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Geodynamics of SW-Pannonian inselbergs (Mecsek and Villány Mts, SW Hungary): Inferences from a complex structural analysis

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Abstract. Three independent methods: paleomagnetic investigation, analysis of reflection seismic sections and structural study of outcrops have been applied to Mesozoic-Tertiary rocks of the Mecsek and Villány Mts (SW Hungary), which form inselbergs in the southern part of the Pannonian Basin. The structural history is marked by Late Oligocene-Early Miocene NW-SE shortening (in present cooridinates); late Early Miocene N-S shortening together with important clockwise rotations of the whole area and local counterclockwise rotations in E-W left lateral wrench corridors; smaller N-S shortening with local wrenching and positive inversion during the Middle Miocene; an important N-S shortening creating large folds and thrust reactivation in Late Miocene; a transtension characterised by roughly WNW-ESE elongation directions, creating left lateral oblique faulting along NE-SW oriented fault segments in Late Miocene; an important NW-SE shortening from latest Miocene to Present. This latter reactivated E-W structures as right lateral transpressive wedges and generated locally important rotations along them.

Comparison of the obtained and regional structural data and rotation pattern strongly modifies our original concepts about microplate behaviour in the Intra-Carpathian realm. The geodynamic history is still dominated by the opposite rotation and consequent interplay of two major terranes: Alcapa and Tisza, but these are no more considered as rigid blocks. Differential rotations and deformations within Tisza are explained by major tears or thrusts across this block. Left lateral wrench zones within the clockwise rotating Tisza block are explained by differential movements due to this rotation. Both paleomagnetic and structural data indicate that the main phase of rotation and complex deformation was in Late Ottnangian (ca. 18 Ma), followed by a more quiescent period in this part of the Pannonian Basin. Several strong reactivations, perhaps with incipient rotation, are experienced from Late Miocene (ca. 11,5 and ca. 7 Ma) on.

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1 Introduction

The investigated area lies in SW Hungary, in the Mecsek-Villány area, in the south- western part of the Pannonian Basin (Fig. 1), where moderately elevated (600 m) inselbergs comprising crystalline and Mesozoic sedimentary rocks rise above the lowlands of young Tertiary rocks. The surroundings of the Mecsek and Villány Mts are parts of a major Intra-Carpathian terrane, called Tisza (Fig. 1). This terrane has outcrops in the mentioned mountains, in the Apuseni Mts of Transylvania (Romania) and in the Slavonian Inselbergs of northeastern Croatia. It was defined by its peculiar Mesozoic nappes, which can be followed from the Slavonian Inselbergs, through the basement of the Great Hungarian Plain as far as the Apuseni Mts and the basement of the western Transylvanian basin (e.g. Kázmér 1986; Bleahu et al., 1996). The Mecsek Mts forms part of the structurally lowermost known tectonic unit of this terrane, while the Villány Mts Mesozoic is the directly overlying nappe. These nappes comprise Variscan crystalline basement and/or granite, Late Palaeozoic, post-Hercynian cover and a Mesozoic sequence of variable thickness (Vadász, 1935; Nagy and Nagy, 1976). Under the Great Hungarian Plain the Cretaceous nappes are sealed by a Turonian-Senonian cover, which might be later deformed. Paleogene is generally missing, only present in a northeastern trough (Szepesházy, 1973) and some restricted basins (Wéber, 1982). An occasionally thick, Early Miocene clastic sequence with ignimbrites is deposited in local basins (Fig. 2). This is followed by a very variable Middle Miocene sequence, from continental in the south to open marine north of the Mecsek (Barabás, 1995). The Mecsek Mts are covered by relatively thick Early and Middle Miocene, while south of this mountain the whole Early-Middle Miocene is thin or completely missing, only preserved in local deeps. The whole area is generally covered by a transgressive clastic Late Miocene-Pliocene, known as Pannonian deposits (Kleb, 1973). These lake-delta and alluvial beds partly cover, partly surround the present elevations.

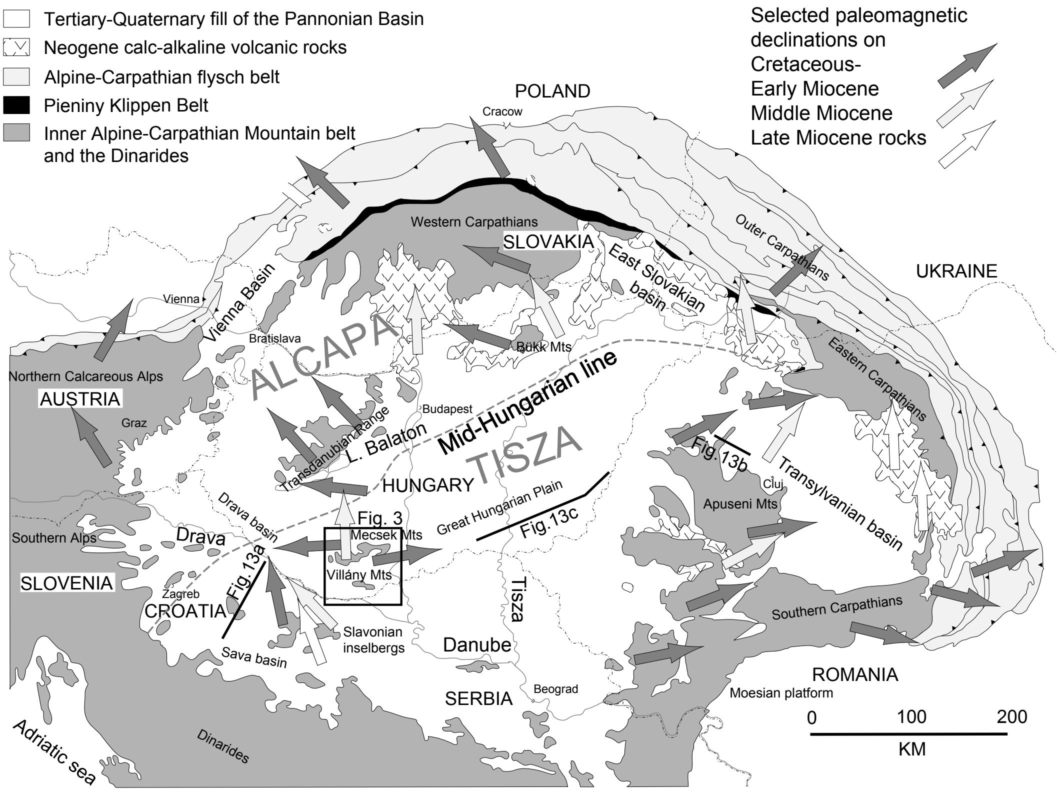

Fig. 1. Tectonic sketch of the Intra-Carpathian area with selected paleomagnetic declination directions in the Tisza unit. Declinations after Bazhenov et al. (1993), Krs et al. (1982, 1991), Márton (1990), Márton and Márton (1989, 1999), Márton et al. (1992, 1999), Panaiotu (1998), Patrascu et al. (1991, 1992, 1994).

2 Aims, methods

Three different, independent methods of structural analysis were applied in the SW Hungarian area in the last decade. All the detailed work has been published elsewhere. In this paper, we concentrate on the main results of these separate analytical studies, in order to arrive at a structural synthesis for the Tertiary and to discuss the geodynamic consequences.

A concise paleomagnetic survey was conducted from the seventies onward. First Paleo-Mesozoic and igneous rocks were studied (Márton and Márton, 1978; Márton, 1986). Since these gave very interesting results, indicating a complicated rotational history, further research was conducted partly to verify the rotations and partly to give better time constraints for the Tertiary rotations. This resulted in an even more complicated rotational pattern, which, together with all the details of paleomagnetic analysis, were summarised in a recent paper (Márton and Márton, 1999). The apparently contradicting paleomagnetic rotations raised a number of questions and needed a structural explanation.

In the sixties-seventies a geophysical survey (e.g. Fülöp et al., 1964; Braun et al., 1977) comprising seismic section analysis was conducted in the Mecsek-Villány area. Faults were interpreted as steep normal faults, or without expressed character. This was not in agreement with surface observations (e.g. Vadász, 1935; Wein, 1967) which made reinterpretation of the seismic sections necessary. This work was done in the framework of a Master's study at the Eötvös University, Budapest (Wórum, 1999). Details of this work are being published (Csontos et al., 2002).

A series of fault slip and meso-scale structural analyses were conducted from the eighties onward. These works concentrated on observation of fault gauges, slickenside lineations and related structures in order to define the slip directions on individual fault planes. Early works (Bergerat and Csontos, 1988; Csontos and Bergerat, 1992) lacked sufficient observation to constrain the timing of structural events. This gap was later covered by description of more Tertiary outcrops in a Thesis work (Benkovics, 1997; Csontos et al., 2002). Fault data can be also important to explain regional structures suggested by paleomagnetic or seismic section analysis.

3 Earlier recognised main structures

Exploration and exploitation of several raw materials lead to early recognition of the structural build-up of SW Hungary. Vadász (1935), then Wein (1967), Rakusz and Strausz (1953), and Némedi-Varga (1983) all concluded that both mountains expose folded, intensively deformed rocks, where thrusting dominates over normal faulting. Five main structural zones were recognised (Fig. 3). In the north of the Me-

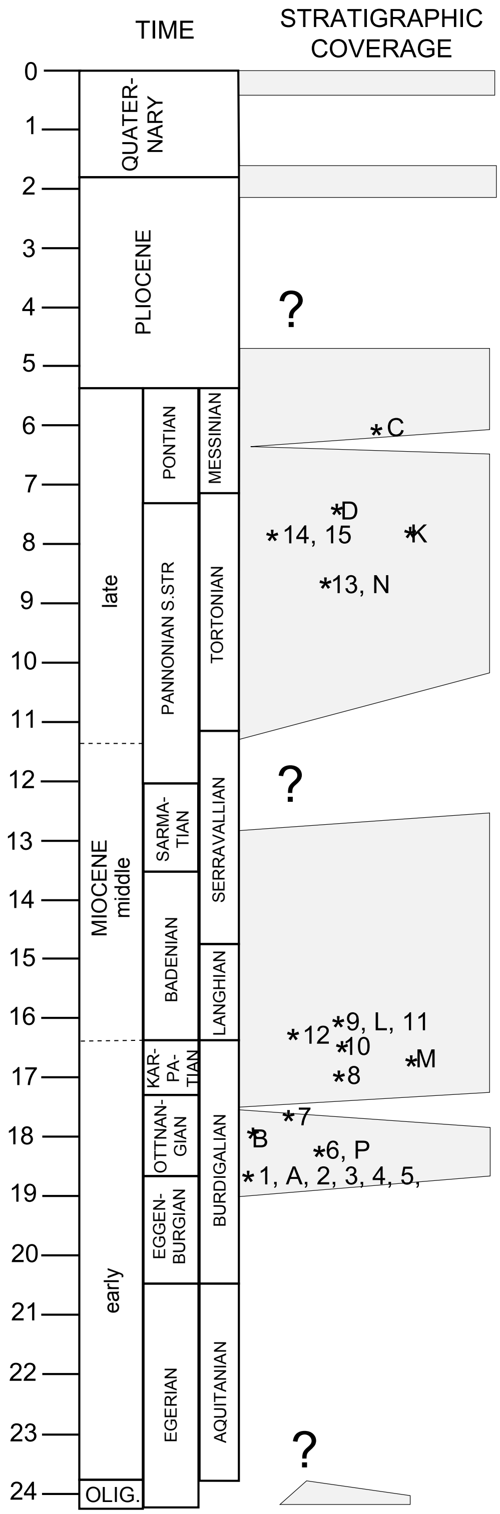

Fig. 2. Tertiary stratigraphic coverage. Local stratigraphic names and ages after Tari et al. (1999), Magyar et al. (1999) and Sacchi et al. (1999). Grey shades indicate time intervals represented by sediments or magmatic rocks. Asterisks, numbers and letters refer to localities studied by paleomagnetic and structural methods. ? = uncertainty in dating.

