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# Tertiary deformation history from seismic section study and fault analysis in a former European Tethyan margin (the Mecsek–Villány area, SW Hungary)

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**Abstract**

Outcrop-scale structural data and seismic section interpretation are combined to unveil a very complicated Tertiary deformation history of a once Tethyan margin: the Mecsek–Villány area of Hungary. This combination of data helped to reconstruct the possible activity of individual fault zones. At least four ENE–WSW striking zones—the Northern Imbricates, the South Mecsek zone, the Görcsöny–Máriakéménd ridge and the Villány Mountains—were confirmed as regional long-lived transpressive zones with very complicated internal deformation, frequently with oppositely dipping thrust faults. Tertiary structural history began with a roughly N–S-directed shortening in the South Mecsek zone. It was followed by a NE–SW-directed transpression activating practically all important wrench zones together with perpendicular transfer faults. Basins were created along some of these deformation zones, but were also affected by major tilts due to inversion. After a relatively quiescent period in the Middle Miocene, the Late Sarmatian inversion followed. Shortly after, this event was relayed by a NE–SW-directed extension–transtension. An important inversion period characterised by NW–SE compression occurred in Late Pannonian (Messinian), when all the former wrench zones were reactivated as right-lateral shear. This event is responsible for the present topography of the region.


*Keywords:* Mecsek–Villány area; Tertiary deformation history; Extension–transtension

## 1. Introduction

A joint effort of Hungarian and French geo-cooperation has led to a new structural model of SW Hungary, which was once part of the European

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Tethyan passive margin. This part of the margin, which is called the Tisza (or South Pannonian) Unit (Vörös, 1977; Balla, 1984; Brezsnyánszky and Haas, 1990; Csontos, 1995), was rifted off the European shelf at the end of Jurassic and integrated into the Alpine–Carpathian–Pannonian structure in the Cretaceous–Early Tertiary (Fig. 1). The Pannonian basin exists from the Middle Miocene (e.g. Horváth, 1993). This extensional back-arc basin has several differently oriented syn-rift periods at the advent of Middle Miocene (e.g. Csontos, 1995; Fodor et al., 1999). As a general rule, the Late Miocene is considered as a post-rift sag phase (Horváth and Royden, 1981), though interrupted by a number of inversion events (Horváth, 1993; Csontos, 1995). Most of the structural data were coming from deeper parts of the Pannonian basin or from northern inselbergs. The Mecsek–Villány Mountains are evidently involved into a very complex Tertiary polyphase tectonics, somewhat different from the general evolution of the Pannonian basin. Therefore, we were mainly interested in the last phases of structural evolution. The aim of this paper is to present seismic and microstructural data in order to constrain the complex Tertiary structural history.

The Tisza Unit (Fig. 1) is an Intra-Carpathian terrane composed of Late Cretaceous north-vergent nappes. The Mecsek Mountains make part of the lowermost known nappe of the Tisza Unit, while the Villány Mountains together with the Bihor nappe of the Apuseni Mountains (Romania) are the immediately overlying thrust sheet (Pap, 1990; Györfi and Csontos, 1994; Bleahu et al., 1996). These nappes are composed of crystalline basement and/or granite, Late Paleozoic, post-Hercynian cover and a Mesozoic sequence. While the Mecsek nappe apparently ends in Hungarian territory, the Villány and Bihor Meso-

