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## Displaced South Alpine and Dinaridic elements in the Mid-Hungarian Zone

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The Mid-Hungarian Zone is a WSW–ENE trending composite structural unit in the basement of the Pannonian Basin that is made up of displaced crustal fragments (terranes) of South Alpine and Dinaridic origin. In the early stage of the Alpine evolution these fragments were located in various sectors of the NW Neotethys region, representing different paleogeographic settings from passive margin through continental slope to oceanic basement. Middle to Late Jurassic closure of the Neotethys led to the development of a suture zone made up of subduction-related complexes that can be followed all along the strike of the Dinarides. During the Cretaceous compressional stages, nappe stacks were formed from the accretionary complex and the fragments of the previously disrupted passive margin. Eastward extrusion (escape) of the ALCAPA Mega-unit during the Oligocene to Early Miocene led to large-scale displacement of fragments of this nappe stack, transporting them to their present-day position, and resulted in dispersal of the northwestern segment of the suture zone. The paper summarizes the basic characteristics of the dislocated blocks, evaluates their relationships and determines their original setting.

Key words: Pannonian Basin, Mid-Hungarian Zone, Mid-Hungarian Line, Periadriatic-Balaton Line, Neotethys, ophiolite mélange, displaced terranes

### *Introduction*

Displaced crustal fragments (terranes) of South Alpine and Dinaridic origin occur in the basement of the Pannonian Basin, along an ENE–WSW trending strip that is defined in the present paper as the Mid-Hungarian Zone (MHZ). During the early stages of the Alpine evolution these fragments were located

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relatively far from each other and developed within different paleogeographic settings. They approached their present day position as a result of eastward extrusion (escape) of the ALCAPA Mega-unit (composite terrane) during the Oligocene to Early Miocene (Kázmér and Kovács 1985), and were subjected to tectonic deformations due to opposite rotation directions of the ALCAPA and Tisza Mega-units in the Early Miocene (Márton and Márton 1978; Fodor et al. 1999; Márton and Fodor 2003).

The aim of the present paper is to display basic characteristics of the displaced blocks, which occur along the southern margin of ALCAPA, evaluate their relationships with the surrounding structural units, and determine their original setting, since this is of critical importance for the reconstruction of the geodynamic evolution and paleogeography of the entire region.

### *Previous concepts*

Based on studies of fossil assemblages of Upper Paleozoic sequences in the Bükk Mts of NE Hungary, already Schréter (1936, 1943, 1959) and Heritsch (1942, 1944) recognized close facies affinities to the Carnic Alps, the Julian Alps and the Dinarides. Balogh (1964) emphasized a striking similarity in terms of lithofacies and the fossil content of the Upper Paleozoic formations found in the Bükk Mts with those of the Jadar Block (Dinarides of West Serbia) and the Žažar area (Julian Alps of Slovenia), respectively, suggesting close paleogeographic relationships amongst the three areas during the Late Paleozoic. The concept of a Late Paleozoic marine connection between the Bükk, South Alpine and Dinaridic realms was supported by the discovery of fusulinidae-bearing limestone in exploration wells south of Lake Balaton (Majzon 1956). These few data provided the basis for Wein's proposal (1969, 1972) for the existence of a narrow seaway connecting the Julian Alps with the Bükk Mts area; he named this area as "Igal-Bükk eugeosyncline". In his later work, already influenced by the concepts of plate tectonics, Wein (1978) interpreted the facies similarity to have resulted from tectonic displacements. He considered the Balaton Line (BAL) as the eastern continuation of the Periadriatic Lineament (Fig. 1), and assumed that the Igal-Bükk unit presently located between the BAL and the Zagreb–Zemplén Line (referred to as the Central Hungarian Line by Szepesházy 1975) was a segment of the southern Tethyan belt prior to its large-scale displacement via wrench-faulting.

Fülöp et al. (1987) proposed the name Central Transdanubian Unit; Haas et al. (1988) suggested the name of Mid-Transdanubian Unit for the pre-Tertiary basement complex between the BAL and Central or Mid-Hungarian Line (hereafter MHL) within the territory of Hungary. The south-western continuation of the Mid-Transdanubian Unit in Croatia was called Zagreb Zone (Dimitrijević 1982) or Supradinaricum and was considered to be a part of the Internal Dinarides (Herak 1986). Pamić et al. (1997) called it the Hrvatsko Zagorje

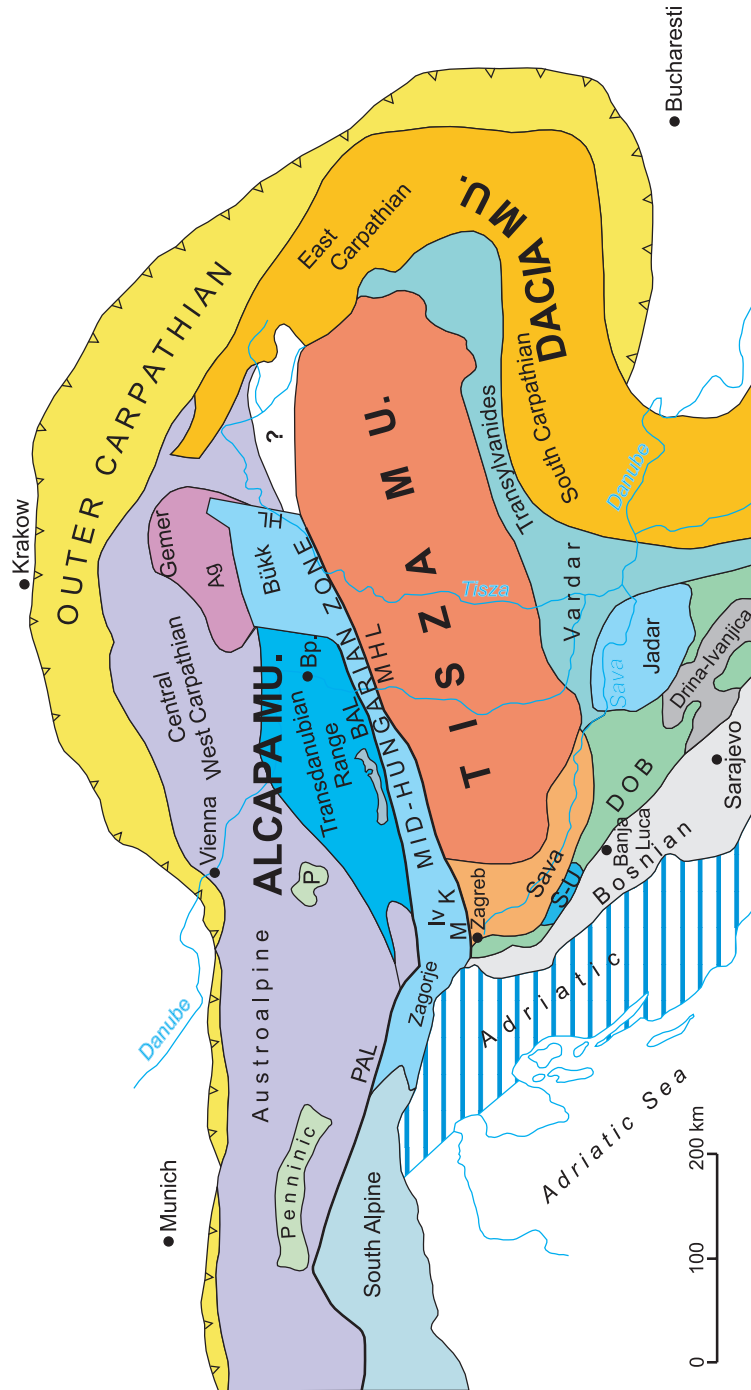


Fig. 1 Major structural units (megaterranes) of the Circum-Pannonian region and position of the Mid-Hungarian Zone. Iv – Ivansőica; M – Medvednica; K – Kalnik; DOB – Dinaridic Ophiolite Belt; S-U – Sana-Uha; Ag – Aggtelek; PAL – Periadriatic Line; BAL – Balaton Line; HL – Hernád Line

Terrane. Several authors assumed that the presence of Internal Dinaridic elements in the Mid-Transdanubian Zone was a result of strike-slip movements along the Zagreb–Zemplin Line (Dimitrijević 1974; Pamić 1997). Pamić and Tomljenović (1998) emphasized that formations exposed in the Hrvatsko Zagorje area (Medvednica, Ivanščica and Kalnik Mts) which show characteristics of the Internal Dinarides, continue northeastward in the Mid-Transdanubian Unit. Accordingly, they proposed the name Zagorje–Mid-Transdanubian Zone for the entire unit.