csek Mts, an E-W stretching narrow deformation belt called Northern Imbricates is limited on both sides by thrust faults. The northern branch involves Lower Pannonian strata (Wein, 1967). The main part of the Mecsek Mts is transected by several ENE-WSW stretching deformation zones. A north-vergent thrust separating Mesozoic from Tertiary was named Hetvehely (-Magyarszék) line by Wéber (1977). A set of major folds with roughly E-W axis builds up the main mass of the Mecsek Mts. These folds were determined as mid-Cretaceous and later reactivated in the Late Miocene (Pannonian; Vadász, 1935; Wein, 1967; Hámor, 1966; Benkovics, 1997).

The third classical deformation zone is the South Mecsek line. This is an E-W to NE-SW oriented deformation zone, where Palaeozoic metamorphic rocks, Permian and Mesozoic sequences are juxtaposed to Late Miocene in the south (Vadász, 1935; Wein, 1967). In the eastern part the classical South Mecsek line separates Jurassic in the north from granite and metamorphic rocks in the south (Pataky et al., 1982). Along the whole line deformation of Late Miocene age occurs (Vadász, 1935; Wein, 1967; Kleb, 1973).

The fourth regional structural zone is an E-W stretching belt of dispersed Mesozoic exposures (Kaszap, 1963), outcropping in small quarries near Máriakéménd. This belt continues to the west, where Palaeozoic metamorphics are found by very shallow (less than 100 m) boreholes at the so called Görcsöny high. These rocks have a thin Miocene cover and Pannonian strata uplifted above the general Pannonian landscape. Finally the fifth deformation belt is the Villány Mts proper. This set of Mesozoic exposures has an elongated E-W shape. The exposures form 5 imbricates, where the Triassic to Early Cretaceous sections are repeated (Rakusz and Strausz, 1953; Nagy and Nagy, 1976). The north-vergent thrusts were interpreted as Cretaceous, but with Late Miocene reactivation (Nagy and Nagy, 1976). Based on fault slip analysis the structure was interpreted as a Tertiary transpressive half-flower structure by Bergerat and Csontos (1988). The Villány Mts does not have an exposed Miocene cover, that is why timing of deformations has been difficult to constrain.

4 Paleomagnetic analysis

4.1 Measurements in differently rotating domains

Several sampling and measuring campaigns lead to a good paleomagnetic coverage of the Mecsek-Villány area (Fig. 3). Cretaceous mafic dykes, Eggenburgian-Ottnangian ignimbrites, subvolcanic andesite and sediments, different Karpatian-Badenian fine grained sediments and tuffs as well as Pannonian (Late Miocene-Pliocene) clays and marls were sampled (Márton and Márton, 1999; Table 1). With the exception of Cretaceous mafic dykes, the Late Palaeozoic-Mesozoic samples of the Mecsek and Villány Mts are not dealt with here, since these are not conclusive for the Tertiary deformations and rotations.

During field-work 29 accessible, non-altered and apparently in situ Tertiary localities were sampled. The total num-

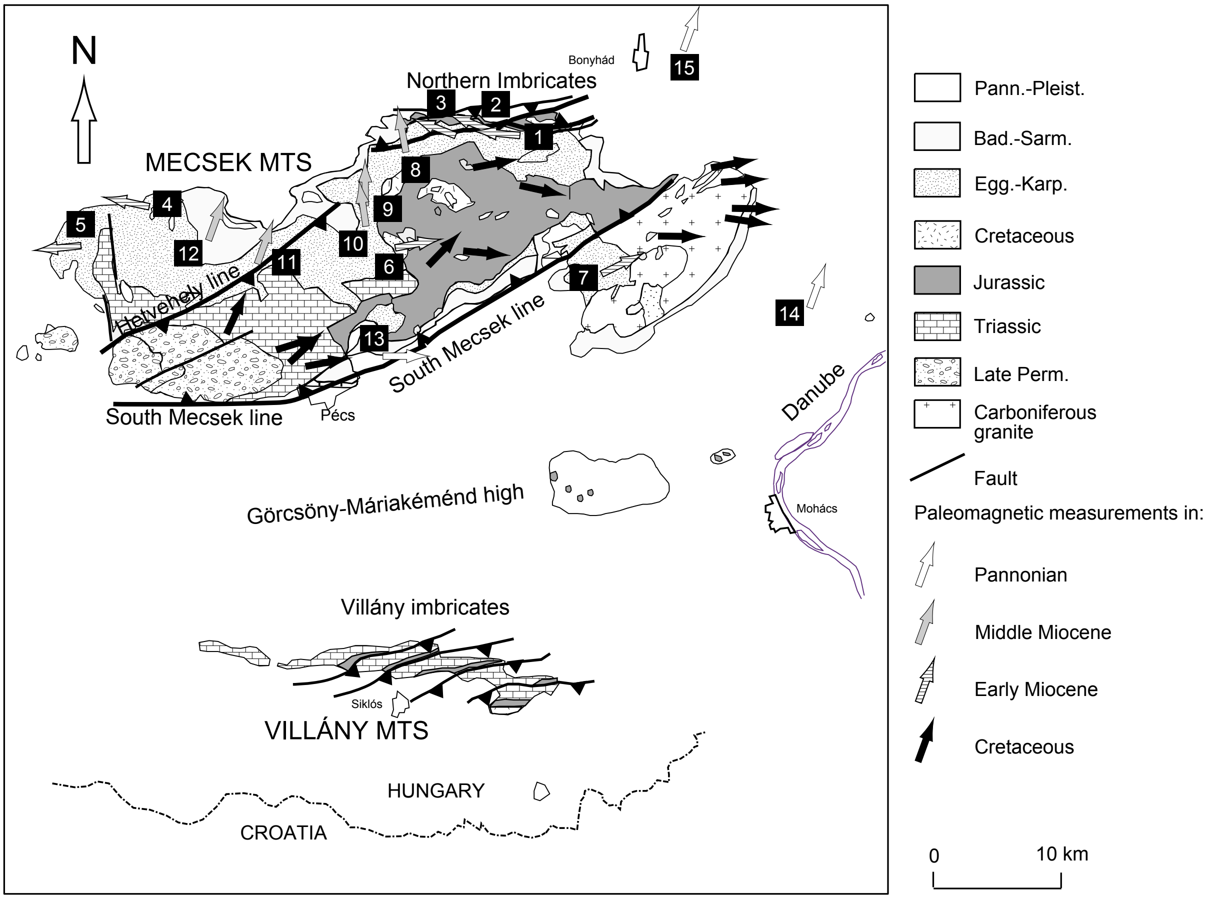

Fig. 3. Location map of the study area with measured paleomagnetic declination directions. Main structural zones are marked in bold. Paleomagnetic sampling localities are indicated by base of arrow and in cases of Tertiary rocks by numbers. Data in Table 1.

ber of drilled samples was 337. Unfortunately, only a fraction of these (146 samples from 15 localities) gave statistically valid paleomagnetic results; in negative localities magnetisation was too weak or too scattered. In this paper only the successful (positive) localities are briefly presented.

All samples underwent the standard measurement-demagnetisation procedures, usually by a combination of thermal and AF demagnetisation, with the aim to separate the components of Natural Remanent Magnetisation (NRM) and to obtain the original (or oldest) magnetisation (Márton and Márton (1999). Magnetic susceptibility and anisotropy measurements were also carried out. IRM acquisition experiments and the thermal demagnetisation of the three- component IRM helped to identify the carrier of the NRM. The results of the positive localities are shown on Fig. 3 and Table 1. After cleaning the eventual effects of the present magnetic field, one component of NRM remained. Inclinations generally corresponded to those expected for the location of the area at the time of rock formation. Statistical parameters were in all cases good or excellent (Table 1), so the quality of measurement in the positive localities was very good. It is all the more surprising, that different areas and different age groups showed very differently rotated declinations.

The Pannonian localities from both the northern and south-eastern periphery of the Mecsek (14, 15 on Fig. 3) showed a slight but consistent clockwise rotation of about 15°–20° with respect to present North. Early Miocene ignimbrites located in a narrow zone at the northern edge of the Mecsek mountains, close to, or within the Northern Imbricates (localities 1, 2, 3, 4, 5 on Fig. 3) showed an important, 60°–80° counter-clockwise rotation. This pattern seems to be confined to this zone. Another group of localities in Early Miocene andesite, Lower Karpatian clastics and Cretaceous dykes show an equally important, ca. 60°–70° clockwise rotation at the south-eastern part of the Mecsek Mts (6, 7 and non-numbered black arrows on Fig. 3). We have to stress that a folded Pannonian locality (13 on Fig. 3) gave the same, 80° clockwise rotation as the surrounding area. This problem is addressed in the next paragraph. Finally, there is a group of localities, comprising Late Karpatian-Badenian sediments and tuffs, very close to both the Northern Imbricates zone and the central-south-eastern part (8, 9, 10, 11, 12 on Fig. 3), which show no rotation, or a very slight, 15° clockwise rotation with respect to present North (Márton and Márton, 1999). This group could be very important for the timing of the different structural-rotational events.

Table 1. Paleomagnetic data from the Mecsek area. Columns: **Site**: numbers referring to outcrops, on Fig. 2. **Age, rock**: age and lithology of samples. **n/n$_0$**: Number of samples giving positive result /total number of samples at the locality. **D**: Declination in geographic coordinates (uncorrected for later tilt). **I**: Inclination in geographic coordinates (uncorrected for later tilt). Negative value means reverse polarity. **k**: Statistical parameter (the greater the better). α_{95}: Apex angle of the 95° confidence cone (the smaller the better). **D$_c$**: Declination in tectonic coordinates (corrected for later tilt). **I$_c$**: Inclination in tectonic coordinates (corrected for later tilt). Negative value means reverse polarity. Numbers in bold represent accepted values (i.e. leaving away or applying tectonic correction). For details see Márton and Márton (1999).