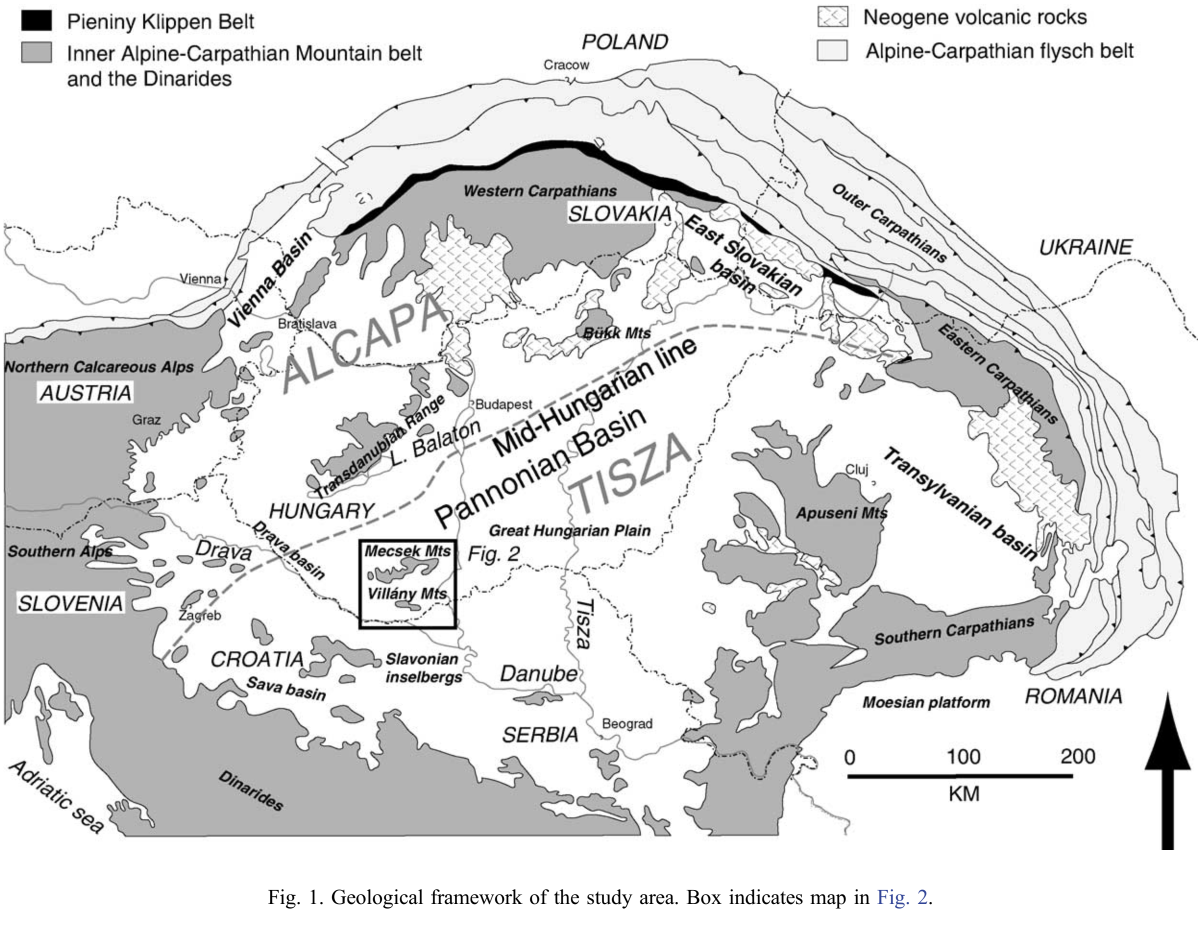


Fig. 1. Geological framework of the study area. Box indicates map in Fig. 2.