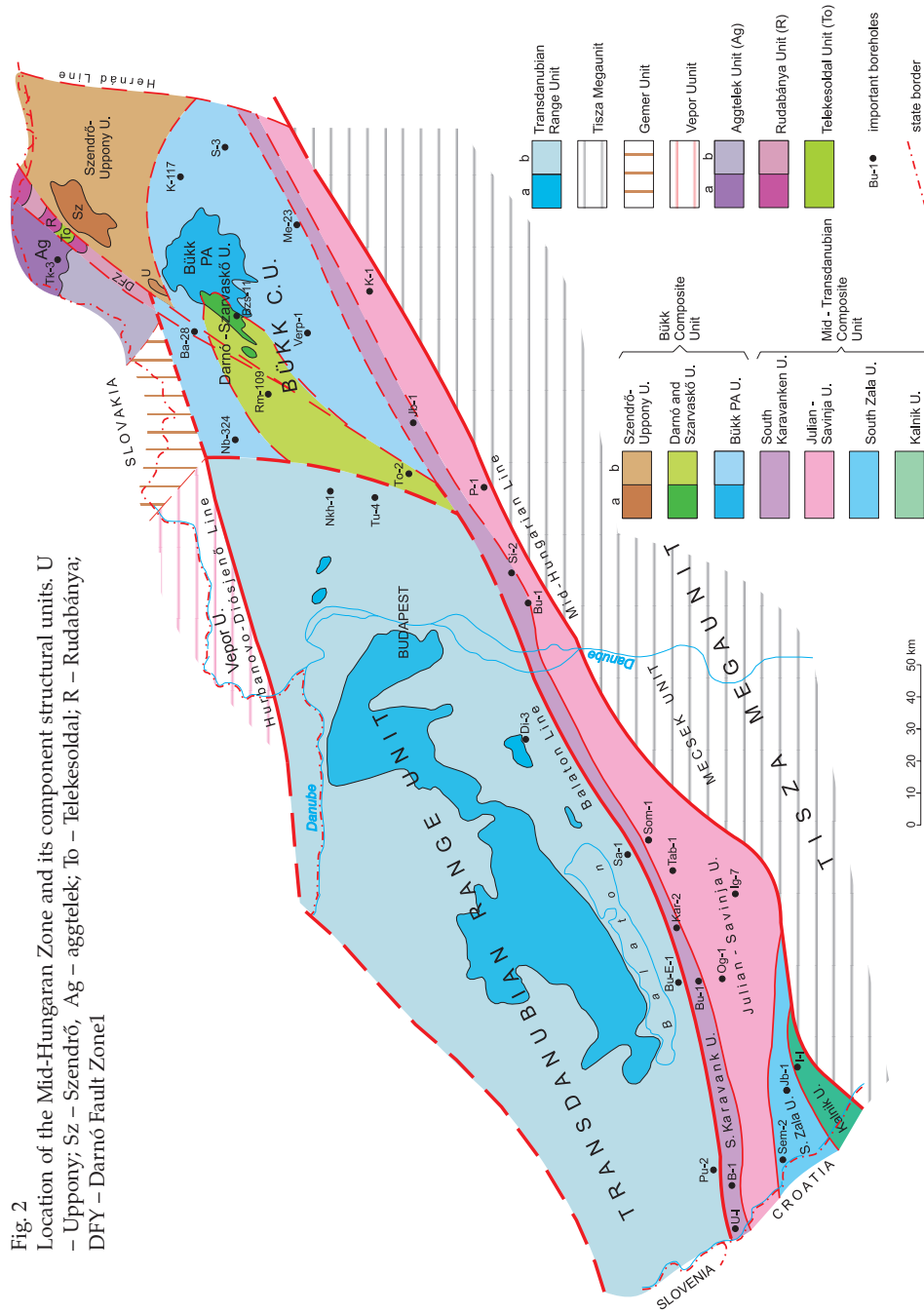
To express the striking Dinaridic characteristics of the Bükk and the Neotethyan affinity of the Szarvaskő, Darnó and Meliata s.s. ophiolite mélanges, Pamić et al. (2002) and Pamić (2003) introduced the term Zagorje–Bükk–Meliata Zone. In the explanatory notes for the Circum-Pannonian tectonostratigraphic terrane map series (Kovács et al. 2004) this zone was named the Zagorje–Bükk–Gemer Composite Terrane (Ebner et al. 2009; Vozárová et al. 2009; Kovács et al. 2010; Haas et al. 2010).

Balla (1984, 1987a) defined the term Mid-Hungarian Zone as a shear zone between the North Pannonian and South Pannonian tectonic units that contains strongly deformed fragments of the neighboring units, including the Szolnok flysch zone.

Breznysnyánszky and Haas (1986) and Fülöp et al. (1987) emphasized the critical geodynamic importance of the MHL as a microplate boundary (i.e. northern boundary of the Tisza Mega-unit) which determined the path of sizable horizontal displacements in the Tertiary.

Results of geologic mapping projects in the Bükk Mts and new borehole data in the Mid-Transdanubian and the Hrvatsko Zagorje areas in the 70s and 80s reinforced the South Alpine and Dinaridic facies affinity of the Paleozoic–Mesozoic rock sequences of these units. The facies affinity was explained by the proximity of the depositional areas, i.e. it was assumed that the Bükk Unit and the elements of the Mid-Transdanubian Unit were originally located in an intermediate region between the Southern Alps and the NW Dinarides from where they were squeezed out, reaching their recent position in the Tertiary (Kovács 1982; Haas et al. 1995). Based on the Permian and Early Mesozoic facies boundaries, Majoros (1980), Kovács (1982), Kázmér (1984), and Kázmér and Kovács (1985) postulated an approximately 500 km-long dextral displacement (tectonic escape) of the Transdanubian Range Unit along the PAL (Periadriatic Line)–BAL system.

Csontos et al. (1992) and Csontos and Nagymarosy (1998) interpreted the zone between the BAL and MHL as a large-scale transpressional zone along which the ALCAPA and the Tisia-Dacia terranes, rotating in opposite senses (Márton 1987), came into juxtaposition during the Late Oligocene–Early Miocene. Rotational reconstructions were proposed by Balla (1987a), Márton and Fodor (1995), Kováč et al. (1998), Csontos et al. (2002), and Kovács I. et al. (2007).