Site	Locality	Age, rock	n/n$_0$	D	I	k	α_{95}	D$_c$	I$_c$	k	α_{95}
1	Vörösvölgy	Ottn. ignimbrite	8/10	139	-33	15	15	**99**	**-80**	15	15
2	Máza	Ottn. ignimbrite	10/10	**118**	**-57**	35	8	118	-57	35	8
3	Balinca	Ottn. ignimbrite	9/9	67	-61	491	2	**111**	**-59**	491	2
4	Kisbeszterce	Ottn. ignimbrite	11/16	007	-67	67	6	**105**	**-52**	67	6
5	Horváthertelend	Ottn. ignimbrite	16/17	**124**	**-53**	33	7	84	-33	33	7
6	Komló	Ottn. andesite	12/12	**56**	**+59**	164	3				
7	Feked	Karpatian basal silt	6/11	**59**	**+55**	22	17	62	+60	22	17
8	Magyaregregy	Karpatian marl	15/23	59	+74	120	3	**355**	**+47**	120	3
9	Mecsekjánosi	E. Badenian silt	5/10	191	+11	23	16	**005**	**+79**	23	11
10	Komló-Kökönyös	E. Badenian tufite	7/12	357	+53	126	5	**350**	**+54**	126	5
11	Orfű	E. Badenian silt	16/18	36	+58	43	6	**19**	**+57**	43	6
12	Husztót	E. Badenian tufitic silt	7/12	355	+63	25	12	**004**	**+68**	36	7
13	Danitzpuszta	E-L. Pann. marl	9/18	**90**	**+60**	19	12	118	+25	60	19
14	Bátaszék	L. Pann. claymarl	10/11	187	-61	136	4	**201**	**-60**	136	4
15	Kakasd	L. Pann. claymarl	5/10	193	-41	75	9	**201**	**-46**	75	9

4.2 Age constraints and problems

Late Pannonian localities (14, 15) in the east are either slightly clockwise rotated, or suffered no rotation with respect to the Miocene pole directions for stable Europe (depending on the definition of the Miocene pole of Europe). Because of uniformity and different locations, we may infer a negligible bulk clockwise rotation of the wider Mecsek area after, or within the Late Pannonian.

Counter-clockwise rotation of the Early Miocene localities in the Northern Imbricates zone seems to be sealed by the non-rotating Middle Miocene rocks which are immediately adjacent. This brackets the time of rotation between the Ottnangian (19 Ma, age of ignimbrite formation of 1, 2, 3, 4, 5) and the Late Karpatian-Early Badenian (16.5–16 Ma, age of non-rotated sediments of 8, 9, 10, 11, 12). Similar arguments can be brought up for timing of the rotation of the south-eastern block: the Komló andesite of Ottnangian age (19 Ma; locality 6), Early Karpatian clastics on the granite (7), plus nearby Cretaceous localites are clockwise rotated, while Early Badenian sediments near Komló (9) are non-rotated. The age bracket of the clockwise rotation is the same as that for the Northern Imbricates zone. The amount of rotation is ca. 60° to 90° with respect to the north.

There is a conflict, however, between the above reasoning and the declinations of Pannonian locality 13 (Fig. 3). This locality at the South Mecsek line shows apparently equal value of clockwise rotation as the whole south-eastern area, so the upper age limit of this rotation could be much higher, post-Early Pannonian, as suggested by Márton and Márton (1999). This high value of clockwise rotation is also in conflict with the practically non-rotated sites of about the same age (14 and 15). Since locality 13 is directly situated upon the classical South Mecsek line, known from surface geology, we now speculate that its anomalous rotation is due to a reactivation of that line, rather than to a late bulk rotation of the whole Mecsek area. In this manner, this sample would not be conclusive for behaviour of the whole south-eastern area, but would indicate local rotation in a late, dextral strike slip zone, which was postulated by Benkovics (1997).

Another major problem is the opposite rotation of the Northern Imbricates and the south-eastern Mecsek areas. There is 150–180° angular difference between the declination directions of rocks of the same age. As mentioned earlier, paleo-inclinations, statistical parameters validate both sets of observations, so no error in measurement, treatment or analysis can account for this difference (Márton and Márton, 1999). This huge difference might be accommodated by a flat detachment, but such a detachment is not known to surface geology. In case the south-eastern Mecsek would be rotated 60–80° clockwise in the Late Pannonian this detachment should imply Pannonian strata as well and differential thrusting and major scissors-like opening should be seen around the detachment. Major angular difference be-

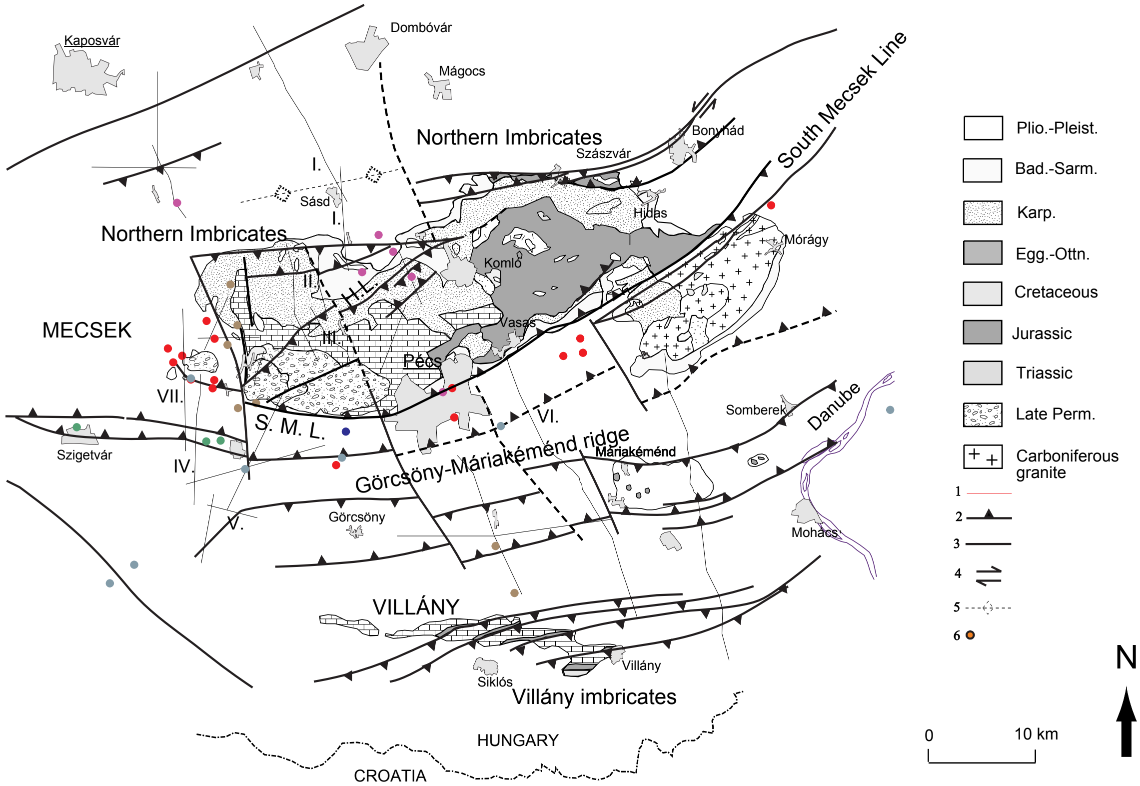

Fig. 4. Structural map of the Mecsek-Villány area based on seismic section reinterpretation (after Wórum 1999, slightly modified). 1 = seismic section network (roman numbers indicate presented sections); 2 = Thrust (dashed: supposed); 3 = Transfer zone; 4 = Strike-slip fault; 5 = Anticline; 6 = Important borehole; S.M.L. = South Mecsek Line; H.L. = Hetvehely Line.

tween declination directions could also be accommodated by a strike slip fault between the two areas. The main task of the other structural studies was to answer these questions.

5 Seismic section analysis

5.1 Main structures

As a result of seismic section analysis, previously recognised structures and main deformation belts (Fig. 4) were confirmed. The Northern Imbricates emerged as a well-correlated complex regional structure limiting the Mecsek Mts. to the north. It could be extended from the outcrops towards the west (compare Figs. 3, 4). The Northern Imbricates are characterised by a conjugate set of relatively steeply dipping thrust faults (junction of sections I and II; Fig. 5a). This double structure can be interpreted as a positive flower structure (c.f. Tari, 1992). Tertiary (Lower Pannonian) is involved in the thrusts on the northern side, but the core of the flower is composed of Mesozoic strata. All this corresponds to the structures described from surface mapping (Wein, 1965), or from coal-exploration boreholes (Wein, 1967).

The next major structure, the Hetvehely line is seen on section III (Fig. 5a) as a flat surface beneath Mesozoic domes, but also folding and overthrusting Miocene deposits.

One of the most prominent structural zones of the area, the South Mecsek line gave the biggest surprise (Fig. 5b). Unfortunately seismic sections loose resolution on the place of the line indicated by surface geology, because it is always associated with an abrupt topographic uplift. On the other hand, there are important structural features beneath the flat Tertiary area. On section IV (Fig. 5b), granitic-metamorphic mass is thrust over a well-layered Paleogene sequence (Late Eocene-Oligocene?; Wéber, 1982). Even the Early Miocene (probably Eggenburgian-Ottnangian) is cut by the fault and a Cretaceous imbricate is involved in the thrust (black arrow). Even onlapping Pannonian seems to be slightly folded (white arrow). These features indicate a later recativation of the basal fault as a blind thrust and a passive roof backthrust of the Pannonian onlap surface. Because of the reactivations and subsequent movements in this structural zone a set of steeper faults branches off this sole thrust and creates individual offsets. One branch, or several relay faults of this splay were previously termed (and mapped) as the South Mecsek line.

