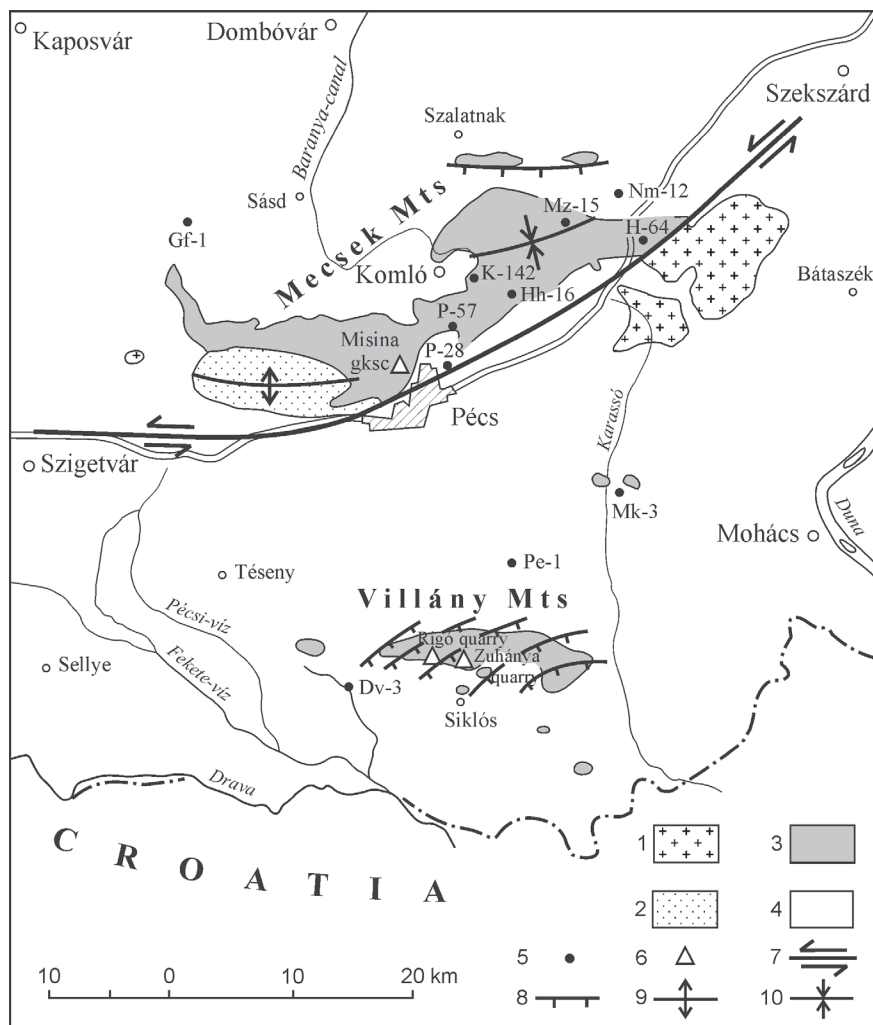


Fig. 2. Geological sketch map of the Mecsek and Villány areas, with location of the boreholes mentioned in the text and on Table 2, and with the sites of conodont studies. 1 — Variscan granitoids; 2 — Permian continental molasse sequence; 3 — Mesozoic in general; 4 — Neogene and Quaternary; 5 — Boreholes mentioned in the text and in Table 2; 6 — Sites of conodont and limestone microfacies studies; 7 — Strike-slip fault (Mecsekalja fault); 8 — Thrust front; 9 — Anticline; 10 — Syncline. **Abbreviation:** Misina gksc = Misina geological key section.

molasse sediments and associated acidic volcanics were accumulated. Other areas of the Hungarian part of the Tisza Megaunit were exposed to erosion during this time (Barabás & Barabás-Stuhl 1998).

The Alpine sedimentary cycle began both in the Mecsek and Villány Zones (at that time they were not separated) with Lower Triassic “Buntsandstein”-type redbeds (Jakabhegy Sandstone Formation; Barabás-Stuhl 1993). (For thickness data of both zones see Fig. 3). Marine transgression commenced in the Early Anisian, with the partly evaporitic Patacs and Hetvehely Formations, corresponding to the Germanic “Röt” (Barabás-Stuhl, op. cit.). In the late Early to early Middle Anisian a strongly bioturbated limestone sequence (Lapis Limestone Formation), corresponding to the Germanic “Wellenkalk” (Török 1993) was deposited. Deeper-water conditions prevailed in the late Middle Anisian (late Pelsonian), indicated by micritic limestones with frequent slump phenomena. These limestones from both areas are included

in the Zuhánya Limestone Formation (Rálsch-Felgenhauer & Török 1993) and contain the conodonts considered below. Equivalents of the Late Anisian, evaporitic “Middle Muschelkalk” are missing in both areas; this interval seems to correspond to a hiatus (Konrád 1998; Kovács & Rálsch-Felgenhauer 2005). The carbonate ramp environment was re-established in the Ladinian, represented by a rather monotonous dolomite sequence (Csukma Dolomite Formation). During the Early and Middle Triassic times the Mecsek and Villány Zones belonged to the same depositional domain, which was not yet differentiated. The total thickness of the Anisian and Ladinian carbonate successions of both areas are not significantly different: 850–1250 m in the Mecsek Hills, and ca. 800 m in the Villány Hills (Nagy & Rálsch-Felgenhauer in Bleahu et al. 1994). From these the Ladinian cover of the Zuhánya Limestone Formation in the Mecsek (Kozár Limestone Member, Kán Dolomite Member, Kantavár Formation) is 50–300 m, whereas in