Csontos and Vörös (2004) considered the Mid-Hungarian Zone as a lateral shear belt and an overthrust zone of flysch nappes (Szolnok Flysch) between the ALCAPA and Tisza-Dacia Terranes that experienced NW–SE shortening and NE–SW elongation synchronously during the Tertiary.

According to Schmid et al. (2008) the Mid-Hungarian Fault Zone is a substantial Miocene dislocation zone which includes "Adria-derived thrust sheets", i.e. the Zagorje–Mid-Transdanubian Unit and the area of Bükk Mts, but without the Uppony and Szendrő Units that were assigned by them to the Inner West Carpathians.

### *Tectonostratigraphic units of the Mid-Hungarian Zone*

The area between the BAL and the MHL is made up of slices of South Alpine and Dinaridic origin, mostly hidden beneath the Tertiary cover. We propose the term Mid-Hungarian Zone for this area although we know that a similar term (Mid-Hungarian Fault Zone) was previously used in a somewhat different sense (Balla 1984; Csontos et al. 1992; Fodor et al. 1998; Csontos and Vörös 2004; Schmid et al. 2008).

The Mid-Hungarian Zone is clearly definable in the area west of the Danube (Transdanubia); it is an approximately 30 km-wide zone between two major lineaments (BAL and MHL). The Transdanubian Range Unit occurs north of the BAL, whereas the Mecsek Unit of the Tisza Mega-unit occurs south of the MHL (Figs 1 and 2). East of the Danube, however, this simple definition is no longer possible. The MHL (actually the northern boundary of the Tisza Mega-unit) can be followed north-eastward as far as the Tisza River, although this assumption is supported by only a few borehole data. Further north-eastward the pre-Tertiary basement is unknown due to an extraordinarily thick Neogene volcanic complex that has not been penetrated by boreholes. The continuation of the BAL further to the northeast is even more uncertain. South of Lake Balaton the BAL is well defined; it runs between the metamorphic Paleozoic formations of the Transdanubian Range Unit in the north and the Triassic carbonates of the Mid-Hungarian Zone in the south (Mid-Transdanubian Unit). In contrast, further northeast there are mostly Triassic platform carbonates on both sides of the line, rendering its recognition difficult. Accordingly, east of the Danube, the position of the southeastern structural boundary of the Transdanubian Range is not precisely known. The Bükk Composite Unit occurs northeast of the Transdanubian Range and the Mid-Transdanubian Units, which are hardly separable in this area. Moreover, the exact position and nature of the structural contact between the Transdanubian Range/Mid-Transdanubian Units and Bükk Unit is not known either. As a matter of fact, in North Hungary the Bükk Composite Unit, including the overthrust Mónosbél, Szarvaskő and Darnó Nappes, is located north of the Tisza Mega-unit, between the MHL and the Diósjenő (=Hurbanovo) Line (Fig. 2). The latter is also the northern boundary of

the Transdanubian Range Unit further to the west. Since these units show a number of common features with elements of the Mid-Transdanubian Unit, we believe that they also belong to the Mid-Hungarian Zone. The Mónosbél, Darnó, and Szarvaskő Units are dispersed elements of the Neotethys ophiolite mélange. Accordingly these elements can also be considered as parts of the Mid-Hungarian Zone, since they participated in the large-scale Tertiary displacement, together with the previously-mentioned elements.

#### *Mid-Transdanubian Composite Unit*

In the northern part of the Mid-Transdanubian Composite Unit non-metamorphosed Permian and Triassic formations form the pre-Tertiary basement, showing affinity with the eastern part of the Southern Alps (Carnic Alps and South Karavanks) (Bérczi-Makk et al. 1993; Rálich-Felgenhauer 1998). The slightly metamorphosed Permian, Triassic and Jurassic formations in the southwestern part of the unit and the ophiolite mélange encountered in a few wells in a narrow strip along the southern structural contact of the unit (Árkai et al. 1991; Bérczi-Makk et al. 1993; Rálich-Felgenhauer 1998) might be the continuation of some complexes exposed in the Medvednica and Kalnik Mts in the Hrvatsko Zagorje area (Croatia), considered as the northwesternmost part of the Inner Dinarides (Haas et al. 2000).

#### Elements showing affinity with the Carnic Alps and South Karavanks South Karavank Unit

In the westernmost part of Hungary, near the Slovenian border and south of the BAL, an approximately 700 m-thick Permian sequence was penetrated in well Újfalu (U-I in Fig. 2). The lower part of this succession is made up of fine-grained siliciclastics with limestone intercalations, similar to the Košna Formation of Velebits (Croatia); Bérczi-Makk and Kochansky-Devidé (1981). The limestone beds are rich in foraminifera and calcareous algae. The foraminiferal fauna (Darvasites-Palaeofusulina assemblage) can be correlated with that of the Lower Permian Trogkofel Limestone of the South Karavanks and the Carnic Alps (Bérczi-Makk and Kochansky-Devidé 1981; Bérczi-Makk et al. 1993). Similar siliciclastics were reported from Vitanje, Konjiška Gora, Boc, Zetale (eastern Slovenia) and Ravna Gora (western Croatia) containing limestone clasts with "Trogkofel-type" fossils (Bérczi-Makk and Kochansky-Devidé 1981). The Lower Permian succession is overlain by sandstone followed by shallow marine dolomite, Middle to Late Permian in age. There is an approximately 5–10 km-wide zone along the BAL where similar Lower Permian marine formations with a similar fossil assemblage were encountered in several wells. Similar sequences have been reported from wells at Karád (Kar-1, -2; Fig. 2) south of Lake Balaton (Bérczi-Makk 1988; Bérczi-Makk et al. 1993).

A marine Upper Permian succession, mostly shallow marine carbonates (limestone and dolomite), was also found in cores east of the Danube (Sári, Si-2 and Bugyi, Bu-1; Fig. 2) (Bérczi-Makk 1978). However, the structural setting of this area could not be determined on the basis of the Upper Permian formations, due to the similar facies characteristics occurring in the Transdanubian Range, the Bükk and the Mid-Transdanubian Units.

Recently, a marine Lower Permian succession was reported from a hydrocarbon exploratory well further to the NE, near Jászberény (Jb-1 in Fig. 2), south of the Bükk Mts in North Hungary (Cserepes et al. 2008). This suggests the continuation of the band of Carnic Alps–South Karavanks relationships and, accordingly, of the Mid-Transdanubian Unit east of the Danube.

A great number of wells encountered Triassic formations in the South Karavank Unit, allowing the compilation of a generalized succession. The Lower Triassic is made up of lilac-coloured variegated shale that is overlain by an interval of alternating limestone, dolomite and shale, representing shallow ramp and lagoon facies. Shallow marine dolomite typifies the Anisian. Coeval platform and basin facies characterize the Ladinian to Carnian interval. Wetterstein-type limestone represents the platform facies. The basin facies is typified by cherty limestone, marl and volcanic tuff in several horizons in the Ladinian, and marl and siltstone in the Carnian. The Norian to Rhaetian is represented by Dachstein-type platform carbonates (Bérczi-Makk et al. 1993; Rálich-Felgenhauer 1998).

The Triassic sequence of the Southern Karavanks is characterized by Werfen-type Lower Triassic, shallow marine Anisian dolomite, coeval platform carbonates (Schlern and Conzen Dolomite) and basin facies consisting of marl with volcanic tuff (Wengen Fm.) in the Ladinian, marl, limestone and sandstone (Raibl Group) in the Carnian, and Hauptdolomit and Dachstein Limestone in the Norian to Rhaetian (Grad and Ogorelec 1980; Ramovš 1989; Gianolla et al. 1998; Cozzi 2000; Dozet 2000), very similar to what was encountered in the wells south of the BAL.