A geological cross-section (section VII, Fig. 6) taken from Barabás and Csicsák (in Barabás, 1995) and prepared on the basis of a large number of boreholes is presented here, because it carries important information about timing. The section crosses the South-Mecsek line (as defined by earlier authors) and is in great part parallel to section IV. The key

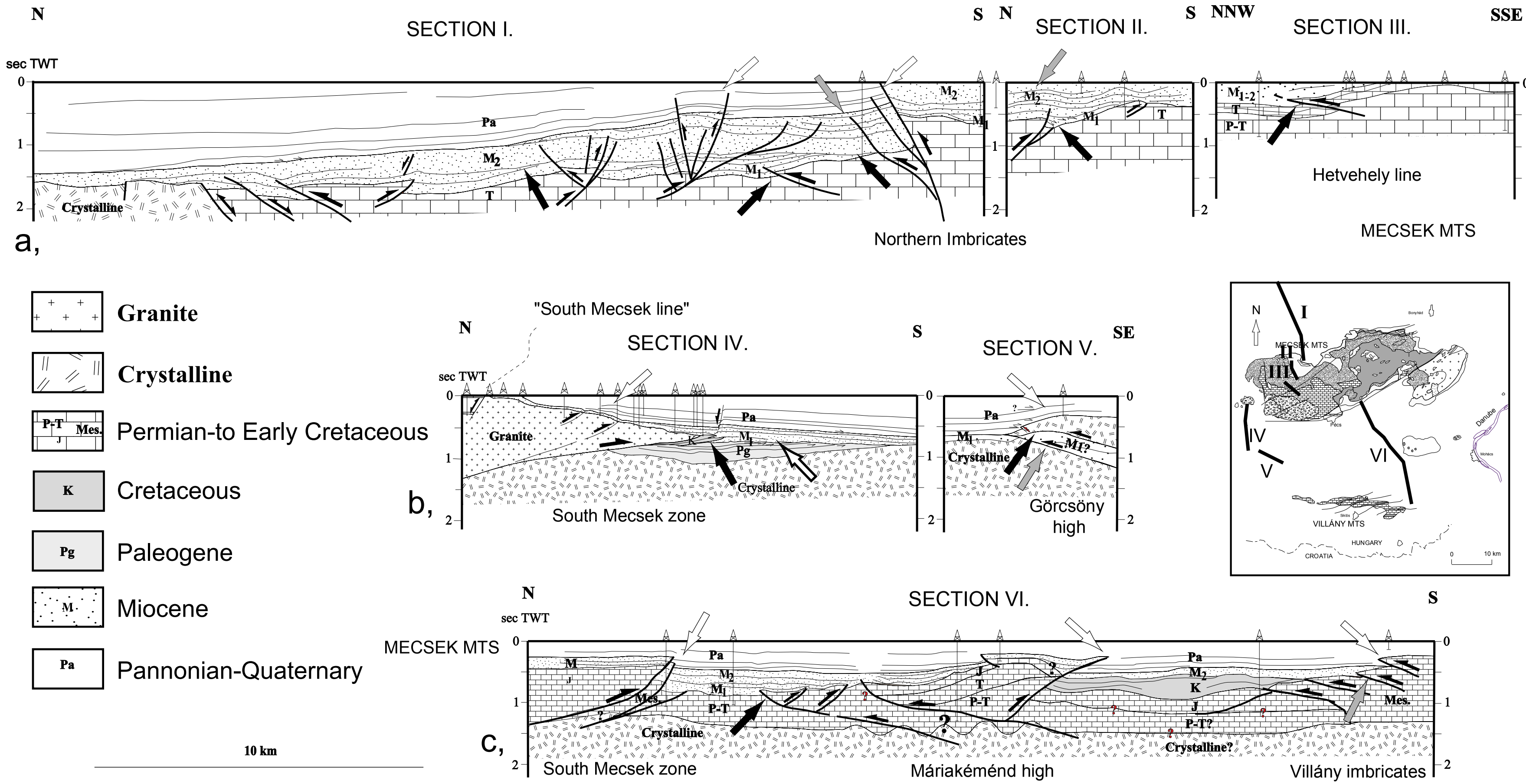

Fig. 5. Line drawing seismic section interpretations of the study area (after Wórum 1999, slightly modified). Insert shows location of sections. Vertical scale in Two Way Travel times. **(a)** Composite section from the northern part of Mecsek Mts. The main body of Mecsek Mts is towards the south (right) of the sections. M_{1-2}: Early and Middle Miocene; Boreholes marked as small derricks. **(b)** Composite section from the southwestern foreland of the Mecsek Mts. The main body of Mecsek Mts is to the north (left) of the sections. **(c)** Section between the Mecsek and Villány Mts. White arrow: structure related to Pannonian shortening. Grey arrow: structure related to Sarmatian shortening. Black arrow: structure related to Late Ottnangian shortening. Bold white arrow: structure related to Late Paleogene (-Early Miocene) shortening.

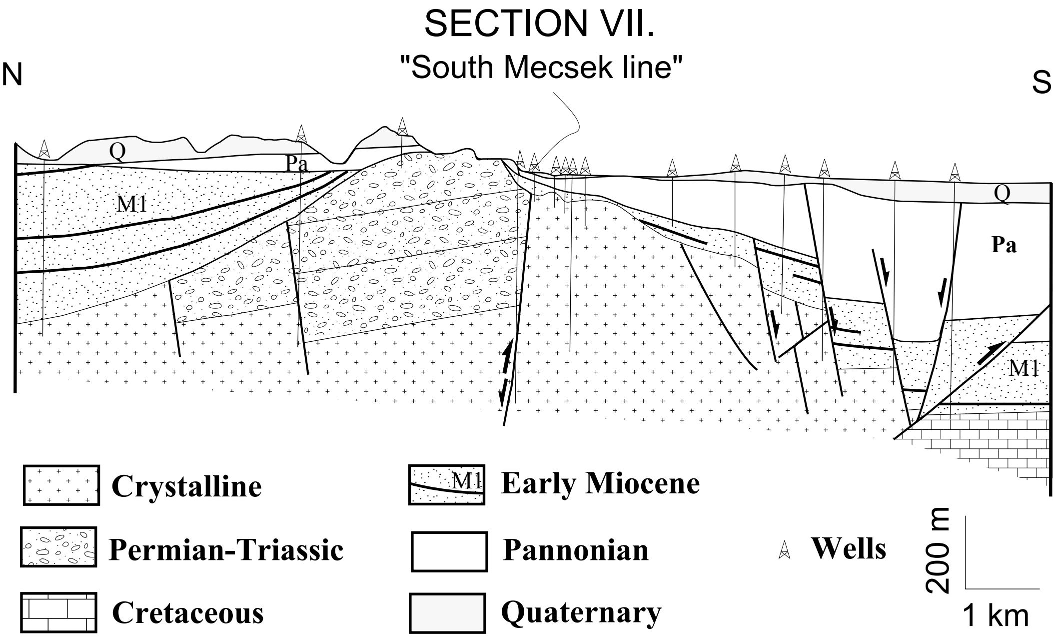

Fig. 6. Geological cross section after Barabás and Csicsák, in Barabás (1995). Section vertically exaggerated 5 times. Location in Fig. 4. Boreholes marked as small derricks. Note the thickness changes of Quaternary strata.

feature of this section is the very thick preserved Quaternary north of this structure, in the now elevated, hilly area, and the very thin deposits of the same age in the southern lowlands. The erosion surface of the pre-Quaternary, and that of basal Pannonian strata are also tilted, in a way that they form a crest near the South Mecsek line. The elevated Quaternary in the north is in an inverted structure. The uplift of the northern part should be younger than the deposition of the Quaternary in the originally deeper northern pool. In other words: one of the inversions is caused by subrecent northerly compression.

The Görcsöny-Máriakéménd ridge (Fig. 4) was crossed by several seismic sections. The Görcsöny ridge (line V on Fig. 5b) is an elevated antiform above a flat surface. In the section a layered package of possibly Miocene sediments is seen beneath the crystalline material (black arrow). Onlapping Pannonian sediments are slightly folded above the crystalline high (white arrow). These suggest a post-Early Miocene (possibly Ottnangian, then Late Miocene or Pliocene?) thrust or transpressional activity.

In the east, on section VI (Fig. 5c) some north- and south-vergent thrust faults limit the Máriakéménd ridge, giving it an aspect of positive flower structure. The southern fault brings Triassic-Jurassic strata above Miocene and even Pannonian sediments (white arrow). This may explain the result of a nearby borehole (Peterd-1), where Nagy and Nagy (1976) described repetition of Triassic, with tectonically intercalated Pannonian (Late Miocene) sediments.

The Villány Mts is an elongated mass of Mesozoic imbricates (Fig. 4). Southwards dipping thrust planes conformable to surface geology are visible at its northern foothills on section VI (Fig. 5c). These thrusts are partly pre-Late Cretaceous, as this latter, identified by an adjacent well seals the northernmost thrust. A more southerly imbricate (grey arrow), however, affects Sarmatian strata as well. Finally, the southernmost imbricate (white arrow) shows thrusting on top of Pannonian (Late Miocene).

Transversal faults (Fig. 4) cut up the whole area. These NNW-SSE striking faults disrupt the general structures described above. Such faults are not always evident in the outcrop pattern of the Mecsek Mts, but these are strongly suggested by gravity anomaly maps (Szabó and Sárhidai, 1989). Apparent offset of some prominent structures (e.g. the Northern Imbricates) may be explained by relay or en echelon structures, but the disappearance of the ridge between Görcsöny and Máriakéménd, the western limits of the exposed Morágy granitic mass, or the difference in composition of the cover and foreland of the granite in the west all indicate transfer faults. These faults seem to accommodate differential movements on thrusts, or eventually reactivate as normal faults.

5.2 Timing of main Tertiary deformations based on seismic sections

Detailed seismic section analysis (Wórum, 1999; Csontos et al., 2002) delineates a complicated tectonic history dominated by thrusting or transpression (Fig. 2). Intra- or post-Pannonian activity is present throughout the whole study area, as indicated by many thrusts, bent bedding planes (white arrows on Fig. 5). Occasionally Pannonian normal or transtensional faulting is also seen (section IV, above black arrow). A possibly Sarmatian, or Early Pannonian thrusting episode is shown by truncation patterns north of the Mecsek Mts (grey arrows on Fig. 5a) and north of the Villány Mts