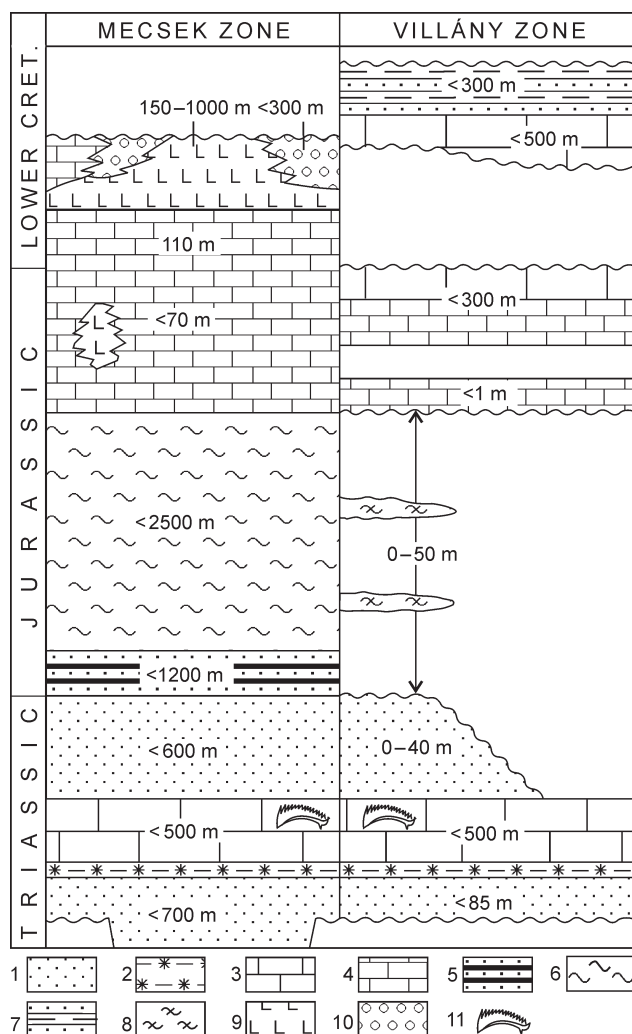


Fig. 3. Simplified Lower Triassic to Lower Cretaceous lithostratigraphy and thickness data of the Mecsek and Villány Zones. **1** — continental siliciclastics ("Buntsandstein", "Keuper"); **2** — evaporites ("Röt"); **3** — shallow water carbonates; **4** — pelagic carbonates; **5** — coal-bearing sequence (Gresten facies); **6** — spotty marl ("Fleckenmergel") sequence (Allgäu facies); **7** — flysch-type sequence; **8** — sandy limestone (in Villány Zone); **9** — alkaline basalts; **10** — volcanoclastic conglomerate; **11** — conodonts. (Modified after Haas, unpublished.)

the Villány area (Csukma and Templomhegy Dolomite Members) it is ca. 370 m.

Separation of the Mecsek and Villány Zones began in the early Late Triassic, probably along the Mecsekfalja (= "Foot of Mecsek") fault zone, which acted originally as a late Variscan sinistral strike-slip zone (Szederkényi 1996 and in Kovács et al. 2000) and is active even nowadays. The future Mecsek Zone became a southward deepening half-graben zone, whereas the adjacent Villány (— Bihor) Zone on the South remained an elevated ridge. This sharp separation persisted throughout the rest of the Alpine sedimentary cycle, till the beginning of middle Cretaceous tectogenesis. Although the ENE-ward continuation of the two zones is fairly well known from borehole data (Bérczi-

Makk 1986; Bérczi-Makk et al. 1996), precise thickness data are known only from the Mecsek–Villány area. Therefore we restrict the brief review on their development only to this area.

The Mecsek half-graben was clearly depicted and precisely documented by Nagy (1969, 1971), but the term "half graben" was first used for it by Sente (1992).

In the initial stage of the Mecsek half-graben zone first the specific Kantavár Formation (black marls with vitrite seams, a possible CH-source rock, in 50–150 m thickness) was deposited in a brackish to fresh-water environment (Monostori 1996), which is already missing in the Villány Zone. Subsidence was accelerated during the deposition of the Late Triassic Karolinavölgy Sandstone Formation: an up to 600 m thick grey, fluvial and lacustrine sandstone sequence deriving from a northerly lying metamorphic-granitic provenance (Nagy 1968). Subsidence became especially intense in the Early Jurassic, when the up to 1200 m thick paralic coal-bearing sequence of "Gresten Facies" accumulated (cf. Figs. 4–5), followed by an up to 2500 m thick "spotty marl" (*Fleckenmergel*, Allgäu Facies) succession till the end of Bajocian (Galács 1984). The siliciclastic detritus derived from the same provenance, as during the Late Triassic (Nagy 1969).

During the same time interval, only the 0–40 m thick Upper Triassic Carpathian Keuper-type sediments and 0–50 m thick Pliensbachian sandy, belemnitic limestones were deposited on the Villány Ridge. In most parts of the Villány Unit, however, the whole Upper Triassic to Middle Jurassic sequence is missing (see Haas 2001, for latest review).

In the Bathonian the Tisia Terrane was separated from its northerly lying continental hinterland due to the Penninic rifting and the sedimentation pattern was basically changed: the siliciclastic input into the Mecsek Zone ceased and *ammonitico rosso*-type pelagic marls were deposited, followed by Callovian to Berriasian pelagic cherty limestones, siliceous limestones and some radiolarites, with a maximum thickness of 180 m (see in Haas 2001 and references therein; Haas & Péró 2004).

On the Villány Ridge a less than 1 m thick iron oolite bank, famous for its fossils, was formed in the Callovian. The Upper Jurassic is represented by an up to 300 m thick limestone succession, first of basinal, than of platform facies (Haas, op. cit.).

During the Early Cretaceous intense alkaline rift-type basaltic volcanism took place in the Mecsek Zone, with a paroxysm during the Valanginian–Hauterivian (Harangi 1994). The thickness of the pyroclastics and lava flows is about 150 m in the SE Mecsek, nearest to the Misina conodont locality, but reaches up to 1000 m on the North in the Kisújbánya Basin, where the eruption centre can be supposed (Bilik 1996; Császár 1998). On the slopes of the partly emerged volcanoes up to 300 m thick volcanoclastic conglomerates and some marls and limestones were accumulated. The Mecsek area seems to have been a dryland from the Albian, partly from the Aptian onward; no younger Mesozoic and Paleogene formations are known in the Transdanubian part of the Mecsek Zone, except some Turonian red marls (Császár 1998, 2003).