Based on the diagnostic Lower Permian marine facies and position of this narrow strip in the neighborhood of the PAL-BAL its derivation from the Carnic Alps and Southern Karavanks is well constrained; the features of the Triassic succession do not contradict this.

Marine Permian formations were also encountered south of the metamorphosed Paleozoic series forming the southern limb of the synform of the Transdanubian Range, in the southern foreland of the Velence Hills (Majoros 1980; Haas et al. 1986). However, in these sequences the Lower Permian marine deposits are missing. Continental red beds occur at the base of the Permian (corresponding to the Val Gardena or Gröden Fm.) that is overlain by evaporitic sabkha and dolomitic lagoon facies (corresponding to the Bellerophon Fm., Fiamazza facies) akin to that in the northeastern part of the Transdanubian Range (and also in the eastern Dolomites). Accordingly this area can be assigned to the Transdanubian Range Unit.



#### Julian-Savinja Unit

South of the above-described narrow strip there is a relatively wide zone where, beneath a Tertiary cover, predominantly non-metamorphosed Triassic platform carbonates were encountered. However, there are only very limited data for a relatively large area, making the evaluation and correlation of this zone rather uncertain. Marine Upper Permian dolomite was found in a single well (Fülöp 1990) but this cannot be considered as a deterministic feature for the facies relations. No data exists for the Lower Triassic. The Middle and Upper Triassic is characterized by typical shallow ramp – platform facies, namely Steinalm-Wetterstein type and Dachstein type facies, respectively (Haas et al. 1988; Bérczi-Makk et al. 1993).

This composite sequence has no real relevance in determining the facies relationships and the original setting of this segment. Continuous Middle to Upper Triassic platform succession, i.e. lack of basin facies, occurs everywhere in the core of platforms in the South Alpine-Dinaridic realm (see Bosselini 1984, 1991; Dimitrijević and Dimitrijević 1991; Gianolla et al. 1998). Most probably Permian-Triassic formations of the Julian Alps and Savinja Alps, respectively, continue eastward beneath the Tertiary cover. Displaced elements of these South Alpine units were probably encountered in the Mid-Hungarian Zone south of Lake Balaton. It is worth mentioning, however, that in the Julian Alps (and also in the Carnic Alps and Southern Karavanks) the Middle Triassic platform carbonates are predominantly dolomitized whereas in the Mid-Transdanubian area mostly limestone was found in the corresponding interval.

#### Elements showing affinity with the Medvednica and Kalnik Units

##### South Zala Unit

The Medvednica Unit is made up of low-grade metamorphic rocks which are exposed in the lower nappe of the Medvednica Mts (Tomljenović 2002) and were also found in some wells in the northeastern part of Croatia beneath Tertiary cover (Haas et al. 2000). In the Medvednica Mts the Silurian to Triassic (Norian) sedimentary and magmatic series (Pamić and Tomljenović 1998) was subjected to very low to low-grade metamorphism in the Cretaceous (110–80 Ma; Judik et al. 2006). The metamorphic alteration may have taken place at temperatures of 300–410 °C and pressures of 3.5–4 kbar (Judik et al. 2006). In the Mid-Transdanubian area, the South Zala Unit, located south of the previously discussed non-metamorphic units (Fig. 2), Upper Permian evaporitic carbonates, Triassic carbonates of basin and slope facies, and Middle Jurassic hemipelagic shale and volcanoclastics affected by low-grade metamorphism, also Cretaceous in age (93–97 Ma), were encountered (Balogh et al. 1990; Árkai et al. 1991; Rálišch-Felgenhauer 1998). It cannot be excluded that the Medvednica and the South Zala Units are parts of a single tectonostratigraphic unit (Haas et al. 2000).

### Kalnik Unit

In Zagorje (Croatia) an ophiolite *mélange* complex considered to be the prolongation of the Vardar Zone was defined as the Kalnik Unit (Pamić 1997, 2000). Mountain Kalnik is made up predominantly of this *mélange* complex and there are also outcrops of it in the Medvednica and Ivanščica Mts (Pamić 1997; Pamić and Tomljenović 1998; Babić et al. 2002; Tomljenović 2002; Tomljenović et al. 2008). The *mélange* complex contains smaller or larger blocks of basalt, gabbro, serpentinite, radiolarite, shale and limestone of varying age in a strongly tectonized shaly matrix. There is evidence for multiple redeposition of elements of the *mélange* complex (Babić et al. 2002; Tomljenović 2002). In the Medvednica and Kalnik Mts blocks of rift-type peperitic basaltoid rocks also occur (Palinkaš et al. 2008). Ladinian and Carnian to Norian radiolarian assemblages were found in radiolarian chert, in direct stratigraphic contact with pillow basalt (Halamić and Goričan 1995; Goričan et al. 2005) constraining a Middle to Late Triassic age of such blocks in the *mélange*. In the Medvednica Mts Bathonian to Callovian radiolarians were encountered in radiolarite beds intercalated into a polymict olistostrome (debrite) succession containing pebble-sized sandstone, siltstone, chert and basalt clasts and olistoliths in a shale matrix (Halamić et al. 1999). Parts of this Jurassic accretionary complex were redeposited in the Late Cretaceous due to intense tectonic movements, and again in the Oligocene, as is confirmed by Cretaceous and Paleogene microfossils found in the matrix in the Medvednica Mts (Pamić and Tomljenović 1998). Detailed studies usually revealed only diagenetic, rarely anchizonal, alteration of the matrix of the ophiolite complex at 120–260 °C in the Medvednica Mts (Judik et al. 2006; 2008).

In a few hydrocarbon exploratory wells (Inke I-I in Fig. 2) at the southernmost part of the Mid-Transdanubian Unit a very low-grade metamorphic complex containing fragments of volcanites, serpentinite, limestone of shallow marine facies and deep-marine black shale and radiolarite of Ladinian and Carnian age were encountered (Kozur in Haas et al. 1985; Dosztály 1994). These were assigned to the *mélange* of the Kalnik Unit (Józsa in Harangi et al. 1996; Rálišch-Felgenhauer 1998; Haas et al. 2000).

### Bükk Composite Unit

The Bükk Composite Unit is made up of the Bükk Unit s.s., and overlying nappes, namely the Mónosbél Nappe consisting of sedimentary formations and the Szarvaskő Nappe containing magmatic rocks intruded into siliciclastics. This structural setting observed in the Bükk Mts continues westward in the Darnó area and in the pre-Tertiary basement of the Mátra Mts (Fig. 2), although in that area the Mónosbél Nappe is overlain by the Darnó Nappe consisting mostly of igneous rocks. Paleozoic series subject to Mid-Cretaceous low grade metamorphism, which are exposed north and northeast of the Bükk Mts (Uppony Hills, Szendrő Hills), are also assigned to the Bükk Composite Unit on

the basis of their facies characteristics ("Bükkium" – Kovács and Péro 1983); however, they show opposing structural vergency. In terms of characteristics and age of their metamorphism, a similarity with the metamorphic complex of the Medvednica Mts was pointed out (Judik et al. 2006).