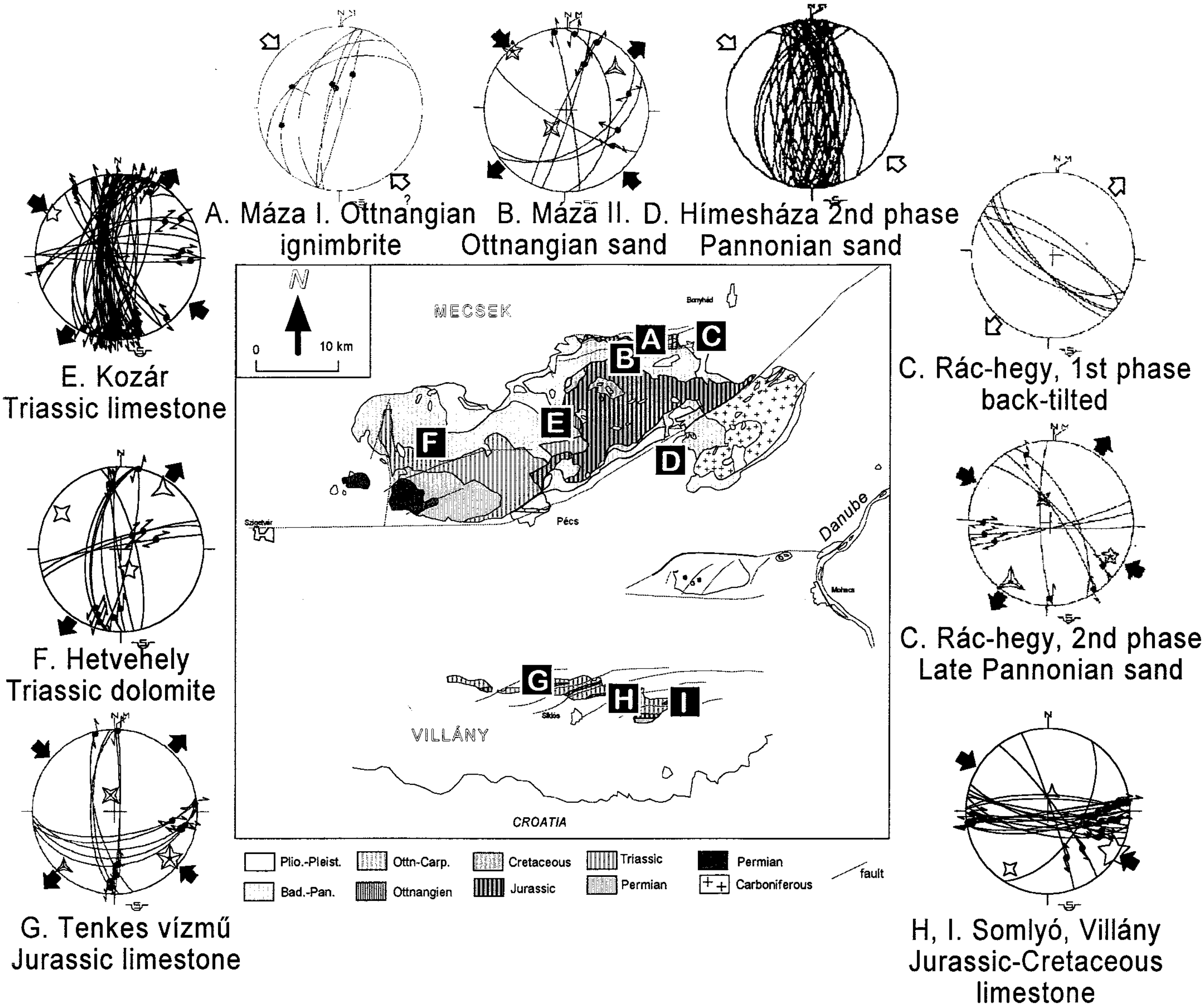

Fig. 7. Structural data from SW Hungary, indicating NW-SE shortening, NE-SW elongation. Data taken from Bergerat and Csontos (1984), Csontos and Bergerat (1993), Benkovics (1997). Measured outcrops indicated by dot and Capital. All stereo-plots in lower hemisphere Schmidt projection. Fault is indicated by trace, striae by dot; small arrows indicate observed offset. Outer large arrows indicate compression and extension directions. Empty arrows indicate stress directions inferred from observed structures. Star, Triangle and Diamonds stand for computed $\sigma 1$, $\sigma 3$, $\sigma 2$ directions, respectively. Extension directions in outcrop C, first phase, are inferred after back-tilting by measured bedding dip value.

(grey arrow on Fig. 5c).

An Ottnangian, possibly pre-Karpatian thrusting activity is also seen at, and in the foreland of the Northern Imbricates (black arrows on Fig. 5a), in some portions of the main South Mecsek sole thrust and at the Görcsöny-Máriakéménd ridge (black arrows on Fig. 5b, c). It is interesting to note that sedimentological arguments (Barabás, 1995) speak in favour of the sudden uplift and deep erosion of the Görcsöny high at the same period.

Finally, there is a Late Oligocene–Early Miocene major thrusting episode along the South Mecsek basal thrust (bold white arrow on Fig. 5b). Since Late Paleogene deposits are generally lacking, the areal extent of this tectonic phase remains obscure.

It has to be emphasised, that no major detachment surface was found on seismic sections between the main body of the Mecsek Mts and the Northern Imbricates. Instead, a complex strike-slip zone can be followed at, and in the surroundings of the Northern Imbricates. The Hetvehely line accounts for a very limited slip and offset of Mesozoic and Tertiary formations. The South Mecsek zone and the Görcsöny-Máriakéménd ridge are also long-lived transpressive zones with very complicated internal deformation (Fig. 4). All the observed features give some kind of shortening in the generally N-S striking seismic sections, therefore the shortening directions of individual tectonic phases may swing within the NW-SE to NE-SW quadrant.

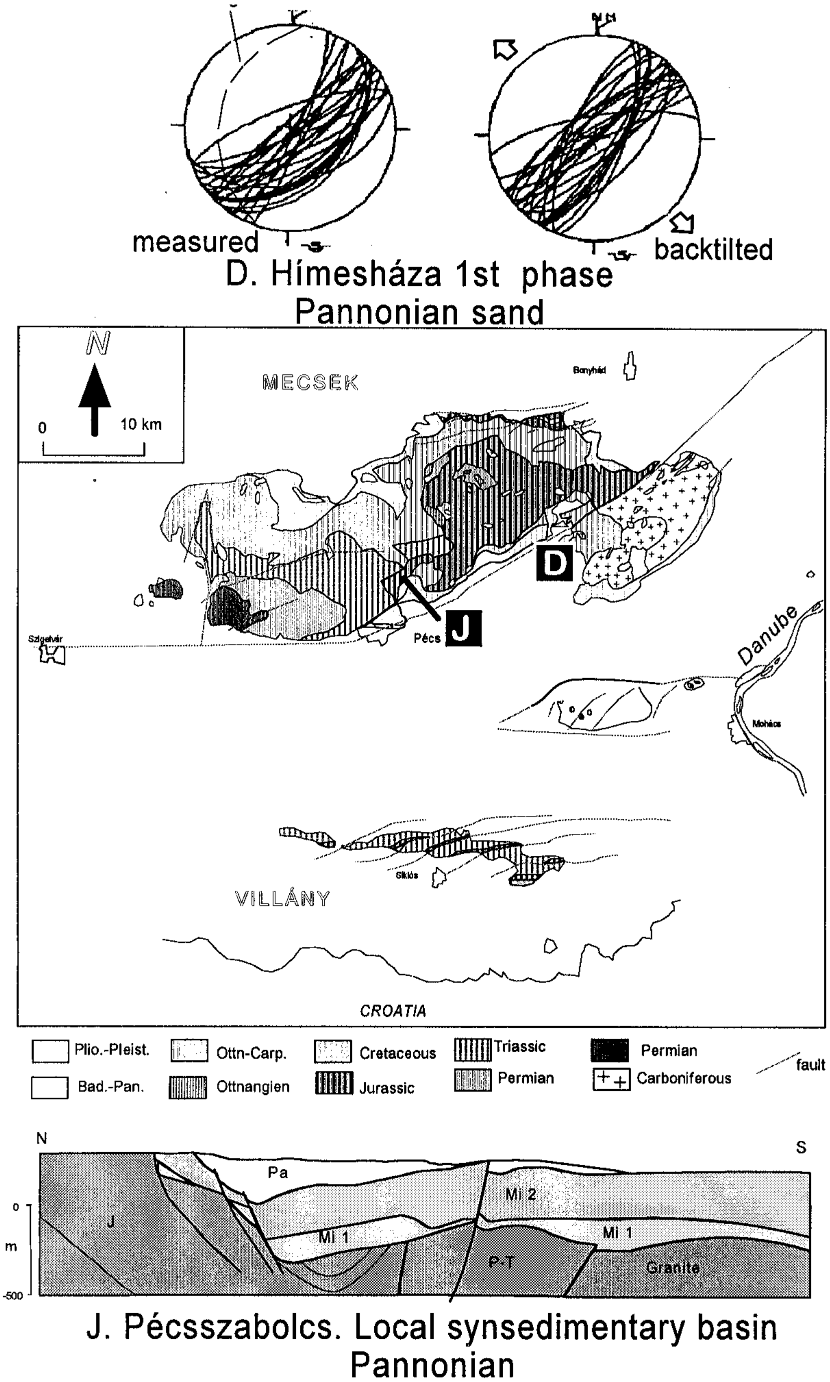

Fig. 8. Structural data from SW Hungary, indicating NW-SE elongation. Data taken from Benkovics (1997). Same legend as for Fig. 7. Extension directions in outcrop D, first phase, are inferred after back-tilting by measured bedding dip value. Section of locality J (Pécsszabolcs) taken from Hámor (1966), modified.

6 Structural analysis

Field structural observations were concentrated on description of outcrops, where folded or faulted structures were found. Faults, slickenside lineations and superposition patterns were measured and observed in order to reconstruct the stress tensors creating the observed motions. Calculations were made after the method of Angelier (1979). Grouping of fault families was made both by the software and "by hand". In some cases later tilt altered the original fault pattern and stress-tensor directions, therefore we also calculated "untilted" directions, removing the effects of later tilt. Dating of successive structural events was based on observation of synsedimentary structures in Tertiary outcrops, but data from nearby Mesozoic localities were also used to corroborate these observations. Only a summary of outcrop data