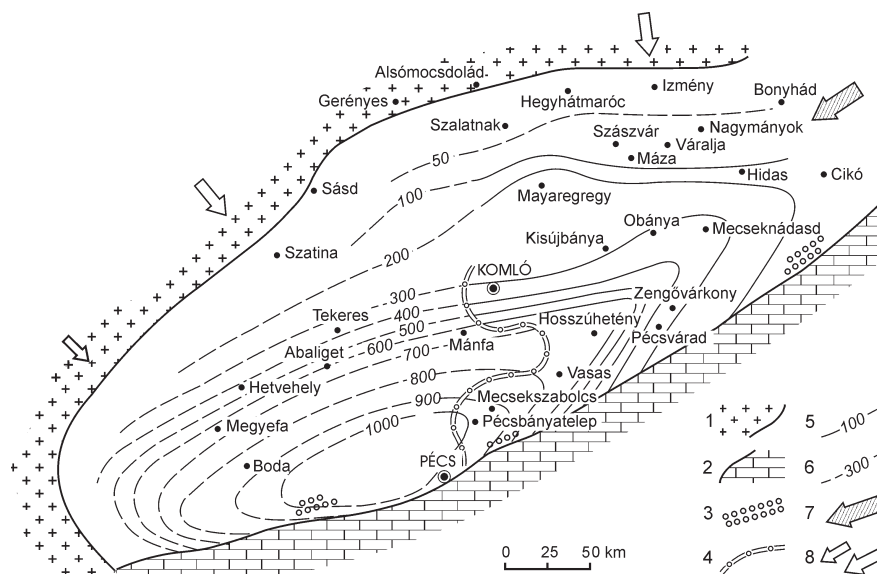


Fig. 4. Thickness and direction of sediment transport of the Liassic coal-bearing sequence (Gresten facies) in the Mecsek area (after Nagy 1969). 1 — granitoid erosional terrain; 2 — carbonatic erosional terrain; 3 — abrasional conglomerate (exposed); 4 — actual western boundary of the coal measures; 5 — isohypses; 6 — postulated isohypses; 7 — current direction; 8 — direction of sediment transport from the granitoid terrain.

In the Villány Zone, after an emerged period, Barremian to Lower Albian Urgon-type platform-type platform carbonates were accumulated, reaching 500 m in thickness on the South, but only 30 m in the northern units (Császár 2003). Sedimentation ended in Albian with flysch-type marly and siliciclastic formations with a maximum thickness of 300 m (Császár 1998).

Summarizing the above described sedimentary (and magmatic) evolution, the Middle Triassic carbonates, embracing the late Middle Anisian conodont-bearing Zuhány Limestone Formation, had been buried by an up to 4300 m thick succession by the Bathonian in the Mecsek half-graben, whereas on the Villány Ridge only by 0 m to maximum 90 m thick sediments. Additional burial took place

during the Late Jurassic to Early Cretaceous with a maximum thickness of 330 m in the southern part of the Mecsek area (where the Misina conodont-bearing locality can be found), but over 1000 m on the North in the Kisújványa Basin area. At the same time in the Villány area a maximum of 630 m thick additional burial can be calculated to the North, but up to 1000 m to the South (Császár, op. cit.). These practically did not change the enormous difference which had developed between the two zones by the Bathonian.

This difference was somewhat compensated during the middle to Late Cretaceous tectogenesis, when the northward thrusting of the Villány Mesozoic sequences took place. However, the resulting tectonic overburden did not influence the colour of the conodonts even in the northern foreland of the hills with the conodont locality Peterd 1 borehole (at 612.2 to 523.5 m depth; Bóna 1976; Kovács et al. 2005), which was overthrust at least by the five thrust sheets recognizable in the surface outcrops.

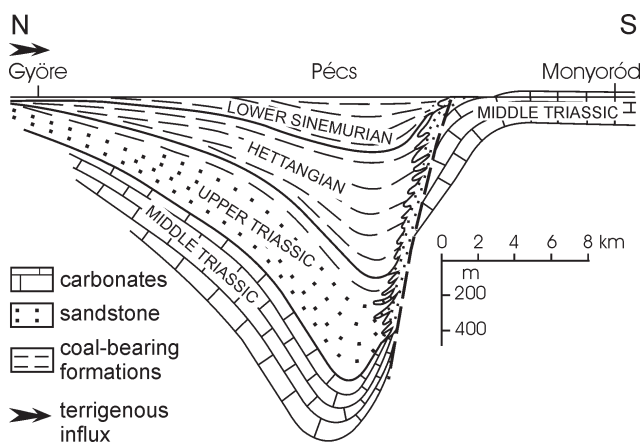


Fig. 5. Tentative cross-section through the Mecsek half-graben and Villány Ridge zones, referring to the Late Triassic and earliest Jurassic time (after Nagy 1969).

Conodonts and their colour alteration indices (CAI)

Mecsek Hills

Conodonts studied from the Mecsek Hills derive from the Misina geological key section, located just before the U-shaped sharp curve of the motor road leading from the town Pécs to the Misina Hill panoramic point (Rálsch-Felgenhauer 1986). The artificially cleaned section exposes the higher part of the Bertalanhegy Limestone Member (crinoidal-brachiopodal grey, nodular, marly limestone) and the lower part of the overlying Dömörkapu Limestone Member (grey micritic limestone with yellow

dolomite mottling). Both lithostratigraphic units contain the same, fairly rich conodont fauna consisting of *Gondolella hanbulogi* (Sudar et Budurov), *G. bifurcata* (Budurov et Stefanov) and *G. bulgarica* (Budurov et Stefanov) (in decreasing order of frequency). From the lowermost part of the key section a *Schreyerites? binodosus* ammonoid specimen was described by Detre (1973). Ramiform elements are very rare. According to this fauna, the whole section belongs to the uppermost part of the Pelsonian Substage, namely to the *binodosus* Zone. Some more details about the section and the conodont fauna can be found in Kovács & Papšová (1986), whereas a detailed one has recently been given by Kovács & Rálich-Felgenhauer 2005.