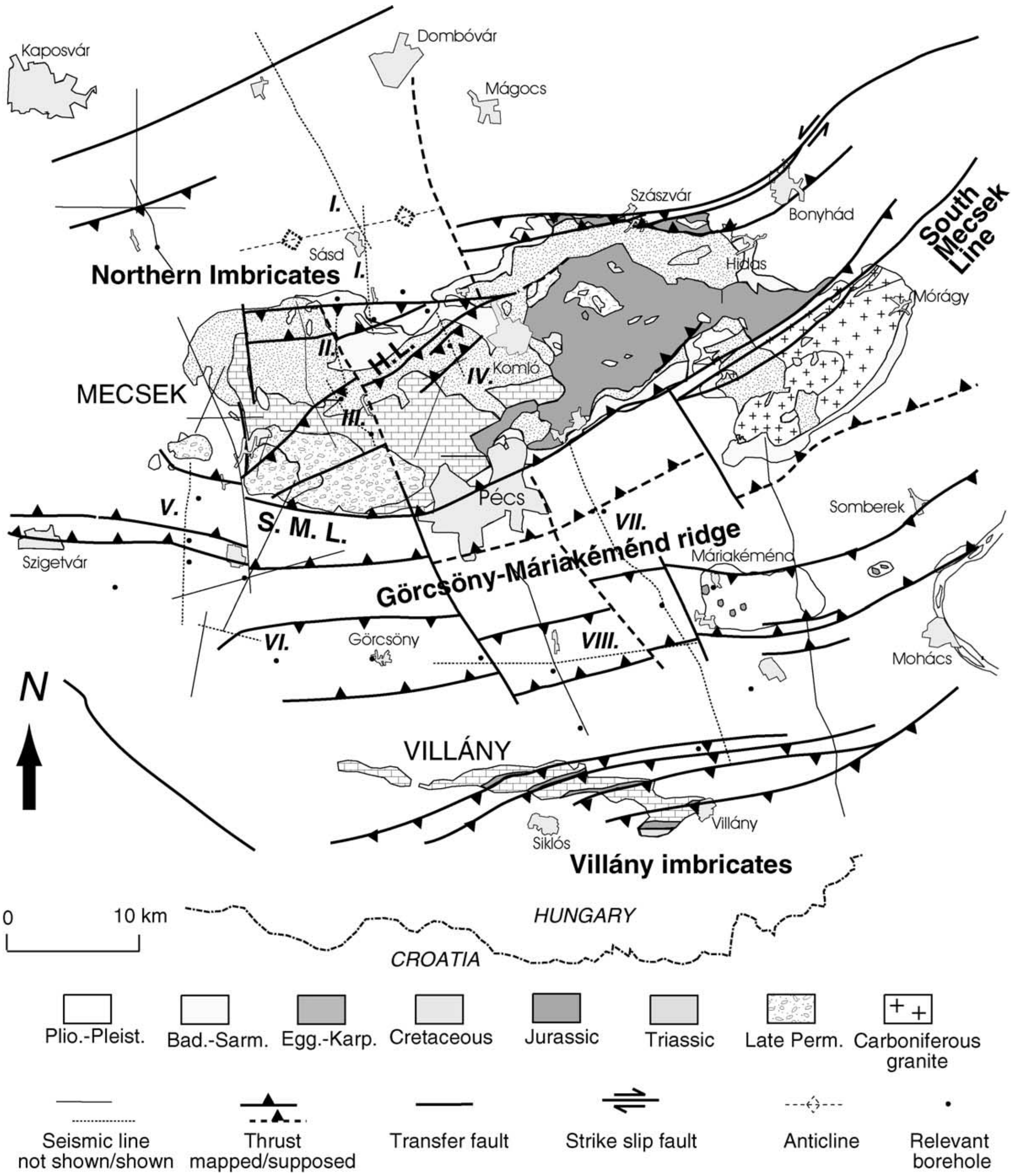


Fig. 2. Structural map of the Mecsek–Villány area based on seismic section reinterpretation (modified after Wórum, 1999). Roman numbers indicate presented sections. S.M.L. = South Mecsek line. H.L. = Hetvehely Line.

zoic sequences are well correlated and followed by boreholes in the Great Hungarian Plain.

In the Mecsek Mountains (Fig. 2), a very thick Upper Permian fluviatile sequence was deposited, followed by Triassic shallow marine clastics and carbonates, and Upper Triassic–Lower Jurassic swamp-coaliferous delta deposits, overlain by calcareous turbidites (Bleahu et al., 1996). The Permian through Lower Jurassic sequence can reach 2500m. A much thinner Middle–Upper Jurassic ends with Lower Cretaceous rift-volcanites and related deposits. In the Villány Mountains, Permian clastics are followed by a thin calcareous Triassic. The Upper Triassic thin continental deposits are overlain by a very condensed Jurassic carbonate sequence with hard grounds. The Upper Jurassic section is composed of shallow water limestone, which passes with a hiatus outlined by local bauxite development into shallow water Lower Cretaceous limestones. The sequence is terminated by Albian–Cenomanian–Turonian marls (Balla and Bodrogi, 1993). Under the Great Hungarian Plain, the Cretaceous nappes are sealed by a Turonian–Senonian cover, which might be later deformed. The Paleogene is generally missing, only present in some restricted places in small remnant basins (Wéber, 1982; Fig. 3). An occasionally thick, Lower Miocene clastic sequence is deposited in local basins. A transition of coarse grain terrestrial facies to deltaic is observed from south to north (Barabás, 1995). An ignimbritic horizon of 19 Ma serves as a general stratigraphic marker. This is followed by a very variable Middle Miocene sequence, going from continental in the south to open marine north of the Mecsek. Several dacitic tuff horizons of 16–15 Ma (Máthé et al., 1997; Fig. 3) are intercalated in this sequence. The Mecsek Mountains are covered by relatively thick Lower and Middle Miocene, while south of the mountains the thin or completely missing Lower–Middle Miocene is only preserved in local deeps. The whole area is generally covered by Upper Miocene transgressive clastic deposits, known as the Pannonian strata (Fig. 3). These lake-delta beds partly cover and partly surround the present elevations (Magyar et al., 1999). Transgressions, deepening periods are frequent during Late Miocene–Pliocene times. A local Paratethys time scale is used throughout the paper (e.g. Magyar et al., 1999; Sacchi et al., 1999; Fig. 3).

## 2. Methods of investigation

In order to tie outcrops to major structures at depth, analysis of seismic sections in the Mecsek–Villány region seemed necessary. The first seismic investigations, aiming mostly at raw material exploitation, were run in the 1960s to 1980s. The interpretation of these data was in some places in conflict with observed structures; therefore, the old lines were reinterpreted (Wórum, 1999). Boreholes around the two mountainous areas were extensively used to calibrate the sections. A detailed subdivision of the lower part of the Miocene is in fact quite difficult, because it is terrestrial and lacks fossils. Recent works (Barabás, 1995; Máthé et al., 1997) with some radiometrically dated tuff horizons have made the picture somewhat clearer.

A series of fault-slip data and mesoscale structural analyses began in the 1980s, first with a French–Hungarian geological cooperation program, then as part of a structural work jointly supervised by the Universities of Lille I, Paris VI and Eötvös, Budapest. Earlier works (Bergerat and Csontos, 1988; Csontos and Bergerat, 1993) lacked sufficient observation to constrain the timing of tectonic events. This gap was later filled by description of more Tertiary outcrops by Benkovics (1997).