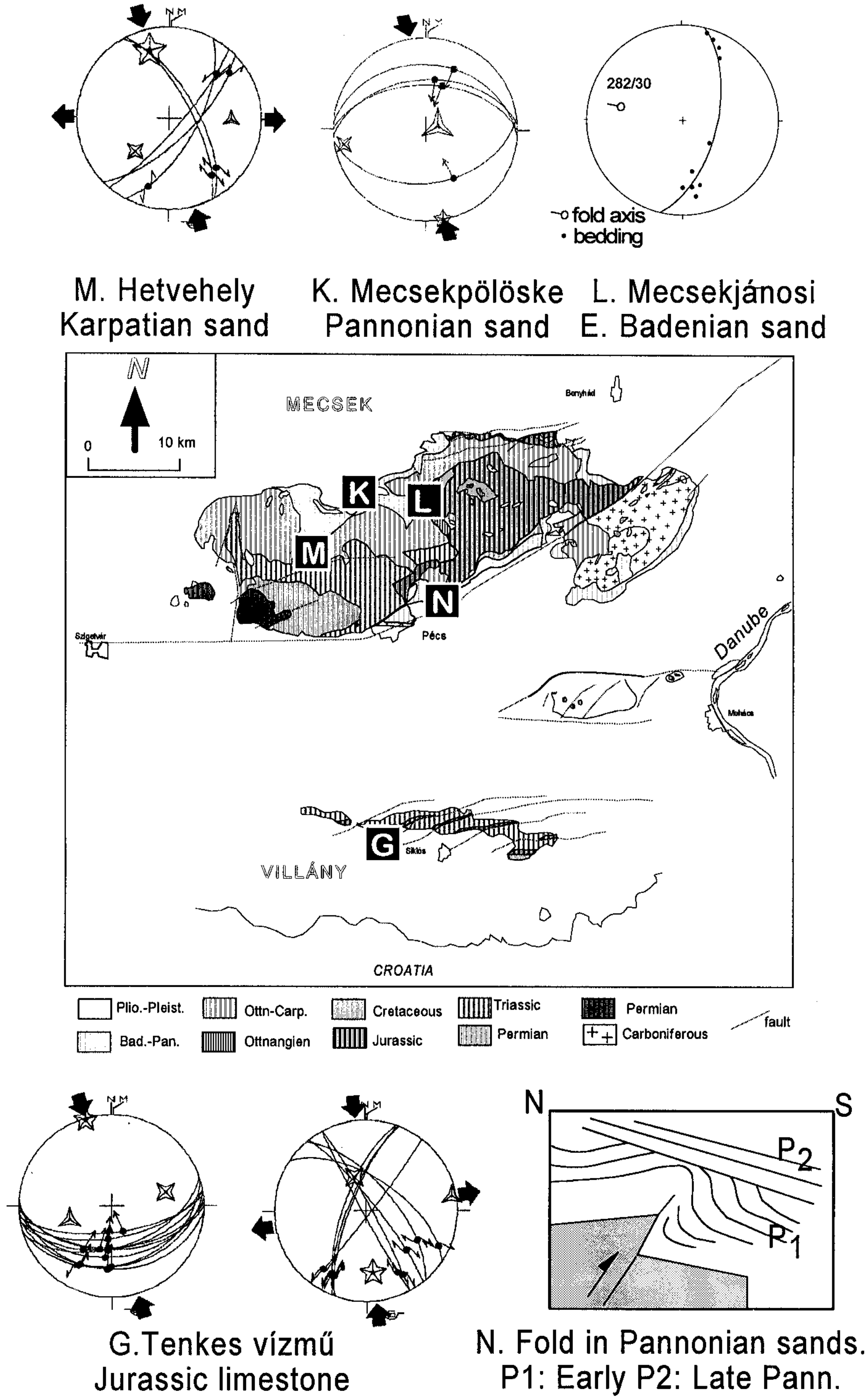

Fig. 9. Structural data from SW Hungary, indicating N-S shortening. Data taken from Bergerat and Csontos (1984), Csontos and Bergerat (1993), Benkovics (1997). Same legend as for Fig. 7. Stereo-plot of outcrop L indicates bedding planes as poles. Axis of fold is drawn as barbed point. Girdle indicates zone circle for bedding poles. Thrust fault and strike slip fault data from outcrop G are shown separately for better visibility. Sketch of outcrop N is an interpretation of Benkovics (1997).

is presented here, since the details of the analysis are described in Bergerat and Csontos (1988), Csontos and Bergerat (1992), Benkovics (1997) and Csontos et al. (2002).

The observed structures can be assigned into four major strain patterns: NW-SE shortening and transpression (Fig. 7), WNW-ESE elongation (Fig. 8), N-S shortening (Fig. 9), and NE-SW shortening and transpression (Fig. 10). These patterns seem to alternate in time in the study area.

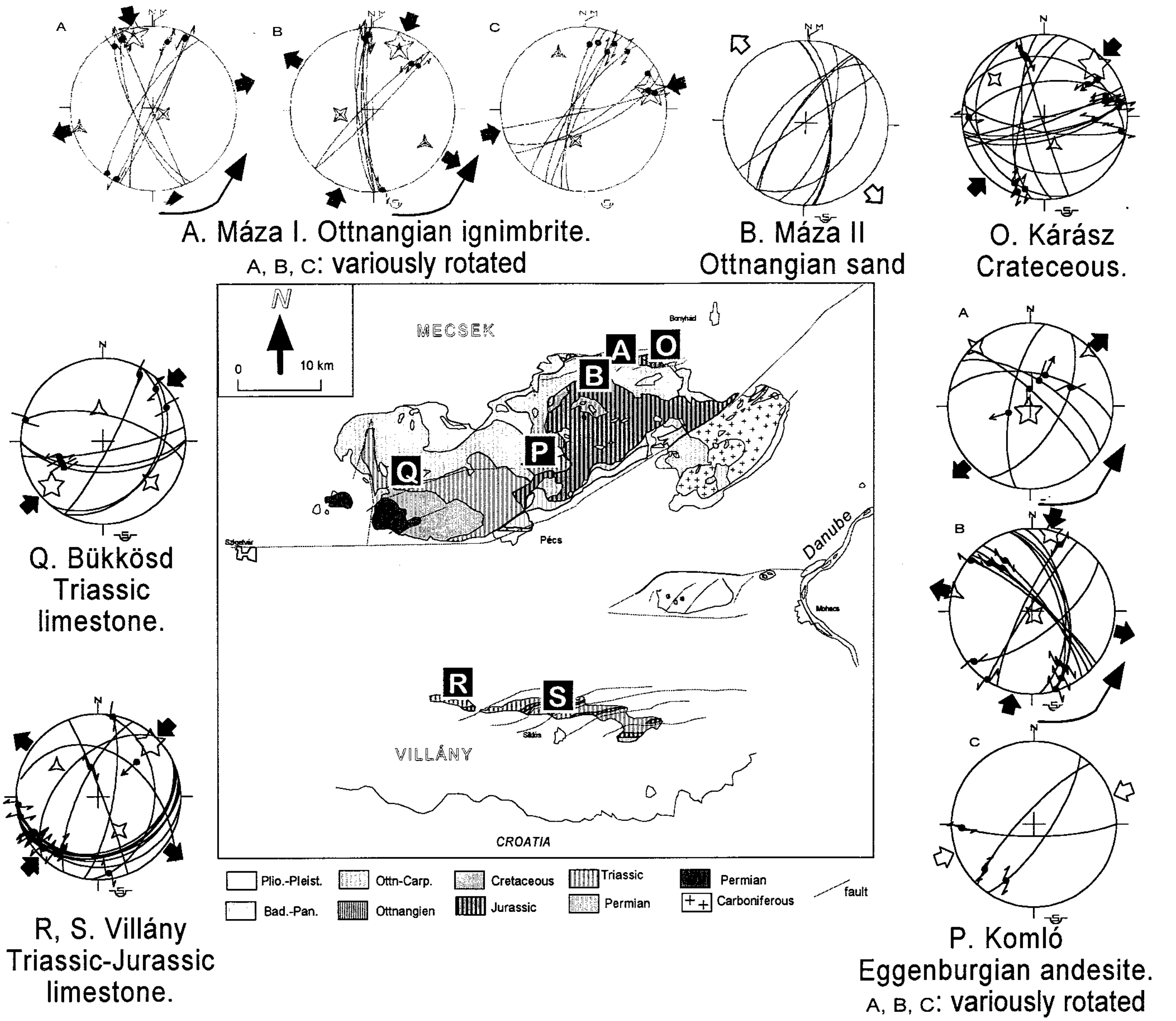

Fig. 10. Structural data from SW Hungary, indicating NE-SW shortening, NW-SE elongation. Data taken from Bergerat and Csontos (1984), Csontos and Bergerat (1993), Benkovics (1997). Same legend as for Fig. 7. In case of outcrops A and P the observed fault set is divided into several conjugate sets (A, B, C). These define apparently rotated stress-fields. Extension directions in outcrop B are inferred after back-tilting by measured bedding dip value.

NW-SE shortening – NE-SW elongation (Fig. 7) is probably the last of the recorded structural patterns, creating right lateral transpression along E-W structural zones. This pattern is dated in Late Pannonian (ca. 7 Ma) exposures as the unique, or second phase (localities C, and D, Fig. 7). This event probably generates late uplift of the Mecsek, Görcsöny-Máriakéménd and Villány areas, where all Pannonian synsedimentary structures are tilted away from the present hilly areas (Fig. 5).

Syn-sedimentary events in local Pannonian basins speak for a reorientation of the elongation directions: WNW-ESE elongation seems to precede the NE-SW one (Fig. 8). This structural pattern has a syn-sedimentary Late Miocene (Pannonian) age (ca. 8 Ma; see also Csontos et al., 2002; their figure 14).

The E-W folds observed in Pannonian (site N, Fig. 9) and Early Badenian (site L, Fig. 9) indicate a syn-post Pannonian stronger N-S shortening phase. Syn-sedimentary N-S shortening and perpendicular elongation is observed also in Karpatian rocks (Site M, Fig. 9). This pattern may have been in vigour throughout a greater time span, from the start and until the end of Middle Miocene and possibly some time in the Late Miocene. Alternatively, the area may have suffered more intensive N-S shortening periods between relatively quiet periods. In this structural pattern ENE-WSW fault zones could play in left lateral transpression and NE-SW oriented faults like the Hetvehely or part of the South Mecsek lines as left lateral faults.

The deformation calculated from measurements in Early Miocene rocks is NE-SW shortening and perpendicular elon-

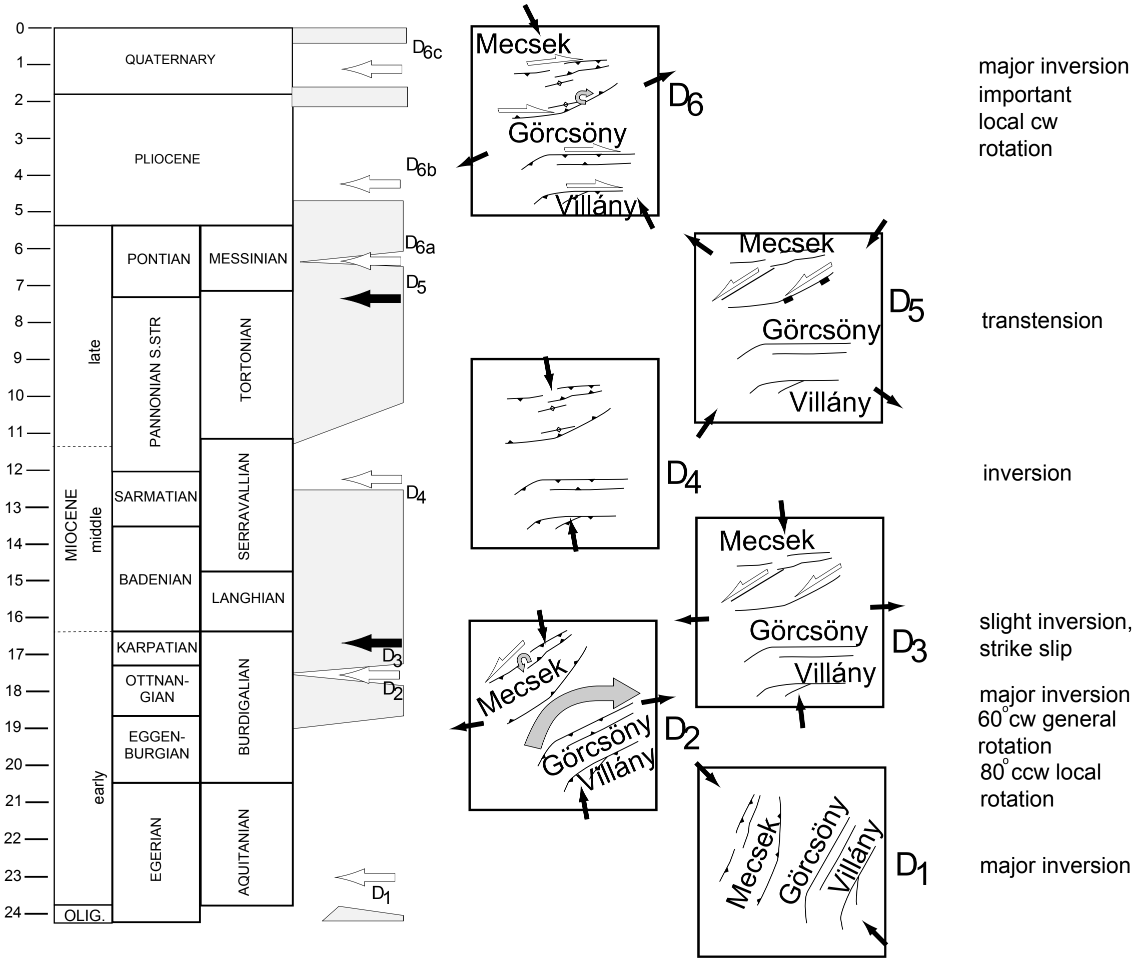

Fig. 11. Synthetic table of structural events. White arrows indicate onset of major structural events. Boxes show structures active during the different deformation phases in original coordinates. Black arrows indicate inferred shortening and elongation directions. Grey arrows indicate rotations. D_1–D_6 refer to tectonic events described in the text.

gation (Fig. 10). Syn-sedimentary NW-SE extension indicates that this structural pattern was in vigour in Early Miocene (site B, Fig. 10). The complex strike-slip fault patterns measured in the Early Miocene magmatic rocks (sites A, P, Fig. 10) seem to reflect virtual rotations of the stress-field. Since major counter-clockwise and clockwise rotations certainly affected these outcrops in the Late Ottnangian-Early Karpatian, it seems logical to postulate a fixed, external, NE-SW compressional stress-field (present orientation), and to rotate the respective outcrops to produce the observed fault pattern (see a similar exercise in Csontos et al., 1991; Márton and Fodor, 1995).