#### Bükk Unit s.s.

The Bükk Unit s.s. (~Nagyfennsík Parautochthonous; Csontos 1999, 2000) is made up of Upper Paleozoic to Jurassic formations which were subjected to diagenetic to low-grade metamorphism in the Early Cretaceous. In the Bükk Mts Middle Carboniferous fine siliciclastic turbidites, corresponding to the "Variscan flysch stage", comprise the oldest formation exposed. This is overlain by late Middle to Late Carboniferous shallow marine shale, sandstone, and shallow marine fossiliferous limestone. After an interval of subaerial exposure, a new depositional cycle was initiated in the Middle Permian with terrestrial sandstone overlain by evaporitic tidal flat deposits, lagoonal and shallow ramp carbonates of the Late Permian (Fülöp 1994). The Permian-Triassic boundary is within a continuous marine succession, and fine siliciclastics and carbonates of shallow ramp facies characterize the Lower Triassic. Extensional tectonics in the Mid-Triassic led to formation of platforms and basins and accordingly accumulation of coeval platform carbonate and basinal carbonate series (Velledits 2000; Csontos 2000; Pelikán 2005) accompanied by intense andesitic and then basaltic volcanism (Szoldán 1990; Harangi et al. 1996). The evolution of carbonate platforms came to the end during the Late Triassic and in the Early Jurassic basins only condensed pelagic carbonates were deposited, locally and episodically. Both the platform carbonates and the basin deposits were covered by radiolarite, sometime within the rather wide Bajocian to Oxfordian age-range (Csontos et al. 1991; Pelikán 2005, Haas et al. in press). This is overlain by a dark gray siliciclastic turbidite succession, probably of Middle or Late Jurassic age, representing the "Eohellenic flysch stage" (Papanikolau et al. 2006).

The Bükk Unit was subjected to anchizonal to low-epizonal metamorphism at 200–350 °C, 1.5–3, locally 5, Kbar (Árkai 1983), and SE-vergent folding (Csontos 1999). Ka-Ar measurements on illite-muscovite of Upper Paleozoic meta-sediments yielded ages of 111–147 Ma, whereas the zircon fission track data scatter between 111 and 167 Ma; the youngest age value may in this case provide the minimum age of metamorphism (Árkai et al. 1995). Another tectono-metamorphic event was recognized at 77 to 82 Ma (K-mica, K-Ar, and zircon fission track; Árkai et al. 1995) resulting in ductile deformation (Csontos 1999).

The marine Late Paleozoic to Triassic succession of the Bükk Unit shows striking affinity with corresponding successions in the Carnic Alps – South Karavanks (Ebner et al. 1991), Julian Alps, Zagorje–Mid-Transdanubian Unit (Haas et al. 2000) and Sana-Una and Jadar blocks of the Dinarides (Pesic et al. 1986; Protic et al. 2000; Filipovic et al. 2003). In the Late Paleozoic these domains

belonged to a deeper internal part of the large marginal bay of the Paleotethys Ocean (Carnic–Dinaridic Microplate – Vai 1994, 1998, 2003). During the Late Carboniferous to the Mid-Triassic interval, sediment deposition took place on a shallow marginal ramp. Westward opening of the Neotethys resulted in the development of an articulated bottom topography, i.e. the formation of platforms and basins on the margin of the newly-formed ocean. In the Early Jurassic progressing of ocean opening led to attenuation of the continental margin and enhanced subsidence that resulted in the establishment of deep-marine conditions, giving rise to deposition of radiolarite and distal siliciclastic turbidites in the Middle Jurassic.

#### Uppony and Szendrő Units

The Uppony Unit is located immediately to the north of the Bükk Unit s.s., but shows an opposite (north-western) structural vergency. Its sequence begins with Upper Ordovician sandstone, followed by a lydite-shale succession of deep-marine facies, with associated Silurian?–Devonian basic volcanics. The Middle Devonian to Lower Carboniferous is represented by platform carbonates and overlying basinal carbonates, which are followed by an alternation of uppermost Lower to lowermost Upper Carboniferous basinal carbonates and shale, coeval with the flysch-type turbiditic succession of the Szendrő Unit, but lacking the characteristics of flysch (Ebner et al. 1998). The unit was affected by a Cretaceous ( $118 \pm 14$  Ma) metamorphism corresponding to the boundary of the anchi/epizone (2.5 Kbar, 350 °C; Árkai et al. 1995).

The Szendrő Unit, which also has a NW-vergent structure, is located NE of the Bükk Unit s.s. and the Uppony Unit. Its oldest formation is a ?Silurian to Lower Devonian lydite – finely siliciclastic (phyllite, metasandstone) formation, followed by Middle Devonian to Lower Carboniferous carbonates of platform and basin facies, respectively (Kovács 1992; Koroknai et al. 2001b). A flysch-type turbiditic siliciclastic succession, containing limestone olistostromes in its lower part, terminates the preserved succession (Ebner et al. 1998). The higher part of the latter formation likely corresponds to the oldest known formation of the Bükk Unit s.s. (Ebner et al. 1991), although the two units show opposite structural vergencies. The unit was affected by a Cretaceous ( $108 \pm 8$  Ma) low-grade metamorphism (400–450 °C, 3 Kbar; Árkai et al. 1995). The Devonian–Carboniferous lithofacies and the Cretaceous metamorphism of the Szendrő Unit corresponds to the Medvednica Metamorphic Complex of the similarly NW-vergent Medvednica Mts in the Zagorje region (Judik et al. 2006; 2008).

*Dispersed elements of the Neotethys subduction related complexes  
in the Bükk-Darnó area*

The Bükk Unit s.s. is overthrust from the NW (according to present-day coordinates) by the Mónosbél Unit (Mónosbél Nappe) (Csontos 1999). Erosional remnants of this nappe occur in the western part of the Bükk Mts and equivalents of this nappe were also encountered in the basement of the Mátra Mts, west of the Bükk Mts. The Mónosbél Unit is made up of Bajocian to Oxfordian (?) deep-marine siliciclastics (mostly shale), carbonates and siliceous sediments with intercalations of olistostrome beds, which contain very heterogeneous clasts that were transported via gravity mass movements into the basin. In the olistostrome beds, along with fragments of acidic, intermediate and basic magmatites, phyllite, siltstone, sandstone, pelagic carbonates and radiolarite, and lithoclasts of redeposited carbonates containing grains of shallow platform origin (ooids, oncoids, skeletal fragments of shallow marine biota) are common. Large blocks (olistoliths), mostly of platform-derived ("Bükkzsérc-type") limestone of Bajocian to Bathonian age, also occur in the Mónosbél Unit.

Gravity deposits of the Mónosbél Unit are also exposed in the Darnó area and in the ore exploration wells at Recsk, Mátra Mts, respectively (Kovács et al. 2008). In a borehole (Recsk, Rm-109) drilled near Kékes Peak (Mátra Mts) Bajocian platform-derived redeposited carbonates, more proximal than those in the Bükk Mts, were encountered in a remarkable thickness (Haas et al. 2006).

The lithologically very heterogeneous Mónosbél Complex was deposited during the Bajocian to Callovian (Oxfordian?) interval under deep-marine conditions, where large amounts of gravity deposits (olistostromes, olistoliths) were accumulated, showing an upward-coarsening trend.

Andesite breccia horizons occurring in the lower part of the Mónosbél Complex of Bathonian to Early Callovian age (Pelikán and Dosztály 2000; Haas et al. 2006). In the higher part of the Mónosbél Complex there is a wide spectrum of the volcanic material along with carbonate lithoclasts of various shallow and deep-marine facies, and small amounts of metamorphic components (of a higher metamorphic grade than the matrix). These polymict olistostromes imply compressional tectonics, imbrication, and onset of nappe stacking.