Field structural observation was concentrated on description of outcrops, where folded or faulted structures were found. Fault planes, slickensides, superposition of striae and crosscutting patterns were observed and measured in order (1) to characterise the different fault sets and (2) to calculate the stress tensors using the methods of Angelier (1979, 1984, 1990). Grouping of fault families was made both by the software and manually. In some cases, it was necessary to remove the effects of later tilting. Details of the analysis are given in Bergerat and Csontos (1988), Csontos and Bergerat (1993) and Benkovics (1997). In soft sediments, slips were difficult or impossible to measure, therefore observed offsets and Mohr couples served as a basis of stress direction estimations.

## 3. Seismic section analysis

The result of seismic section analysis was the recognition and the location of previously known

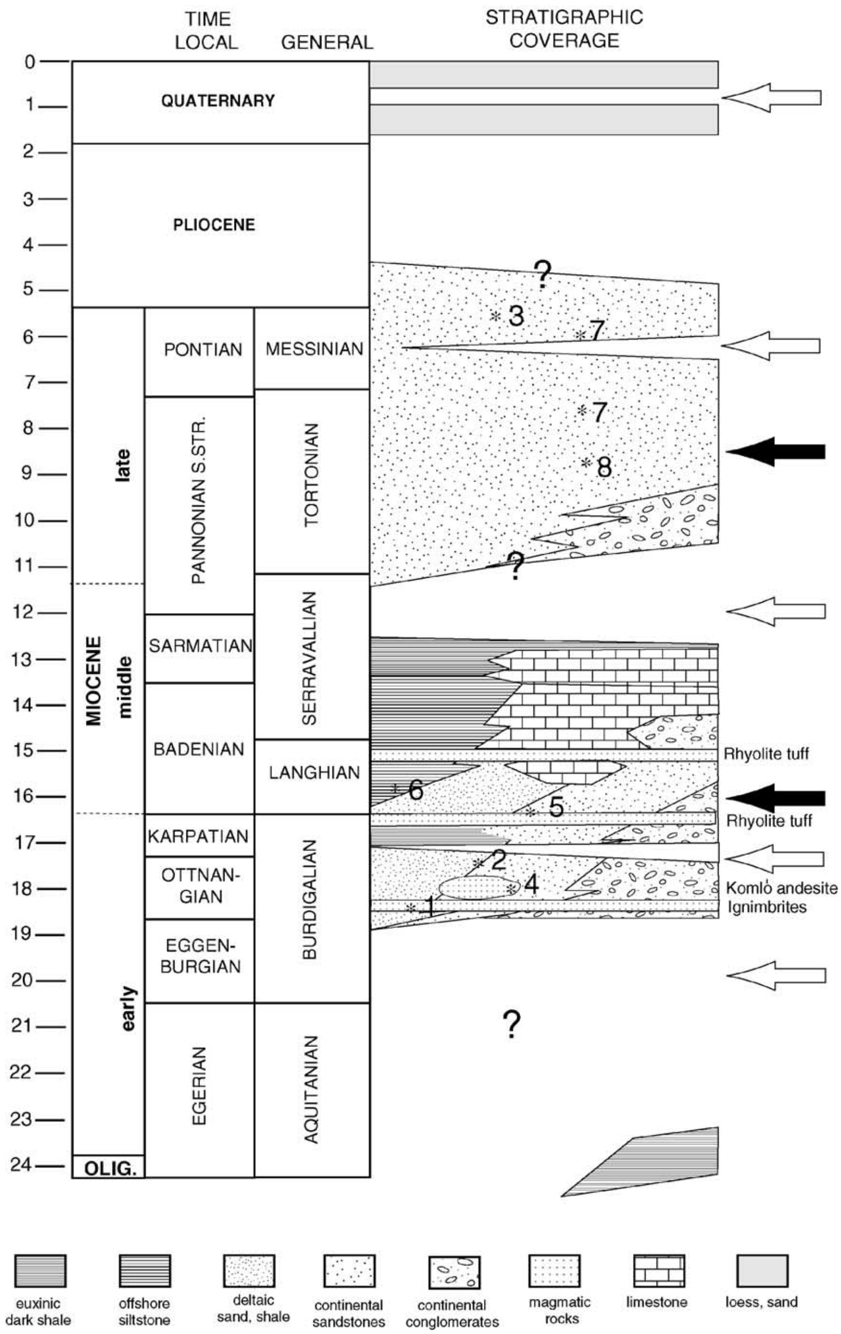


Fig. 3. Stratigraphic sketch of the Mecsek–Villány area. Time is given in Ma at the left of the diagram. Stage names after Tari et al. (1999) and Sacchi et al. (1999); stratigraphic content simplified after Barabás (1995) and Máthé et al. (1997). Asterisk and number refers to studied outcrops described in the text (see Fig. 7 for location). White arrow indicates a shortening or transpressive tectonic episode, black arrow indicates an elongation or transtensional tectonic episode.