All conodont elements are uniformly dark grey coloured (CAI=4 according to Epstein et al. 1977), except in part the tips of the denticles on the carina, which may have remained whitish.

Villány Hills

The conodonts involved in the present study derive from the Zuhány Limestone Formation of the drill-core section Peterd 1, from the depth interval 612.2 to 523.5 m. They were first described and illustrated by Bóna (1976). A taxonomical revision is given by Kovács et al. (2005). The fauna consists of the same taxa and indicates the same age, as in the Mecsek Hills.

Two samples investigated from the Zuhány quarry, type locality of the formation, yielded some, mostly broken conodont elements.

Conodont elements from both localities are yellowish white (CAI=1 according to Epstein et al. 1977).

Vitrinite reflectance data

A great number of vitrinite reflectance data (altogether 179) in connection with coal petrological and oil-gas prognostic research were published by Laczó (1982, 1984) from Triassic (mainly Upper) and Jurassic (mainly Liassic) sedimentary rocks of the Mecsek region (Table 2). Unfortunately, on the other hand, only 4 samples were investigated from the Lower and Middle Triassic of the Villány region and none from the Upper Triassic to Middle Jurassic deposits, which are very reduced or missing there. As we had no opportunity to carry out new investigations by this method, we extended our comparisons to other areas of Hungary, from where both CAI and published vitrinite reflectance data are available (see Table 3).

Except the somewhat anomalously high ($R_o=1.54$) value of a single Lower Triassic sample from the Mecsek region, they show practically the same ($R_o=1.37-1.39$) values for the Lower-Middle Triassic of both regions in spite of the enormous difference in their burial depth, that can be calculated for the end of the Early Cretaceous.

Samples from the Upper Triassic sandstones of two boreholes at Pécs nearest to the Mecsekalja fault zone (Pécs-28 and -57) also show similar values ($R_o=1.32$ and 1.36 , re-

Table 2: Vitrinite reflectance data published by Laczó (1982, 1984) from the Mecsek and Villány areas, mentioned in the text. For location of the boreholes see Fig. 2.

Borehole	Depth	Age	Lithology	R_o	n
Mecsek Hills area					
Hosszúhetény 16 Hh-16	350.0–704.0 m	J ₁	clayey marl, sandstone	1.33	4
Hidas 64 H-64	275.0–1000.0 m	J ₁ –J ₂	clayey marl, marl	1.33	8
Komló 142 K-142	242.0–643.0 m	J ₁	clayey marl, marl, sandstone	1.17	5
Komló Kossuth shaft	445.0–460.0 m	J ₁	coal	0.81	12
Komló, Zobák shaft	618.0–641.0 m	J ₁	coal	0.87	16
Máza 15 Mz-15	354.0–1000.0 m	J ₁	clayey marl, marl, sandstone, coal	0.83	92
Máza 15 Mz-15	1000.0–1161.0 m	J ₁	clayey marl, marl, sandstone, coal	0.90	
Máza 15 Mz-15	1168.5–1233.7 m	T ₃	sandstone, siltstone	1.03	10
Nagymányok 12 Nm-12	355.5–538.0 m	T ₃	sandstone, siltstone	1.21	3
Pécs 28 P-28	61.3–446.7 m	T ₃	sandstone	1.36	5
Pécs 57 P-57	66.0–781.0 m	T ₃	sandstone, marl	1.32	5
Kantavár, quarry		T ₂ –(T ₃)	clayey marl	1.37	1
Gálosfa 1 Gf-1	1665.0–1835.0 m	Ta ₁	siltstone	1.54	1
Villány Hills area					
Dióviszló 3 Dv-3	401.7 m	T ₂	clayey marl	1.39	1
Máriakémed 3 Mk-3	778.0–990.0 m	Ta ₁	clayey marl, sandstone	1.37	3

n = number of samples

Table 3: Vitrinite reflectance and conodont CAI data from other regions (Transdanubian Range, Rudabánya Mts) mentioned in the text, after Laczó (1984) and Árkai & Kovács (1986). CAI data from borehole Zsámbék 14 are after Kristan-Tollmann et al. (1991) and from borehole Bakonyszűcs 3 after unpublished investigations by S. Kovács. Note: in the Szőlősdárdó 1 borehole vitrinite reflectance data are given in R_{max} (°) in Árkai & Kovács (1986).

Borehole	Depth	Age	Lithology	R_o	n	CAI
Transdanubian Range						
Zsámbék 14	324.3–687.0 m	T ₂ –T ₃	marl, limestone	0.41	10	1
	461.4–653.8 m	T ₃	limestone			
Bakonyszűcs 1	789.0 m	T ₁	siltstone	0.80	1	
Bakonyszűcs 3	268.15–380.8 m	T ₂ –T ₃	limestone			1
Rudabánya Mountains						
Szőlősdárdó 1 (Laczó 1984)	439.7–440.3 m	T ₂	siltstone, claystone	3.65	2	
Szőlősdárdó 1 (Árkai & Kovács 1986)	440.3–450.8 m	T ₂	siltstone, claystone	*4.712–4.769	59	3–5
	75.6–114.6 m	T ₃		*3.852–4.100	35	
	4.60–444.3 m	T ₂ –T ₃	limestone			

* R_{max} ; n = number of measurements

spectively; $n=5$ in both), such as from the Liassic of two other nearby located boreholes (Hosszúhetény-16 and Hidas-64; $Ro=1.33$ in both; $n=4+8$). The Liassic of the northwesterly located Komló-142 borehole shows somewhat lower values: $Ro=1.17$; $n=5$. An interesting decrease in vitrinite reflectance was found in the sequence of Máza-15 borehole located in the northern margin of Mecsek Hills, where sediment thickness (and burial) was less: $Ro=1.03$, $n=10$ in the Upper Triassic part of the sequence, decreasing to $Ro=0.90$, resp. 0.83 ; $n=92$ upward in the Liassic coal-bearing part (see Table 2).