7 Discussion on geodynamics

In the following we summarise the information coming from the above methods in order to give a model for the structural evolution of the study area. The confrontation of this model to other observations also leads to a model for the Tertiary development of the Tisza unit.

7.1 Structural evolution of the Mecsek-Villány area

D_6, The last, possibly still active structural event is an E-W right-lateral wrenching and N-S to NW-SE shortening (Fig. 11). This event created imbrication at the Northern Thrusts, at the South Mecsek line, at the wings of the Görcsöny-Máriakéménd ridge and at the northern foothills of the Villány Mts. This event is also responsible for the tilt, eventually folding of layers above the granitic wedge in the South Mecsek zone and above the Görcsöny high (because of reactivation of the blind sole thrusts of the granite and metamorphics). It may be synchronous to a negligible clockwise rotation of the area (with respect to the Miocene North) and major local clockwise rotation along the transpressive right lateral South Mecsek line. It possibly started in Late Pannonian (D_{6a}, ca. 7 Ma) as suggested by outcrops near the Northern Imbricates, and seismic sections to the NW of the Mecsek Mts (Vakarcs, 1997; Sacchi et al., 1999).

D_5, A possibly older, Pannonian (10–7 Ma) event is an ENE-WSW extension, which could be a manifestation of large scale left-lateral transtensional wrenching frequently observed in the Intra-Carpathian basin (Horváth and Royden, 1981; Csontos, 1995; Csontos and Nagymarosy, 1998; Fodor et al., 1999).

D_4, An even earlier, Early Pannonian or Late Sarmatian (12–11 Ma) shortening is recorded in seismic sections north of the Northern Thrusts. Either this, or the intra-Pannonian (D_{6a}) event created major folds within the Mecsek Mts, as seen in outcrop, or in seismic lines. Folding also affected pre-Miocene strata (Benkovics, 1997). Direction of shortening was probably close to N-S. Late Sarmatian – Early Pannonian positive inversions are widespread in SW Hungary and elsewhere in the Intra-Carpathian basin (Balla et al., 1987; Horváth, 1995; Csontos, 1995; Csontos and Nagymarosy, 1998; Fodor et al., 1999).

There is no structural event recorded during the Badenian. This situation is possibly due to lack of data, since facies-and subsidence analyses (Báldi K. et al., 2002) in Badenian sediments north of the Mecsek Mts. indicate an intra-Badenian shallowing possibly due to tectonic causes, i.e. shortening.

D_3, In the Karpatian strike-slip type deformation prevailed. N-S shortening may have some minor indication on seismic sections in the northern part of the Mecsek Mts, but did not create regional structures or unconformities. Limited left-lateral slip might have occurred along the Hetvehely line and South Mecsek line at this time (Fig. 5).

D_2, Late Ottnangian-Early Karpatian fault patterns indicate left-lateral wrenching along the ENE-WSW oriented Northern Imbricates (Fig. 4). Because of very important movements, blocks within, or adjacent to the Northern Imbricates rotated counterclockwise during faulting. This internal and localised rotation may be corroborated by apparently rotating conjugate fault sets as well (Fig. 10). A thrusting or transpressive episode along the sole thrust of the granite happened at that time in the South Mecsek zone and possibly at the Görcsöny high. Clockwise paleomagnetic declinations in the SE Mecsek area could be explained by bulk clockwise rotation of almost the whole area. The very important rotations combined with important strike slip- and thrust faulting (followed by a longer quiescent period) suggest that this was a quick and very important structural phase affecting the whole Tisza unit.

D_1, The earliest recorded Tertiary structural event is a major thrusting along the southern sole thrust of the Mecsek Mts (Fig. 5). This was the first major positive inversion of a former Late Palaeozoic-Mesozoic half-graben. The age of the event, as shown by seismic sections, is Late Oligocene-Early Miocene. This timing corresponds well to basin inversion and folding in the structural belt now north of the Mecsek zone (Csontos and Nagymarosy, 1998).

7.2 Tertiary evolution of the Tisza terrane

Large Tertiary clockwise rotation of eastern outcrops of the Tisza-Dacia terrane (Fig. 1) are evidenced by Surmont et al. (1990), Patrascu et al. (1990, 1992, 1994), Bazhenov et al. (1993), Panaiotou (1998), and Haartman et al. (1998). At a first glance this rotation corresponds perfectly to those measured in the Mecsek Mts (Márton and Márton, 1999). Newer, more accurate dating (Panaiotou, 1998) gave a narrower rotational time frame, which differs from that in the Mecsek Mts. In Transylvania a 20° clockwise rotation is interpreted during Early Miocene, while a ca. 60° clockwise rotation is measured in the bulk of Mecsek Mts during the same period. The Early Badenian to Early Pannonian was a time of major, 50° clockwise rotation in the Transylvanian Basin, while there was practically no rotation in the Mecsek area. Finally, there was no general rotation after Pannonian either in the Transylvanian basin or in the Mecsek-Villány area, but Márton et al. (1999) measured ca. 30° counter-clockwise rotations even in Pontian sediments of the Slavonian Inselbergs of Northeast Croatia (Fig. 1). These outcrops are also held members of the Tisza terrane.

The Tisza and other (Alcapa, Dacia) Intra-Carpathian terranes were defined (e.g. Balla, 1984; Brezsnyánszky and Haas, 1990; Bleahu et al., 1996) by the tectono-stratigraphic concept, i.e. similarities in stratigraphic, facies, paleobiogeographic and tectonic evolution of different outcrop and subcrop areas. In the case of Tisza, distant outcropping sequences can be very well correlated, even down to minute details (e.g. Szepesházy, 1973; Bleahu et al., 1996). That was the reason, why the Tisza terrane was considered as a uniform, more or less rigid body by previous geodynamic reconstructions (e.g. Balla, 1984; Kovác et al., 1994; Csontos, 1995). First apparently supporting, paleomagnetic results now seem to contradict this rigid concept. Instead, they suggest, that this tectono-stratigraphic unit has a complex rotation history, differing in its southwestern, central, and eastern parts (Fig. 12). The only way to preserve both strong arguments is to divide the Tisza terrane in smaller, differently deforming blocks, with the help of major, within-terrane detachments. In other words, the rigid block concept of Tisza has to be abandoned, to be replaced by a once uniform block torn apart by Tertiary deformations (Fig. 12).

The Slavonian Inselbergs have to be decoupled from the Mecsek-Villány area, because they suffered no rotation while the latter was clockwise rotated (Figs. 1, 12). Then they were counterclockwise rotated, while the Mecsek-Villány was not rotated. A probable site for detachment between these blocks is the Drava fault (Fig. 13a), which is supposed to be a major strike slip-normal fault operating from Late Oligocene times. Early Miocene sediments are described from the deepest, Croatian part of the trough (Prelogovic et al., 1998; Tari and Pamic, 1998). Because of different rotations, the Drava fault should have decoupled Mecsek-Villány from the Slavonian Inselbergs twice: first in the Late Ottnangian-Early Karpatian, then in or after the Pontian. The first decoupling is seen as a major oblique normal faulting, the second as a main thrust faulting episode on the schematic section across the fault area (Fig. 13a).

Comparison of the rotations between the Apuseni Mts.-Transylvanian Basin and the Mecsek-Villány areas (Fig. 12) suggests a relative convergence in Early Miocene, since the eastern parts (Apuseni) are less rotated, than the central parts. This calls for across-strike thrust faults (Figs. 12, 13b). At