In the upper part of the Mónosbél Complex olistostromes consisting mostly of fragments of platform carbonates and large platform limestone ("Bükkzsérc-type") blocks occur. It is plausible that the platform-derived carbonate sediment was affected by cementation prior to disintegration and redeposition. However, the fact that along with the very common oolitic limestone clasts, individual ooid grains and bioclasts of platform and foreslope origin also occur in the olistostromes, imply that unconsolidated shallow-marine sediments were also present in the source area of the gravity mass movements.

In the area of the Bükk Mts the Middle Jurassic platform-derived, redeposited ("Bükkzsérc-type") limestone is a significant component of the olistostrome beds, and olistoliths of this type of carbonates are also typical. This is of critical value

from the point of view of the interpretation, providing data for the primary carbonate factory, the environment of secondary deposition, the post-depositional diagenetic conditions and also the age of these processes; even the source area can be determined with high confidence. Based on foraminifera a Bajocian to Bathonian age was determined (Haas et al. 2006); the carbonate grains were formed on a carbonate platform and redeposited penecontemporaneously, prior to cementation of grains. In a wider region of the northwestern end of the Neotethys the carbonate platforms were drowned at the end of the Triassic (in the Northern Calcareous Alps and West Carpathians) or by the late Early Jurassic (in the area of the Trento Plateau and Julian Alps). The huge Adriatic-Dinaridic Carbonate Platform (ADCP) was the only place in the region where the platform conditions continued during the Middle and Late Jurassic and even in the Cretaceous, although the extent of the platform changed (Tilšjar et al. 2002). Consequently the ADCP was the only significant active shallow-marine carbonate factory in the Middle to early Late Jurassic which may have supplied the ambient basins.

Coeval with the opening of the westernmost sector of Neotethys, an extensional trough system formed. The Slovenian Trough, which separated the block of the Julian Alps from the ADCP (Buser 1989, 1996), was a part of this system. However, development of similar troughs may have caused the dismembering of the Bükk, Sana-Una and Jadar Blocks from the ADCP. All along the margin of these troughs platform-derived, mostly oolitic limestone was deposited in the Early and Middle Jurassic, mainly during the Late Bajocian to Bathonian highstand platform progradational interval, interfingering with basin facies farther from the platform.

Redeposited Jurassic oolitic limestone and carbonate lithoclastic slope deposits were reported from the Slovenian Trough (Rožič and Popit 2006), the Zumberak Mts of Croatia (Bucković et al. 2004; Bucković 2006), and also from the Pre-Karst and Bosnian Flysch Zone in Hercegovina and Montenegro (Dragicević and Velić 2002). It cannot be determined which part of the hundreds of kilometers-long platform foreslope was the source area of the clasts of olistostromes and large blocks in the Mónosbél Unit, but the northwestern segment is the most realistic candidate.

The Mónosbél Unit is overthrust from the NW by the Szarvaskő Unit (Szarvaskő Nappe) in the western part of the Bükk Mts (Balla 1983; 1987b; Csontos 1999). Fine mid-Jurassic siliciclastics with intruded gabbros and extruded basalt and basalt lava rocks of the Szarvaskő Unit were formed in a backarc or a marginal oceanic basin (Balla 1983; Harangi et al. 1996). West of the Bükk, in the Darnó area and also in the basement of the Mátra Mts, the Darnó Unit occurs above the Mónosbél Unit. The Darnó Unit is made up of Mid-Triassic peperitic and amygdaloidal basalt, similar to that in the Kalnik Unit (Palinkaš et al. 2008; Kiss et al. 2008) formed in the rift zone during the incipient stage of the opening of the westernmost sector of the Neotethys Ocean (Kovács et al. 2010), and of

Mid-Jurassic basalt similar to that of the Szarvaskő Unit. The Darnó Unit represents the northwesternmost occurrence of this Triassic peperitic facies in the Neotethyan domain (Kovács et al. 2010). Accordingly these predominantly magmatic complexes represent various evolutionary stages and various sectors of the Neotethys Ocean, including its marginal and subduction-related backarc basins.

As opposed to former considerations (e.g. Kovács 1984; Csontos 1988; Kozur 1991) the Darnó Unit, forming part of the S-vergent Dinaridic Bükk nappe system, cannot be structurally equivalent to the Meliata Unit (s.s.) forming part of the N-vergent Austroalpine-Gemeric nappe system, although they were both derived from the northwestern end of the Neotethys (cf. Haas and Kovács 2001; Kovács et al. 2008).

In the Dinarides (Fig. 1), ophiolite mélangé complexes comparable to those in the Bükk-Darnó area occur in the Dinaridic Ophiolite Belt (Dimitrijević et al. 2003). In the DOB the ophiolite mélangé contains fragments of obducted ophiolites (Iherzolite), Triassic and Jurassic limestone olistoliths, and polymict olistostromes containing clasts of Middle Triassic to Upper Jurassic radiolarian chert, greywacke, basalt, gabbro, ultramafic rocks, granite along with Triassic carbonates (Middle-Upper Triassic platform carbonates and basin facies – Bulog-, Hallstatt-, Bódvalenke-type) and Jurassic redeposited carbonates in a Jurassic argillaceous, silty matrix (Karamata et al. 2000; Pamić et al. 2002; Karamata 2006). According to radiometric dating (K/Ar) the age of metamorphism of the sole below the obducted ultramafic slices is between 181 to 157 Ma (Karamata 2006). The mélangé was locally covered by shallow marine deposits of Tithonian to Early Cretaceous age.

In the Vardar Zone (Main Vardar Zone – Karamata 2006) the Jurassic olistostromes contain clasts of greywacke, radiolarian chert, basalt, gabbro, and ultramafics in a siltstone matrix (Karamata et al. 2000). Based on K-Ar dating of amphibolite of the metamorphic sole, closure of the Main Vardar Zone basin began between 182 and 187 Ma (Karamata 2006). The ophiolite mélangé was overlain by Tithonian reef limestone, suggesting the end of the active closure by this time.

#### *Neotethyan mélangé complexes in the area of Rudabánya Hills, Aggtelek Karst and Slovak Karst*

##### *Rudabánya Hills*

The wedge-like, narrow strip of the Rudabánya Hills is located within the strongly tectonized Darnó Fault Zone (Fig. 2). It is made up of the anchi/epizonal metamorphosed Martonyi (formerly Torna) Unit, the non-metamorphosed Bódva Unit, and the low-grade metamorphosed Telekesoldal Unit (Less 2000; Kövér et al. 2008). The latter likely represents part of a Middle to Late Jurassic subduction-related sedimentary complex (probably inter-arc/back-arc basin

setting) containing black shale, locally with sandstone turbidites and olistoliths, as well as limestone-rhyolite olistostromes and acidic subvolcanic bodies (olistoliths) (Kovács 1988). The grade of metamorphism is at the boundary between anchi and epizone; a range of 120–140 Ma was measured for age of peak metamorphism and 90 Ma for nappe overthrusting (Kövéér et al. 2009). The Martonyi Unit is characterized by Middle-Upper Triassic basinal limestone. It significantly differs from the Turna Unit s.s. due to the lack of any basic volcanism, which occurs in the type locality of the latter (Turna Valley, Slovakia; Mello et al. 1997). The Bódva Unit is made up of Lower Triassic shallow-marine siliciclastics and marl, early Middle Triassic ramp carbonates (Gutenstein, Steinalm), that is overlain by deep water carbonates (Bódvalenke Limestone, followed by Hallstatt Limestone). The Middle – Upper Anisian to Upper Carnian Bódvalenke Limestone represents a transitional facies between red, pelagic limestone and red radiolarite (Kovács 2010). Blocks of similar limestone (Bódvalenke-type limestone) are common in the ophiolite mélangé of the Dinaridic Ophiolite Belt and Maliaç Zone of the Hellenides (Kovács et al. 2010). In this context it is worth mentioning that the northwesternmost occurrence of this facies in the Neotethys domain is found in the Rudabánya Mts (Kovács 2010); it is not known to occur in the West Carpathians and Eastern Alps.