It is worth mentioning, that in black coals from two mines at Komló considerably smaller values were measured: $Ro=0.87$; $n=16$ from the Zobák shaft and

$Ro=0.81$; $n=12$ from the Kossuth shaft. These can be explained by the more distal setting in relation to the depocenter of the half-graben structure, and, consequently, by the smaller burial depth. Unfortunately, Middle Triassic conodont-bearing limestones are not known in this region.

Conodont alteration and vitrinite reflectance data from other regions

For comparison we include two other areas from Hungary, where both conodont CAI and vitrinite reflectance data are available (Table 3). The colour of conodonts in

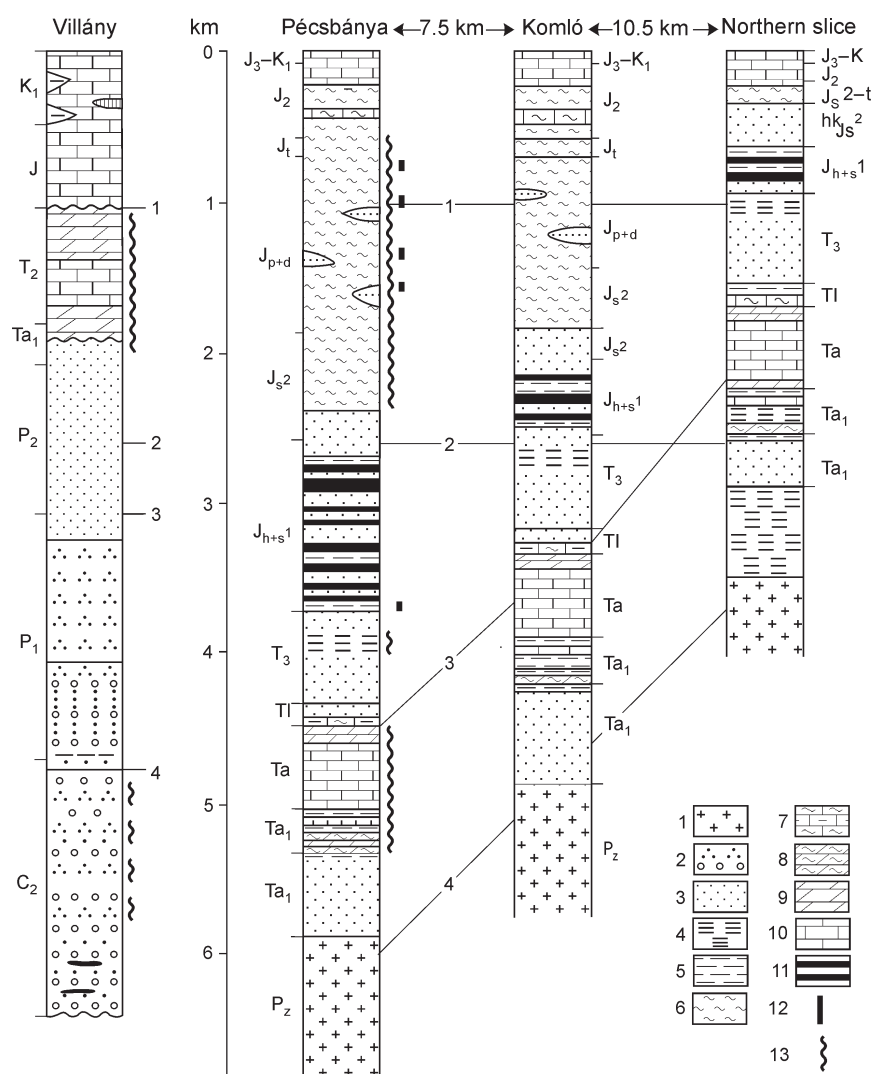


Fig. 6. Position of the oil zone at the end of the Triassic and in the Early Cretaceous in the Mecsek Zone, and at the end of the Permian and in the Early Cretaceous in the Villány Zone, respectively (after Horváth et al. 1982, slightly modified). **1** — Pre-Alpine metamorphics; **2** — Continental conglomerates and sandstones (Upper Paleozoic); **3** — Continental siliciclastics (Lower and Upper Triassic) and major sandstone horizons Lower Jurassic; **4** — Siltstones (Triassic); **5** — Shales (Triassic, Jurassic); **6** — Marls of the Allgau (Fleckenmergel) facies in the Lower Jurassic; **7** — Calcareous marls, marly limestones; **8** — Dolomitic marls; **9** — Dolomites; **10** — Limestones; **11** — Major coal measures; **12** — Probable source rocks; **13** — Probable confining horizon. **Horizons:** **1–2** — top of the oil zone (1 — at 60 °C) and its base (2 — at 135 °C) in the Early Cretaceous; **3–4** — top of the oil zone (3 — at 60 °C) and its base (4 — at 135 °C) at the end of the Triassic (Mecsek area) or at the end of the Permian (Villány area), respectively.

the first case is similar to those of the Villány area, but in the second case to those of the Mecsek area.

Triassic conodonts throughout the Transdanubian Range show uniform $CAI=1$ values, for example they do not reflect any thermal overprint. Vitrinite reflectance data together with CAI data are available from two boreholes drilled at the northwestern margin of the range. Reflectance data from the Carnian Veszprém Marl Formation of Zsámbék 14 borehole shows $R_o=0.41$; $n=10$ (Laczó 1984). The sporadic conodont elements from here, with $CAI=1$ value are figured in Kristan-Tollmann et al. (1991). A Lower Triassic siltstone sample from the Bakonyszűcs 1 borehole shows $R_o=0.80$; $n=1$ (Laczó, op. cit.). Late Anisian-Ladinian conodonts with $CAI=1$ value are known from the nearby drilled Bakonyszűcs 3 borehole (unpublished investigations of the first author).