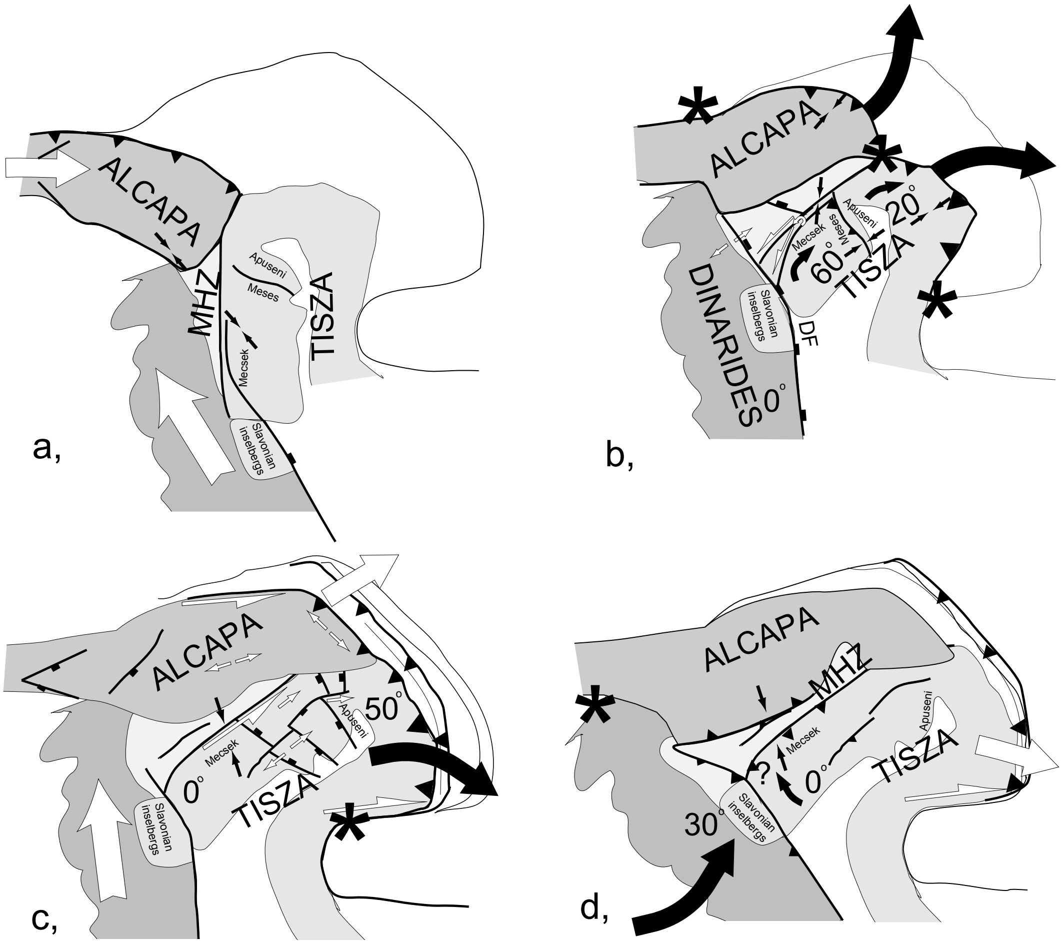

Fig. 12. Schematic Tertiary evolution and geodynamic sketch of the Tisza terrane. Thin lines indicate contours of the Moesian promontory and future Carpathians. Big asterisks indicate rotation poles. White shear arrows indicate local shear, small white arrows indicate elongation, small black arrows indicate shortening. Curved black arrows stand for rotations. Large white arrow indicates block translation. Major normal faults are indicated by brick (on hangingwall), major thrusts by triangles (on hangingwall). **(a)** Pre-Ottnangian. Note thrusting in Mecsek area, due to the push of Alcapa. **(b)** After major rotations, Karpatian. Note the differential rotation of western, central and eastern part of Tisza and the consequent deformations. Mecsek area is characterised by bulk clockwise rotation, local left lateral shear and counter-clockwise rotation. **(c)** After major rotations in the east, Pannonian. Note the differential rotation of the central and eastern part of Tisza and consequent graben opening. **(d)** After rotation of the Dinaridic block, Pliocene-Quaternary (?). All rotation and northwards push causes multi-directional thrusting and positive inversion.

least one of these can be seen at the NW margins of the Apuseni Mts. This is the Meses fault (Fig. 13b; Stefanescu, 1989; Balintoni, 1994; Huismans et al., 1997; Linzer et al., 1998; Györfi et al., 1999; their figure 4), which puts Late Cretaceous granitoids on top of Late Eocene-Oligocene sediments. Probable time of activity of this fault is Late Oligocene-Early Miocene. Naturally, it is not meant that the Meses fault alone could accommodate the required shortening; other such faults are expected.

On the other hand, the non-rotation of the Mecsek-Villány area and the large clockwise rotation of the Apuseni part calls for across-strike normal faults operating during Badenian-Early Pannonian. Sphenochasm-like NW-SE striking openings (Fig. 13c) range along the western Apuseni and adjoining areas beneath the Great Hungarian plain (e.g. Balla, 1984; his figure 10; Györfi and Csontos, 1994). Sedimentary fill of these basins suggests an Early Badenian (or Karpatian) NE-SW directed opening (Györfi and Csontos, 1994; Tari et al., 1999), synchronous to the major rotations in the Transylvanian Basin.

Stratigraphic, paleontologic, facies arguments attach the Northern Imbricates and covered basement north of it to the Tisza terrane. Still, different, major and synchronous rotations are observed in the Northern Imbricates and the main body of the Mecsek-Villány area. A possible explanation of this feature could be to attach the Northern Imbricates to an entirely different terrane, e.g. Alcapa, which rotated counter-clockwise (Márton, 1990), but the above listed arguments oppose this idea. We rather speculate, that the counter-clockwise rotations in the Northern Imbricates area are the result of local block rotation due to important left-lateral shear (see above). The major, Late Ottnangian wrenching

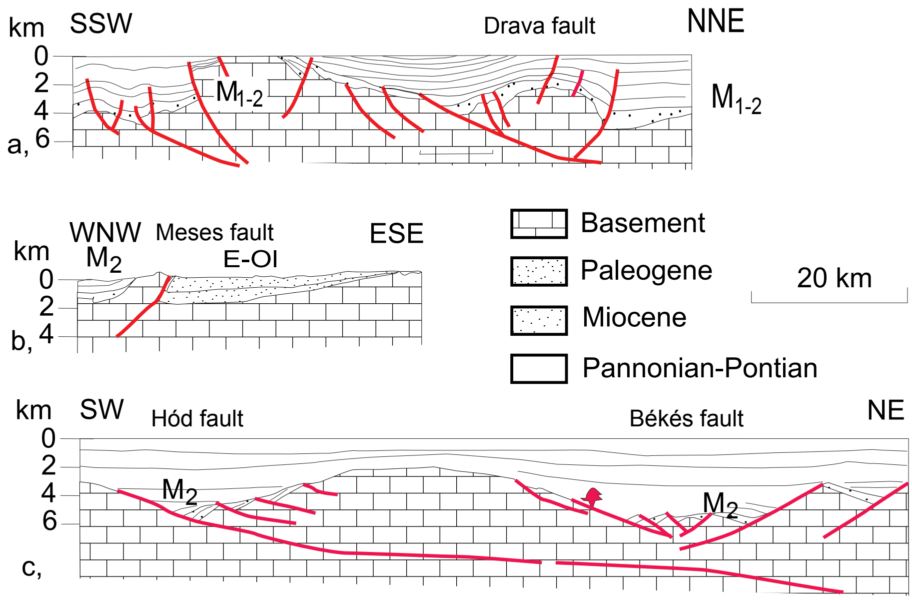

Fig. 13. Main proposed detachment surfaces across the Tisza terrane. Sketch drawings of published seismic and geologic sections. Location in Fig. 1. Vertical scale in km. **(a)** Schematic section across the Sava-Drava faults. Redrawn, simplified and re-interpreted after Tari and Pamic (1998). M_{1-2}: Early and Middle Miocene. Note early major faulting and late positive inversion. **(b)** Schematic section across the Meses fault. Redrawn, simplified and re-interpreted after Stefanescu (1989). E-Ol: Eocene and Oligocene. Note major thrusting involving Oligocene and a slight reactivation in Late Miocene. **(c)** Schematic section across the Hód-Békés-Zarand basins. Redrawn, simplified and re-interpreted after Tari et al. (1999). M_2: Middle Miocene. Dark figure indicates deep intrusion. Note major low angle normal faults and deep basins above tilted blocks.

is synchronous, so possibly genetically linked to the bulk clockwise rotation of the Mecsek-Villány main mass. In this perspective the Northern Imbricates could be a segment of a slightly arcuate transfer belt (Fig. 12a, b), accommodating relative motion between the Mecsek-Villány and Mid-Hungarian areas. Differential NE-SW stretching in the Tisza and Mid-Hungarian belts could produce a transfer zone, part of which could be the left-lateral Northern Imbricates zone.

7.3 Possible dynamic causes of observed structures

Reconstructed (i.e. back-rotated, though in part hypothetical) Late Paleogene shortening directions of the Mecsek are ca. NW-SE (Fig. 12a). This convergence may be due to the eastward push exerted by the Alcapa terrane escaping from the Alpine sector (e.g. Balla, 1984; Fodor et al., 1999). At this time Tisza seems to be fixed at the Moesian buttress.

Late Early Miocene (ca. 18 Ma) was a period of quick rotations and major displacements of Intra-Carpathian terranes. Alcapa rotated counter-clockwise around a pole at the southern tip of the Bohemian Massif, while Tisza rotated clockwise around a pole at the NW tip of the Moesian Platform (Fig. 12b). The two terranes were fixed at a common NE pole, near Poiana Botizii, N Transylvania, Romania. The Mid-Hungarian belt was attached to both terranes and was the site of major across-strike shortening and along-strike elongation. Rotation could not be directly driven by a Dinaridic source, because large oblique normal fault detachment is required between the bulk of Tisza and the Dinarides. On the other hand the north-westward movement of the Dinaridic body and its drag on Tisza versus the eastward extruding Alcapa could produce buckling.

Propagation into the Carpathian embayment could not be possible without synchronous subduction of the European lithosphere (Balla, 1984; Csontos et al., 1992; Kovác et al., 1994). It seems that the eastern parts of Tisza and perhaps Alcapa could not entirely follow the rotations of the main body(ies). The lagging frontal part(s) with respect to the quickly eastward propagating central part(s) indicate, that subduction roll-back was not fast enough to open all the required space by the quick opposite rotations.

One of the consequences of opposite rotations was a NW-SE convergence and NE-SW elongation (actual directions) in the space between the two Intra-Carpathian terranes. The differential movements between this deformation belt and the rotated parts were accommodated by local transfer fault zones, e.g. the Northern Thrust of the Mecsek Mts.

Once the two terranes amalgamated at the end of the Ottnangian, they filled the space available in the Carpathian embayment. In the Mecsek N-S compression and E-W extension prevailed from the Karpatian on. This compression could produce local shortening, or alternatively NE-SW left lateral regional shear, as indicated by seismic sections (Csontos, 1995). When there was available space in the east, parts of the Tisza-Dacia terrane escaped towards the east as well (Csontos et al., 1992; Linzer, 1996). This escape was performed along ENE-WSW oriented left lateral and complementary right lateral transtensional belts. Such wrench-related basins are present throughout Hungary in the Badenian and in the Early Pannonian (Horváth and Royden, 1981; Fodor et al., 1999).

In the eastern parts of the Tisza-Dacia and Alcapa terranes the structural evolution was more intensive during Middle Miocene. Paleomagnetic rotations suggest that these portions rotated further towards the east. This rotation pattern produced a complicated network of sphenochasms in the contacting part of Alcapa and Tisza (e.g. Balla, 1984; Csontos and Nagymarosy, 1998; Fig. 12c). Activity of this eastern portions suggests a driving force in the east, the most plausible being subduction rollback of the remaining European oceanic lithosphere. A consequence of this rotation was the synchronous extensional (Györfi and Csontos, 1994; Tari et al., 1999) and compressional (Huismans et al., 1997; Linzer et al., 1998; Ciulavu et al., 2000) deformation respectively west and east of the Apuseni Mts.

Because of limited space within the SW part of the Intra-Carpathian basin, even a small rotation of the Dinaridic block and eventually clockwise Tisza around its pole or an opposite rotation of Alcapa would inevitably cause roughly N-S shortening. The numerous shortening episodes from Sarmatian until Recent could in fact be explained by smaller or bigger increments of rotation (Fig. 12d). In the study area minor clockwise rotation was measured on Late Pannonian sediments. Future investigations are needed to fully evaluate it. Perhaps the positive inversion events registered in the study area are induced by small rotations of Alcapa, or more possibly, of the Dinarides (Márton et al., 1999). An alternative model to induce the observed Late Tertiary shortening episodes is a slight change in the direction of convergence of the Dinarides (Tomljenovic and Csontos, 2001).

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