#### *Aggtelek Karst*

Tectonically incorporated slices of serpentinite, gabbro and basalt of MORB-affinity (Tornakápolna Unit) (Réti 1985; Horváth 2000) occur in Upper Permian evaporites forming the sole of the Aggtelek and (?)Bódva Units. In the Tornakápolna-3 (Tk-3 in Fig. 2) borehole dark gray to black siliceous shale and silicified sandstone of supposed Jurassic age, similar to those of the Darnó Unit, were found between two large serpentinite slices of lherzolitic origin (Józsa et al. 1996; Kovács et al. in Haas 2004). In a single red radiolarite-mudstone intercalation in pillow basalts, penetrated by the same borehole, Ladinian radiolarians were found (Kozur and Réti 1986; Dosztály and Józsa 1992).

The Aggtelek Unit is located NW and N of the Rudabánya Mts; it is part of the Silica Nappe s.s. (sensu Kozur and Mock 1973). The southeastward facing Aggtelek reef occurs in the NW part of the unit; it is the oldest (Upper Anisian to lowermost Ladinian) platform margin reef of the Alpine Triassic (Velledits et al. 2008) The eastern part of the unit is characterized by a southward-facing Carnian Wetterstein carbonate platform (reefal facies in the S and lagoonal facies in the N) and Ladinian to Carnian slope facies in its southern foreland (Kovács 1997; Péro et al. 2002, 2003). Both the platform carbonates and the slope deposits are covered by Upper Carnian to Norian Hallstatt Limestone.



### *Slovak Karst*

The Meliata Unit in SE Slovakia is also a displaced fragment of the Middle to Late Jurassic (Upper Callovian to Lower Oxfordian – Kozur and Mock 1985; Vozárová and Vozár 1992; Kozur et al. 1996) subduction-related Neotethyan sedimentary complexes. It is made up of olistostromes with larger olistoliths in a black shale and radiolarite matrix. Among the olistoliths Lower to Middle Anisian limestone, Ladinian radiolarite, Ladinian basalt (in Jaklovce), Upper Triassic basinal limestone, and Jurassic deep-marine deposits and volcanic rocks (predominantly basalt) were found (Kozur and Mock 1973; Vozárová and Vozár 1992; Mello et al. 1995; Kozur et al. 1996; Mock et al. 1998). The Meliata Unit is overthrust by the Silica Nappe and accordingly a number of tectonically disintegrated blocks of the Meliata Unit, including MORB-type basalt bodies, were emplaced into the Permian-Lower Triassic evaporitic sole of the overriding nappe (Mello et al. 1997).

### *Discussion*

#### *On the northeastern continuation of the Periadriatic-Balaton Line*

Whereas the south-western part of the Mid-Hungarian Zone is well defined by the bordering MHL to the SE (that forms the northwestern boundary of the Tisza Mega-unit) and the PAL–BAL to the NW (see Fig. 1), which stretches from the Zagorje region in NW Croatia (Kalnik, Medvednica and Ivanščica Mts) to the Danube River, its northeastward continuation in the Bükk-Gemer area (cf. Less and Mello 2004) is rather problematic. This zone was named the "Zagorje–Bükk-Meliata Zone" by Pamić et al. (2002) and Pamić (2003). South of the Bükk Mts the continuation of the MHL is still defined by borehole data as far as east of the Tisza River (cf. Fig. 2). The direct northeastward continuation of the BAL, however, is rather ambiguous. The prominent Darnó Fault Zone (DFZ) was considered its continuation by a number of authors (Szalai 1961; Dank and Bodzay 1971; Wein 1978; Channel et al. 1979; Ustaszewski et al. 2008). However, elements of the Bükk Composite Unit (at least the mélangé complex of the Mónosbél Unit) continue NW of the DFZ, in the pre-Tertiary basement of the Recsk Paleogene volcanic complex (Haas and Kovács 2001; Kovács et al. 2008), which represents the northeasternmost-known occurrence of the Periadriatic magmatic chain (Kovács et al. 2007; Földessy et al. 2008; Less et al. 2008). Accordingly the tectonic boundary between the Bükk Composite Unit and the Transdanubian Range Unit can be considered as the continuation of the BAL. This poorly defined fault zone running somewhere in the Zagyva Trough (see Haas et al. 2010) is dislocated by the Hurbanovo–Diósjenő Fault. North of the Hurbanovo–Diósjenő Fault the northeastern continuation of the Darnó Fault Zone is the western boundary of the Bükk Composite Unit (Uppony and Szendrő Hills), whereas it is bordered by the Hernad Fault eastward.

*Is there any Neotethyan suture zone in the Circum-Pannonian region?  
Mid-Hungarian Zone versus "Meliata–Hallstatt Suture"*

The suture zones of the Neotethys Ocean can be continuously traced in the Alpine–Himalayan orogenic belt from SE Asia and Indonesia up to Serbia and Bosnia (Robertson and Karamata 1994; Robertson 2004; Robertson et al. 2009) over a length of more than 12,000 km (Robertson 2007), represented by huge obducted ophiolite mélanges, exposed at surface practically continuously over an extent of hundreds or thousands of km<sup>2</sup>. The northwesternmost completely preserved cross-section of this closed ocean can be seen just south of the Pannonian Basin, in the Bosnian-Serbian sector (cf. Dimitrijević 2001; Karamata 2006, and references therein). Further northward, northwestward, and northeastward, in the Circum-Pannonian region, only small, dispersed remnants of these Neotethyan accretionary complexes occur, of a few km<sup>2</sup> (but sometimes even a few m<sup>2</sup>) surface or subsurface extent. They have been dispersed (thus representing typically small "disrupted terranes" in the sense of Howell (1989) by late Mesozoic to Tertiary (pre-Middle Miocene) nappe movements and sizeable strike-slip displacements.

The Mid-Hungarian Zone represents a prominent transpressional zone in the Circum-Pannonian region, where displaced Dinaridic and South Alpine elements were encountered in wells over a distance of 400–500 km up to the Bükk Mts, where remnants of Neotethyan accretionary complexes are visible in a few km<sup>2</sup>-large surface extent in the Bükk (Szarvaskő) – Darnó area. Nevertheless, this zone can hardly be interpreted as an *in situ* "suture zone" (see above).

On the other hand, a "Meliata–Hallstatt suture zone" was supposed by several authors to run along the northern border of the Transdanubian Range Unit (i.e. along the Hurbanovo–Diósjenő Line); further westward it continues along the southern margin of the Northern Calcareous Alps up to the Salzburg region (Schweigl and Neubauer 1997; Plašienka et al. 1997; Kováč and Plašienka 2002; Csontos and Vörös 2004).

Neotethyan remnants (some ophiolite and radiolarite) are known in the northernmost part of the Gemer–Bükk area, related to the basement of the Stratena Nappe (Havrila and Ozvoldová 1996; Mello et al. 1995, 2000). Further westward no real evidence of such remnants is known up to the southeastern corner of the NCA (Mürztal Alps; Mandl and Ondrejčiková 1991, 1993; Kozur and Mostler 1992). Although Vojtko (2000) assigned a slightly metamorphosed evaporitic sequence at the base of the Muráň nappe to the "Meliaticum", it can hardly be considered as proof for an oceanic remnant.