Vitrinite reflectance data from the Szőlőszárd Unit of the Aggtelek-Rudabánya Mts, measured on the Anisian Bódvarákó Formation and Carnian Szőlőszárd Marl Formation of the drill-core section of Szőlőszárd 1 borehole show already anchizonal values (see Table 3; note, that reflectance data in Laczó 1984 are given in R_o , whereas in Árkai & Kovács 1986 in R_{max} values). However, "illite crystallinity" indices clearly still refer to the diagenetic zone: KI (whole rock) $=0.536 \pm 0.114 \Delta 2\theta$, $n=8$; KI ($<2 \mu m$) $=0.544 \pm 0.160 \Delta 2\theta$, $n=16$ (Árkai, in Árkai & Kovács 1986) and conodonts also show $CAI=4-5$ values (similar to those of Mecsek Mts, with no sign of recrystallization or deformation (see in Kovács & Árkai 1989: Pl. 2, Figs. 5-6 and Pl. 4, Fig. 5). This controversy is explained by Árkai & Kovács (op. cit.) by a short-time heating, which did not reset the KI and CAI values.

Discussion

The Middle Triassic carbonates of the Mecsek area reached the maximum 4300 m burial depth by the end of the Bajocian (170 Ma), and stayed there until about the end of the Albian (100 Ma), that is over a 70 Myr long period. Applying the CAI method of Epstein et al. (1977) and projecting the $CAI=4$ value of the Mecsek area onto the Arrhenius plot (Fig. 7), supposing this about 70 Myr staying at the maximal burial depth, a paleotemperature of about 200 °C can be calculated. It is less, then estimated by Horváth et al. (1982: Fig. 1) for the nearby located Pécsbányatelep mining district, the succession of which was deposited in (or near to) the depocenter of the half-graben. Here the maximal burial depth, up to 4.5 km can be counted for the top of the Middle Triassic carbonates at the end of the Early Cretaceous. They counted with 5 °C geothermal gradient after Nagy (1969, 1971), with 20 °C surface temperature for that time. Accordingly, the top of the Middle Triassic carbonates could be at the 245 °C isotherm. At the same time, the top of the Liassic coal-bearing sequence of Gresten-type, at 2.7 km depth, could be at the upper limit of the oil-window, at 135 °C (see Fig. 6 herein). The conodont-bearing upper Middle Anisian (upper Pelsonian) Bertalanhegy and Dömörkapu Limestone

Members beneath the 150–300 m thick Ladinian carbonates could easily be at the 250 °C isotherm. If we do not count with this anomalously high 5 °C/100 m "Pannonian" geothermal gradient, but with the average 3 °C/100 m, and with a 20 °C surface temperature for the end of the Early Cretaceous, then the resulting temperature would be only 155 °C for 4.5 km depth. We should add to this point, that in the non-metamorphosed units of Aggtelek-Rudabánya Mts, NE Hungary, all $CAI \leq 5$ values should have formed below 200 °C temperature according to "illite crystallinity" (KI) data (Árkai & Kovács 1986).

The northern thrust unit of Mecsek Hills is characterized by considerably less sedimentary thicknesses, reflecting the more marginal position of its depositional area in respect to the depocenter of the half-graben (cf. Figs. 2, 4, 5 and 6). Here the top of the Middle Triassic carbonates could be only ca. 1300 m deep at the end of the Early Cretaceous and the upper temperature limit of the oil window could be at their base (Horváth et al. 1982; Fig. 6 herein). Unfortunately, we have no conodonts from this area.

On the other hand, the top of the Middle Triassic carbonates of the Villány area was either on the surface or at a maximum 90 m burial depth at the end of the Bajocian, and only at maximum 1000 m burial depth at the end of the

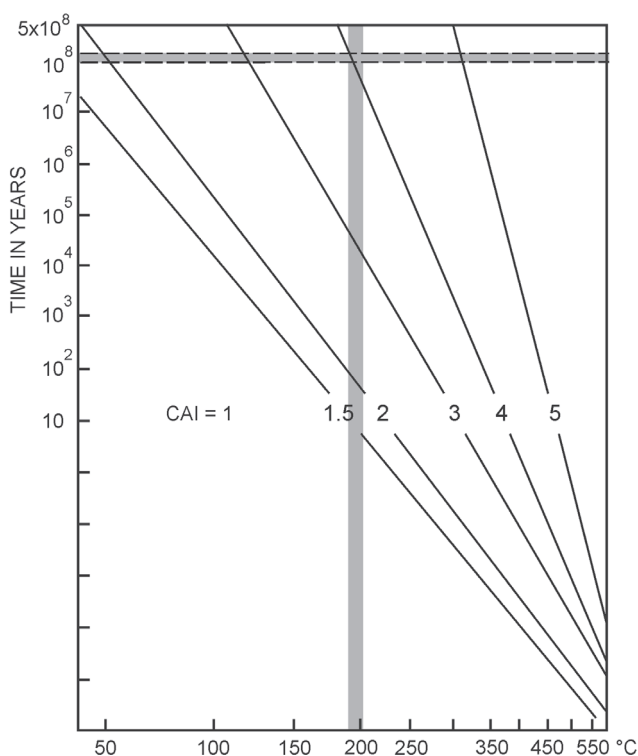


Fig. 7. Projection on the Arrhenius plot (after Epstein et al. 1977 and Rejebian et al. 1987) the colour of the Mecsek conodonts ($CAI=4$) suggests about 200 °C paleotemperature for the time of the maximal burial, namely from the beginning of Bathonian till the end of Albian (ca. 70 Myr). This estimation is somewhat higher, than what can be calculated from available vitrinite reflectance data nearest to the conodont locality (cf. Fig. 2 and Table 2). The Villány conodonts having $CAI=1$ suggest accordingly a paleotemperature for this time even below 50 °C (not shown on the figure).