structures and deformation belts (Figs. 2, 4–6). The "Northern Imbricates" (Wein, 1967; Tari, 1993) are a well-correlated complex regional structure bounding the Mecsek Mountains to the north. The structure can be seen on sections I and II (at 72 000–75 500 and at 1500; Fig. 4). The Northern Imbricates are characterised by steeply dipping thrust faults in a transpressive flower structure (see also Wein, 1967; Tari, 1993). Tertiary is involved in the thrusts, but the core of the flower is composed of Mesozoic strata. All this corresponds well to the structures described from surface mapping (Wein, 1965), or from coal-exploration boreholes (Wein, 1967). At least three Tertiary tectonic events, marked by a compressive component, are seen on section I (and less clearly on the others as well). Deformed Lower Miocene is partly eroded by Karpatian sediments. Two wells (L-14 and Msz-1) on either side of the main Northern Imbricates thrust indicated that a uniform Karpatian–Badenian cover transgressed a Mesozoic basement within the Northern Imbricates, while to the north, Ottnangian strata with a thin ignimbritic marker were preserved.

Middle Miocene strata (including Sarmatian) are gently folded and eroded (e.g. between 70 000 and 73 000; Fig. 4). The unconformity is covered by Pannonian strata, which are overthrust by Miocene along the Northern Imbricates. The Pannonian–Pontian age of this latter thrust was proved by boreholes (Wein, 1965). Most early thrusts in the vicinity of the Northern Imbricates are reactivated and show features similar to positive flower structures (e.g. 67 000, 64 000; Fig. 4), indicating that transpression was distributed between parallel structural zones. Section I shows that the Pannonian strata dip away from the Mecsek Mountains. This suggests a Pannonian cover and a later uplift, tilting and erosion of these strata.

The next major structure, the Hetvehely line (Wéber, 1977), is located approximately at the northern limit of Mesozoic exposures of the West Mecsek (Fig. 2). The Hetvehely line is seen on seismic sections III (at 1000) and IV (at 500) as a flat surface beneath basement and Miocene folds (Fig. 4). The south-dipping surface clearly cuts Miocene strata, even slightly deforming the over- and underlying layers. Based on this evidence, the line is a north-vergent thrust or transpressive shear, active during or after Miocene times.

One of the most prominent structural zones of the area, the South Mecsek line (e.g. Vadász, 1935; Kleb, 1973), is not seen on the seismic sections (Fig. 2). Some of the sections terminate before reaching it, or they loose resolution because the South Mecsek line is always associated with an abrupt uplift of Paleozoic–Mesozoic formations to the north against young Tertiary lowlands to the south. On the other hand, beneath the flat Tertiary area, a seismically chaotic, granitic–metamorphic mass (calibrated by nearby boreholes) is thrust over a well-layered sedimentary package above a flat reflector (Fig. 5, on section V, between 6000 and 8000). The layered package is identified in a calibrating well as Paleogene (Upper Eocene–Oligocene?; Wéber, 1982). An upper layered package, identified in the same borehole as Lower Miocene, covers the tectonic contact. In seismic section V (Fig. 5) even the Lower Miocene (probably Eggenburgian–Ottnangian) is cut by the fault and a Cretaceous imbricate is involved in the thrust. Slight bends of onlapping Miocene and even Pannonian beds (at 8200) possibly indicate a later reactivation of the basal fault as a blind thrust. The main fault is also extensionally reactivated during the Pannonian time (at 5500).

At the southeastern foothills of the Mecsek Mountains, south of the known boundary fault, wells and seismic sections (e.g. section VII, at 6000, Fig. 5) indicate that there should be a tectonic contact between older, exposed formations in the north and Tertiary in the southern foreland. In the Nk-2 well, Jurassic is thrust on top of Lower Miocene. The poor quality of data does not make possible an interpretation as clear as in the west. There is a compressional reactivation after Pannonian, since even these young strata are offset by the fault at 6000.

The Görcsöny–Máriakéménd ridge (Fig. 2) strikes E–W between the Mecsek and Villány Mountains. This is a more or less elevated ridge composed of crystalline material in the western portion, and of Jurassic–older Mesozoic in the eastern portion. This zone was crossed by several seismic sections. The Görcsöny ridge (section VI in Fig. 5) is an elevated antiform above a flat surface (at 1500). In this section, crystalline material is thrust upon a duplex of layered package, which may be Miocene. The duplex is thrust on Miocene, which is followed from section V. On section VI (Fig. 5), Pannonian strata onlapping the crystalline ridge (at 2500) are slightly curved, flexed