Detailed structural and facies analyses of Kováč P. and Havrila (1997) pointed out that the Ladinian platform carbonate units in the Hronic region (formerly classed among the "North Gemic" units or "Spišcum" – Andrusov 1968; Mahel 1986) are parts of the Triassic platform (Wetterstein, Ramsau carbonates) and basin (Reifling Limestone) system of the Hronicum. In spite of these studies, Kováč M. and Plašienka (2002) and Csontos and Vörös (2004) still considered

these "North Gemic" units as the SE margin of the "Meliaticum". Accordingly they interpreted the paleogeographic position of the "Meliaticum" further northwestward. In the light of Havrila's results this paleogeographical assumption has lost any credibility.

Interpretation of geophysical data concerning to the Hurbanovo-Diósjenő Line is another problem in this context. Balla (1989) interpreted the marked magnetic anomaly along the line as "Meliatic" bodies. However, detailed petrological studies have proved that those cores which were mentioned by Balla as belong to the "Meliaticum" represent the continuation of the Southern Veporicum without any "Meliatic" relic (Koroknai et al. 2001a).

The Lower Cretaceous Gerecse Flysch occurs south of the Hurbanovo Line and contains large amounts of sand-sized ophiolite detritus; it is considered to have been displaced from the southern neighborhood of the Rossfeld flysch basin near Salzburg in the NCA (Kázmér and Kovács 1985; Sztanó 1990; Császár and Árgyelán 1994). Thus it cannot provide unambiguous evidence of an oceanic domain lying just to the north of the present Hurbanovo Line.

All these facts provide arguments against a continuously preserved "Meliata-Hallstatt suture" stretching from the Gemic area to the southern part of the NCA. Indeed we can speak of small dispersed Neotethyan remnants along this strike, rather than of a continuous "zone". The strike-slip dispersion of these Eohellenic (Late Jurassic) elements, however, should have preceded the Middle-Late Cretaceous Palealpine nappe stacking, when they were incorporated into the north-vergent Austroalpine nappe pile (cf. Frank and Schlager 2006). The sinistral offset of the Upper Permian to Upper Triassic facies zones (especially the Hallstatt Limestone facies) occurring in NE Hungary (cf. Haas et al. 1995) may have been the result of the same process already taking place in the Late Jurassic, and not in the Tertiary as suggested in the first escape model by Kázmér and Kovács (1985). The track of the Jurassic strike-slip suggested by Frank and Schlager (2006), however, has been almost entirely obliterated by younger, Cretaceous and Tertiary movements. The Hurbanovo–Diósjenő Fault is considered to be a young, Tertiary sinistral strike-slip fault zone and kinematically cannot be the westward continuation of the Cretaceous thrust-faults in the Gemic area (Lubeník-Margecany and Rožňava Lines, respectively).

### *Summary of the evolutionary history*

The elements of ALCAPA were subject to complex, multistage deformations and large-scale displacements. The Transdanubian Range Unit located north of the Periadriatic-Balaton Line was situated between the Southern Alps and Northern Calcareous Alps prior to the large-scale displacements (Majoros 1980; Kovács 1982; Kázmér and Kovács 1985; Haas and Budai 1995; Haas et al. 1995). Those blocks which occur at present between the PAL–BAL and the MHL, i.e. in the Mid-Hungarian Zone, belonged to the eastern sector of the Southern Alps

and the western sector of the Dinarides. In the northern part of the Zagorje–Mid-Transdanubian Unit, displaced fragments of the Southern Alps (Carnic Alps, South Karavanks, Julian and Savinja Alps) occur. They were not affected by Alpine metamorphism. In the southern part of the Zagorje–Mid-Transdanubian Unit and also in the Bükk Unit, Alpine metamorphic complexes and Jurassic ophiolite mélangé, showing affinity with the subduction-related Dinaridic ophiolite mélangé complexes, are present. These elements may have been parts of a domain which accreted prior to the large-scale Tertiary displacements, and were dispersed as a result of these tectonic movements.

Mid-Triassic opening of the Neotethys Ocean resulted in the formation of early rift-type volcanics, remnants of which occur in the Kalnik and in the Darnó Units, respectively (Pamić and Tomljenović 1998; Haas and Kovács 2001; Palinkaš et al. 2008). Coeval extensional tectonics led to the formation of the Slovenian Troughs (Buser 1989, 1996; Šmuc and Car 2002) and other similar troughs which resulted in dismembering of the platform of the Julian Alps and other isolated platforms (among them the Bükk Platform) from the large Adriatic-Dinaridic Carbonate Platform (ADCP).

During the sea-floor spreading stage in the Late Triassic to Early Jurassic interval attenuation of the continental lithosphere took place along the oceanward outer shelf margin. It resulted in drowning of the dismembered platforms, while the platform development continued on the ADCP during the entire Jurassic (and also in the Cretaceous), supplying the ambient basins with carbonate grains.

Subduction of the Neotethys was initiated in the Middle Jurassic. The Hellenic-Dinaridic ophiolites are classed mostly among the supra-subduction zone-type (SSZ) ophiolites (Robertson 2004; Robertson et al. 2009). The metamorphic soles formed by the underplating of cold oceanic crust to hot over-riding ophiolitic mantle were dated at 174–162 Ma by the Ar/Ar method and 174–147 by the K/Ar method in the Dinarides (Robertson et al. 2009). During subduction, in the frontal accretion zones gravitationally reworked material was accumulated in the trench or forearc basin, i.e. mélangé complexes were formed. The subduction-related ophiolite mélangé was subject to multiple displacements, restructuring and later reworking.

In the Dinaridic area ophiolite emplacement took place mostly in the Middle Jurassic to Early Cretaceous interval, although the western belt of the Vardar Zone remained an oceanic basin till the end of the Cretaceous (Usztasewski et al. 2008; Robertson et al. 2009). Development of the ADCP still continued coevally on the margin of the Adria Microplate. Collisions of the Adria Microplate with plate fragments occurred between the African and the European Plates, induced nappe stacking and related regional metamorphism in two stages in the late Early Cretaceous (110–120 Ma) and in the Late Cretaceous (75–95 Ma), respectively. These tectono-metamorphic events were also recognized in several units of the Mid-Hungarian Zone (Bükk Unit s.s., Uppony, Szendrő, Medvednica,

South Zala) which may have been segments of Dinaridic (Internal Dinaridic) nappe stacks, probably formed in two stages during the Cretaceous. In general the ophiolite mélangé complex was overthrust upon the previous continental margin sequences, which is reflected in the usually lower-grade metamorphic alteration of the mélangé. The non-metamorphosed units represent the uppermost member of the nappe stack.

Shearing, disintegration and squeezing out of the nappe stacks between the PAL–BAL and MHL may probably have initiated in the latest Cretaceous, but the main stage of the transpressional displacement took place in the Paleogene to Early Miocene, when northeastern movement and counter-clockwise rotation of the ALCAPA led to large-scale nappe stacking in the Outer Carpathian flysch basin (Balla 1987a; Royden 1988; Ratschbacher et al. 1991; Horváth 1993; Csontos and Nagymarosy 1998; Csontos et al. 1992; Fodor et al. 1999; Horváth et al. 2006; Kovács et al. 2007; Ustaszewski et al. 2008). The Mid-Hungarian Zone was established at this time, in the final stage of accretion of the basement of the Pannonian Basin that subsequently began to develop.

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