Fig. 8. Conodonts and fish remains with different CAI values from the two sides of the Mecsek half-graben zone. **1–11** — Villány Zone: 1 — *Gondolella hanbulogi* (Sudar et Budurov) subadult ontogenetic stage. Borehole Peterd 1, 606.0–612.0 m. 2 — *Gondolella bulgarica* (Budurov et Stefanov) subadult ontogenetic stage. Borehole Peterd 1, 610.0–612.2 m. 3 — *Gondolella hanbulogi* (Sudar et Budurov) juvenile ontogenetic stage. Borehole Peterd 1, 610.0–612.2 m. 4 — *Gondolella hanbulogi* (Sudar et Budurov) medium ontogenetic stage. Zuhány quarry. 5 — “*Hibbardella magnidentata*” morphoelement of the *Gondolella*-apparatus. Borehole Peterd 1, 610.0–612.2 m. 6 — “*Neohindeodella triassica*” morphoelement of the *Gondolella*-apparatus. Borehole Peterd 1, 575.4 m. 7 — “*Ozarkodina tortilis*” morphoelement of the *Gondolella*-apparatus. Zuhány quarry. 8 — “*Ozarkodina tortilis*” morphoelement (small form) of the *Gondolella*-apparatus. Borehole Peterd 1, 610.0–612.2 m. 9 — Thick fish tooth. Borehole Peterd 1, 523.5–527.2 m. 10 — Thin fish tooth. Borehole Peterd 1, 589.5–598.0 m. 11 — Gnathoid fish scale. Borehole Peterd 1, 606.0–610.0 m. (Exact location of the samples see in Kovács et al. 2005: Fig. 2). **12–21** — Mecsek Hills, geological key section at the road curve to Misina. 12 — *Gondolella hanbulogi* (Sudar et Budurov) adult ontogenetic stage. Sample Mecsek-T2, in Kovács & Papšová (1986). 13 — *Gondolella hanbulogi* (Sudar et Budurov) adult ontogenetic stage. Sample Bh-11. 14 — *Gondolella bifurcata* (Budurov et Stefanov) adult ontogenetic stage. Sample Bh-11. 15 — *Gondolella bulgarica* (Budurov et Stefanov) subadult ontogenetic stage. Sample Bh-11. 16 — *Gondolella hanbulogi* (Sudar et Budurov) medium ontogenetic stage. Sample Mecsek T2. 17 — “*Enantiognathus ziegleri*” morphoelement of the *Gondolella*-apparatus. Sample Bh-11. 18 — “*Cypridodella muelleri*” morphotype of the *Gondolella*-apparatus. Sample Mecsek-T2. 19 — Big gnathoid fish scale. Sample Bh-6. 20 — Thin fish tooth. Sample Bh-7. 21 — Thick fish tooth. Sample Bh-6. All magnifications are 65×, except 19, which is 33×.