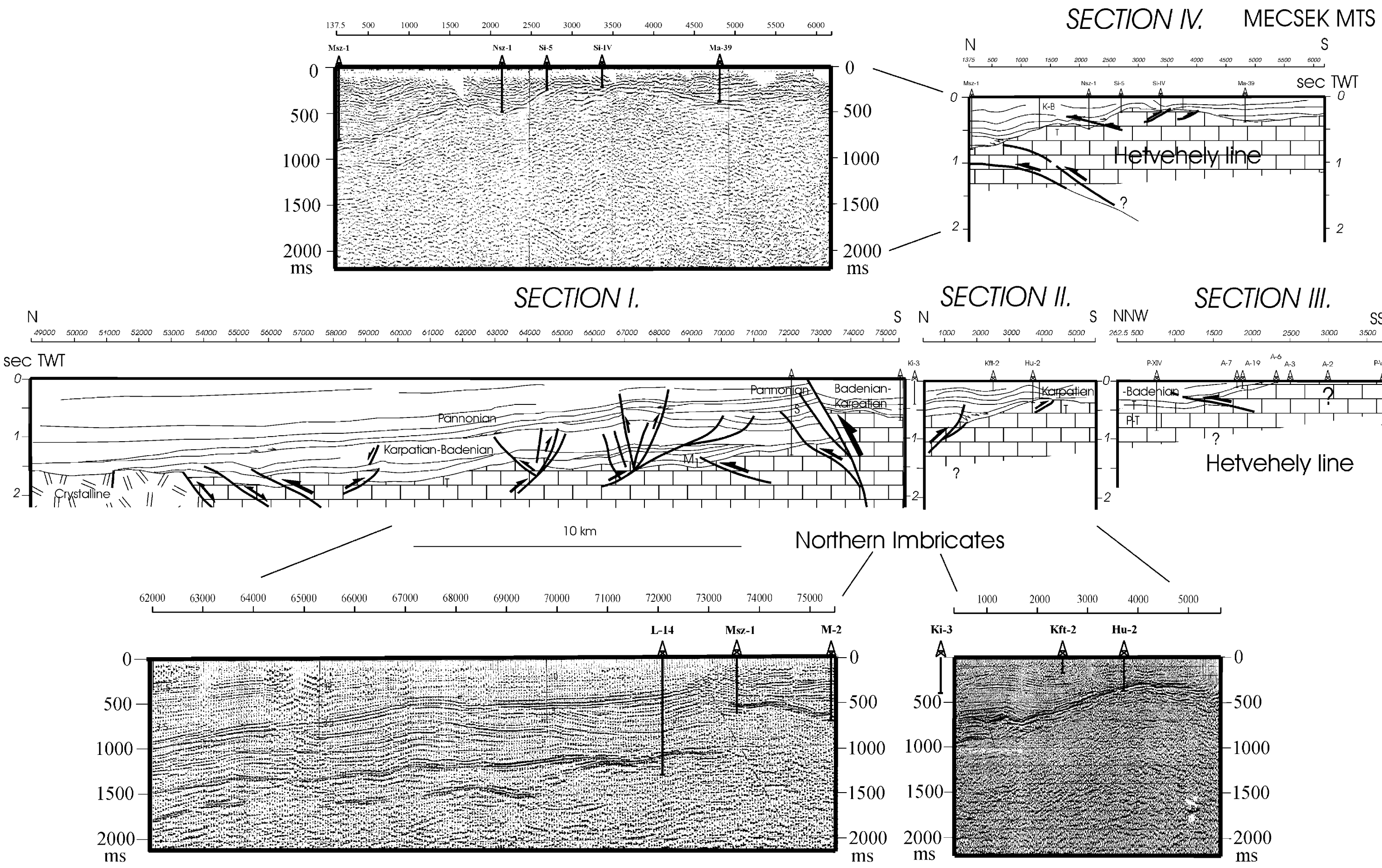


Fig. 4. Seismic section interpretations across the northern part of Mecsek Mountains, after Wórum (1999). Small numbers indicate reference points. Vertical scale in Two Way Travel times. The main body of Mecsek Mountains is towards the south (right) of the sections. S: Sarmatian; K–B: Karpatian–Badenian; $M_1$: Early Miocene; T: Triassic; P–T: Permian–Triassic. Boreholes marked as small derricks. Thin lines indicate the portions of lines illustrated by original seismic profiles.