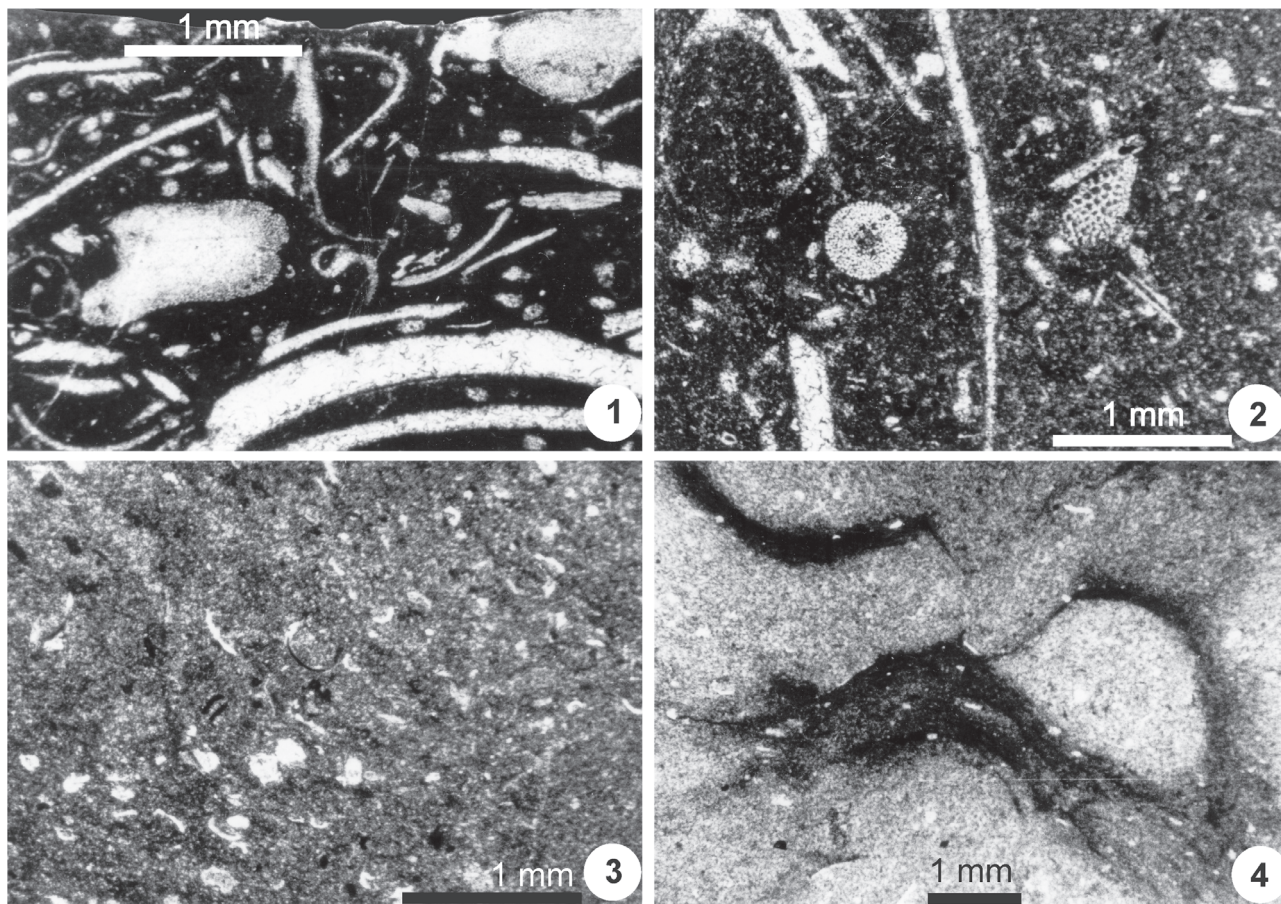


Fig. 9. Textural types of the conodont-bearing Middle Triassic limestones hosting the conodonts shown on Fig. 8. **1–2** — Mecsek Hills, Misina road curve geological key section: **1** — brachiopodal-crinoidal biomicrite, mudstone; sample Bh-1, 25 $\times$; **2** — biomicrite, mudstone, with echinoderms and brachiopod shells; sample Bh-12, 25 $\times$; (exact location of the samples see in Kovács & Rálich-Felgenhauer 2005: Fig. 2). **3–4** — Villány Hills, Rigó quarry: **3** — ostracod-bearing microsparite, mudstone; bed No. 1, 25 $\times$; **4** — microsparite with argillaceous material (black) within the clasts; slump structure typical for the Zuhány Limestone; bed No. 2, 12.5 $\times$. (Sample numbers of 3–4 are after unpublished documentation by Rálich-Felgenhauer.) Note, that even the Mecsek samples yielding the conodonts with CAI=4 do not show any sign of even incipient foliation (compare with the texture of the least metamorphosed parts of the Bükk Mts, NE Hungary, which yielded conodonts of the same CAI=4 value, but weakly foliated; see in Sudar & Kovács 2006: Fig. 14.1).

Early Cretaceous. Again assuming a 5 °C/100 m geothermal gradient, with 20 °C surface temperature, as in the case of the Mecsek area, 60 °C temperature can be calculated for this depth at that time. According to Horváth et al. (1982) (see Fig. 6 herein) the Middle Triassic carbonate succession of the Villány area could be within the oil window at the end of the Early Cretaceous. The thickness of the Ladinian dolomites overlying the conodont-bearing Zuhány Limestone reaches 370 m; counting 400 m of additional burial, conodonts of the Villány area were affected by a max. temperature of 90 °C at that time, which is consistent with the CAI=1 value. Tectonic overburden resulting from middle-Late Cretaceous N-ward thrusting did not change this value.

Vitrinite reflectance data from the Triassic of the Transdanubian Range ($R_o=0.41$, $n=10$ in the borehole Zsámbék 14; $R_o=0.80$, $n=1$ from borehole Bakonyszűcs 1) are consistent with the CAI=1 value. However, data known from the Triassic of the Villány area ($R_o=1.37\text{--}1.39$) are the same, as in the Mecsek area and are anomalously high for the CAI=1 value. We can suppose two reasons for this

controversy: **1** — the vitrinite grains were redeposited; **2** — or a short-time local heating (like in the case of the Szőlőszárd Unit of Aggtelek-Rudabánya Mts; see above). The second case could possibly be caused by a nearby located alkaline basalt sill of Early Cretaceous age — however, these are not known in the Mesozoic of the Villány Hills. In the future it will be necessary to carry out more vitrinite reflectance determinations from the Villány Hills area.

Conclusions

1 — The present study confirms, that observation of conodont colours up to the value $CAI \leq 5$, in conditions of burial diagenesis, is a useful method to reveal thermal history of sedimentary basins. However, combined application with other methods (vitrinite reflectance, “illite crystallinity”, etc.) is highly recommended; anomalous values given by one or other method can be eliminated in this way. On the other hand, above $CAI \geq 5$, in conditions

of regional dynamothermal metamorphism, where fluid pressure also plays a decisive role, the colour of conodonts cannot be used for direct paleotemperature determinations (cf. Árkai & Kovács 1986; Kovács & Árkai 1987, 1989; Sudar & Kovács 2006).

2 — The necessity of application of different methods for paleotemperature estimations is also underlined by different vitrinite reflectance and overburden thickness data related to the same CAI values in different regions, as in the Appalachians, USA (Epstein et al. 1977 and Table 1 herein), in the *Rheinisches Schiefergebirge*, Germany (Königshof 1992) or in our case.

3 — In the studied area, Middle Triassic carbonates of the Mecsek half-graben zone had been buried in the depocenter by a sediment pile up to 4.3 km thick by the boundary of Bajocian/Bathonian. On the other hand, those of the Villány Ridge were either subareally exposed during this period, or buried only by several 10 m (max. 90 m) thick Upper Triassic to Middle Jurassic sediments. The colour of conodonts (CAI=4 in the Mecsek Zone, but only CAI=1 in the Villány Zone) characteristically reflect this enormous difference in burial depth.

4 — Late Jurassic–Early Cretaceous additional overburden (max. 1000 m in both zones) did not change this difference; the Middle Triassic rocks remained at the maximal burial depth for about 70 Myr, till the end of the Early Cretaceous.

5 — The Early Cretaceous alkaline basaltic volcanism did not influence the colour of the studied conodont assemblages.

6 — Albian flysch sedimentation marks the beginning of tectonic activity in the Villány Zone. Tectonic overburden resulting from N-ward overthrusting in this zone did not influence the colour of conodonts. Unload resulting from the formation of the large SW Mecsek antiform in the Mecsek Zone likely began at the same time (Wein 1967), or even in the Aptian (Császár 2003).

Acknowledgments: Preparation of the present contribution was supported by the Hungarian National Research Fund, grants No. T 029654 and T 037595 (S.K.). Mária Hámor-Vidó is thanked for her kind help in evaluation of vitrinite reflectance data, Ágnes Siegl-Farkas and György Don for helping in colour photographing for Fig. 8. Our thanks are extended to Dezső Simonyi, who prepared Fig. 8, and to Károly Szoldán for preparing all other figures and tables. Péter Árkai (Budapest), Fritz Ebner (Leoben) and Ján Mello (Bratislava) reviewed the earlier version of the manuscript: their critical notes and helpful suggestions are kindly acknowledged herein.

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