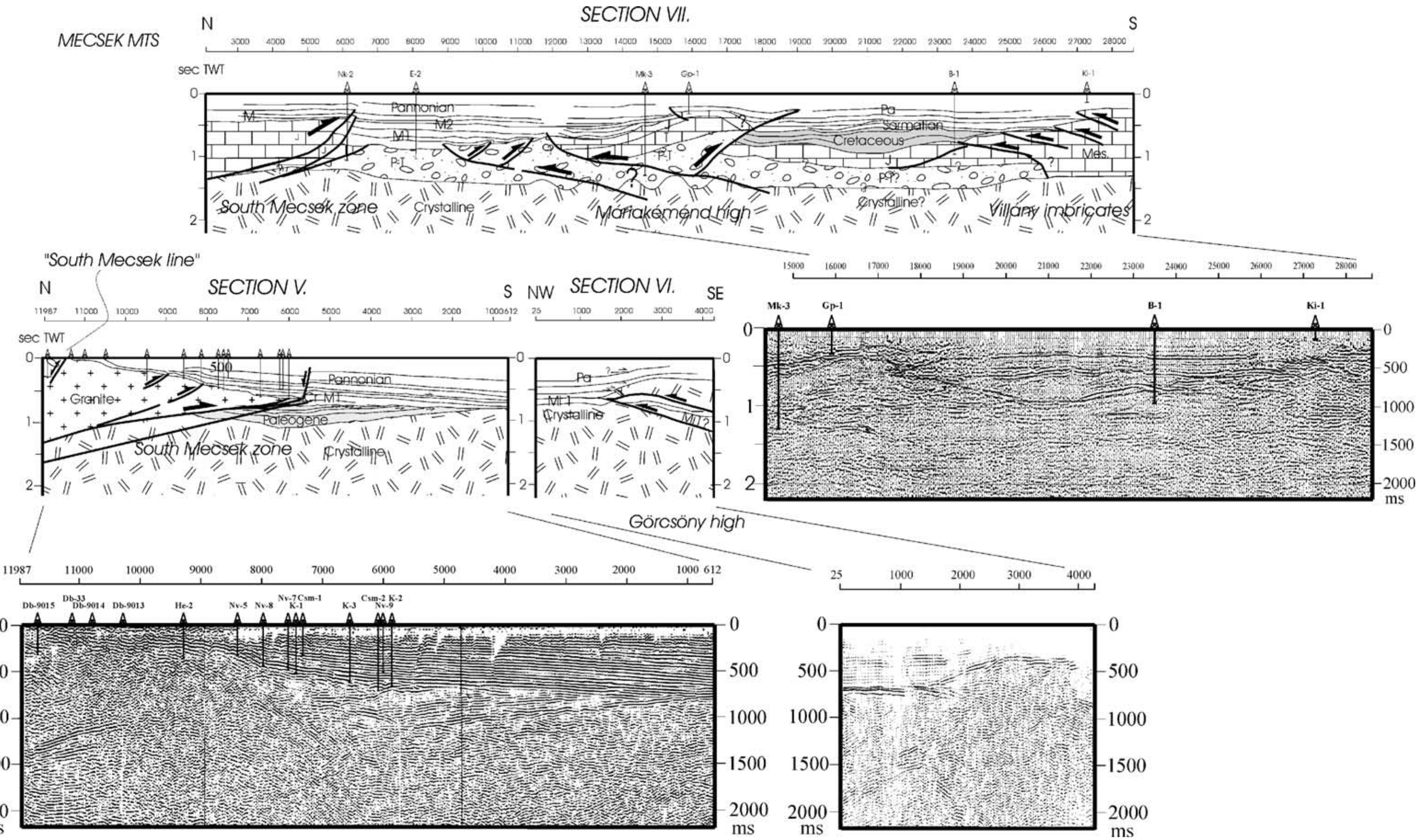


Fig. 5. Seismic section interpretations south of Mecsek, north of Villány Mountains, after Wórum (1999), slightly modified. Small numbers indicate reference points. Vertical scale in Two Way Travel times. The main body of Mecsek Mountains is towards the north (left) of the sections. Pa: Pannonian s.l., Late Miocene–Pliocene; $M_2$: Middle Miocene; $M_1$: Early Miocene; Cr: Late Cretaceous; J: Jurassic; T: Triassic; P–T: Permian–Triassic; Mes: Mesozoic. Boreholes marked as small derricks. Thin lines indicate the portions of lines illustrated by original seismic profiles.

and indicate an intra- or post-Pannonian reactivation of the blind thrust. Younger Pannonian or Pontian beds may onlap this flexure.

On section VII (Fig. 5), some north- and south-vergent thrust faults seem to limit the Görcsöny–Máriakéménd ridge at 15 500 and 19 000, giving it an aspect of positive flower structure. These thrusts affect Miocene and Pannonian deposits. This may explain the result of a nearby borehole, Peterd-1, where Nagy and Nagy (1976) described repetition of Triassic, with tectonically intercalated Lower Pannonian sediments.

The Villány Mountains constitute an elongated mass of imbricated Mesozoic sequences (Fig. 2). Southward dipping thrust planes, conformable to surface geology, are visible at the northern foothills of the Mountains on section VII at 24 000–27 000 (Fig. 5). These thrusts are partly pre-Late Cretaceous, as this latter, identified by borehole B-1 seals the northernmost thrust. A more southerly imbricate (at 26 500), however, affects Miocene (possibly Sarmatian) strata as well. Finally, the imbricate at 27 000 thrusts Pannonian.

Transversal faults seem to cut up the whole area. These NNW–SSE striking faults disrupt the general structures described above. Such faults are not evident in the outcrop pattern of the Mecsek Mountains, but are strongly suggested by gravity anomalies (Fülöp et al., 1964; Wórum, 1999). Apparent offset of some prominent structures (e.g. the Northern Imbricates) may be explained by relays or en échelon structures, but the sinking of the ridge between Görcsöny and Máriakéménd, or the western limits of the exposed Morágy granitic mass, suggest transfer faults. Such faults are

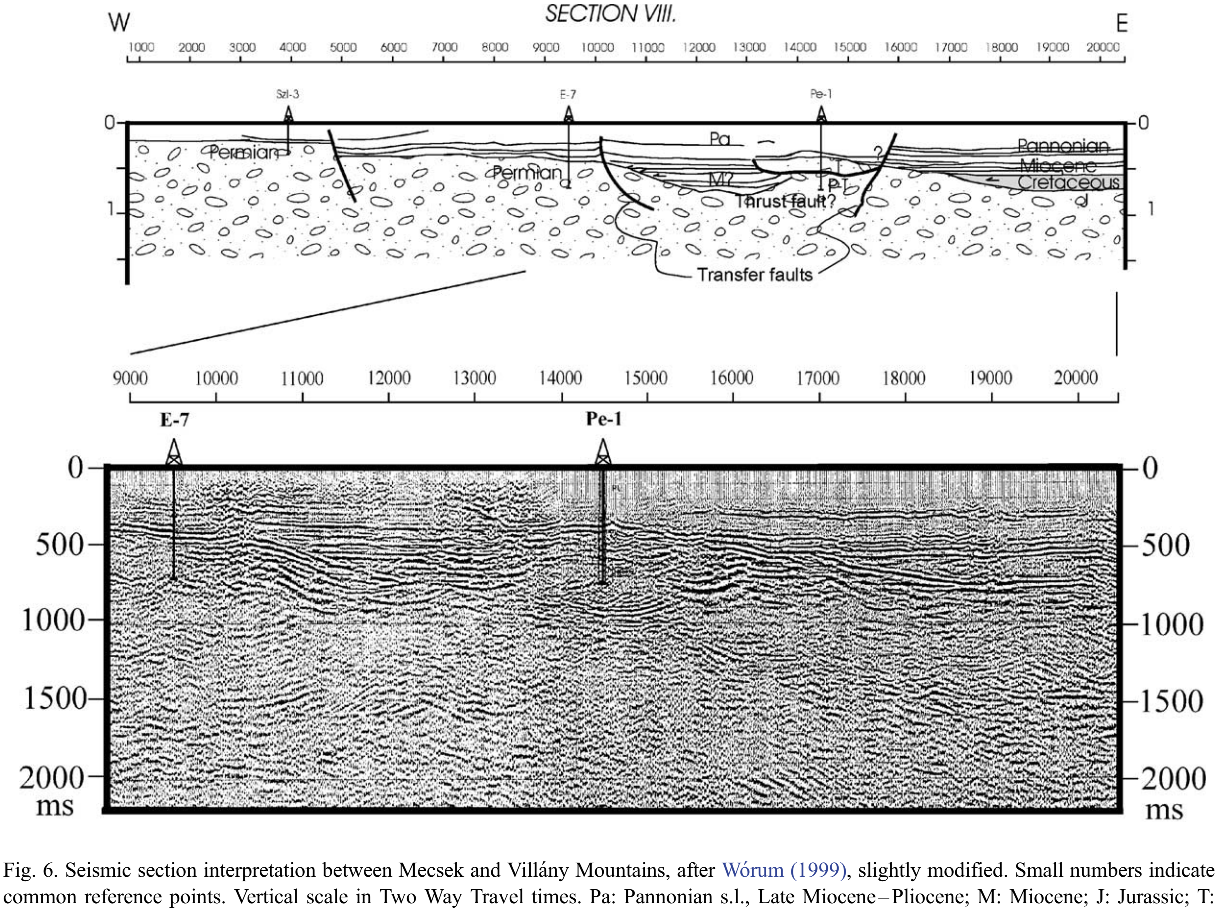


Fig. 6. Seismic section interpretation between Mecsek and Villány Mountains, after Wórum (1999), slightly modified. Small numbers indicate common reference points. Vertical scale in Two Way Travel times. Pa: Pannonian s.l., Late Miocene–Pliocene; M: Miocene; J: Jurassic; T: Triassic; P–T: Permian–Triassic. Boreholes marked as small derricks. Thin lines indicate the portion of line illustrated by original seismic profile.

seen as subvertical or steeply inclined surfaces on section VIII, near 5000, 10 000 and 16 000 (Fig. 6). They seem to accommodate differential movements on thrust planes. The transversal faults on the mentioned section offset Pannonian strata as well.

## 4. Microstructural analysis

In this section, we concentrate on the analysis of the few outcrops that are crucial to constrain the timing of deformation and for structural style. Unfortunately, only a handful of Tertiary outcrops show signs of syn-depositional tectonics. More outcrops were measured, mainly in the Mesozoic, but these provide poor time constraints. Most of these sites were analysed in earlier works (Bergerat and Csontos, 1988; Csontos and Bergerat, 1993). These older sites were used herein, however, to reinforce the observations and conclusions made in Tertiary. Fig. 7 (see also Table 1) illustrates some characteristic sites in Mesozoic and Cenozoic formations of Mecsek and Villány Mountains. However, since in SW Hungary only the Mecsek Mountains has a Tertiary cover,

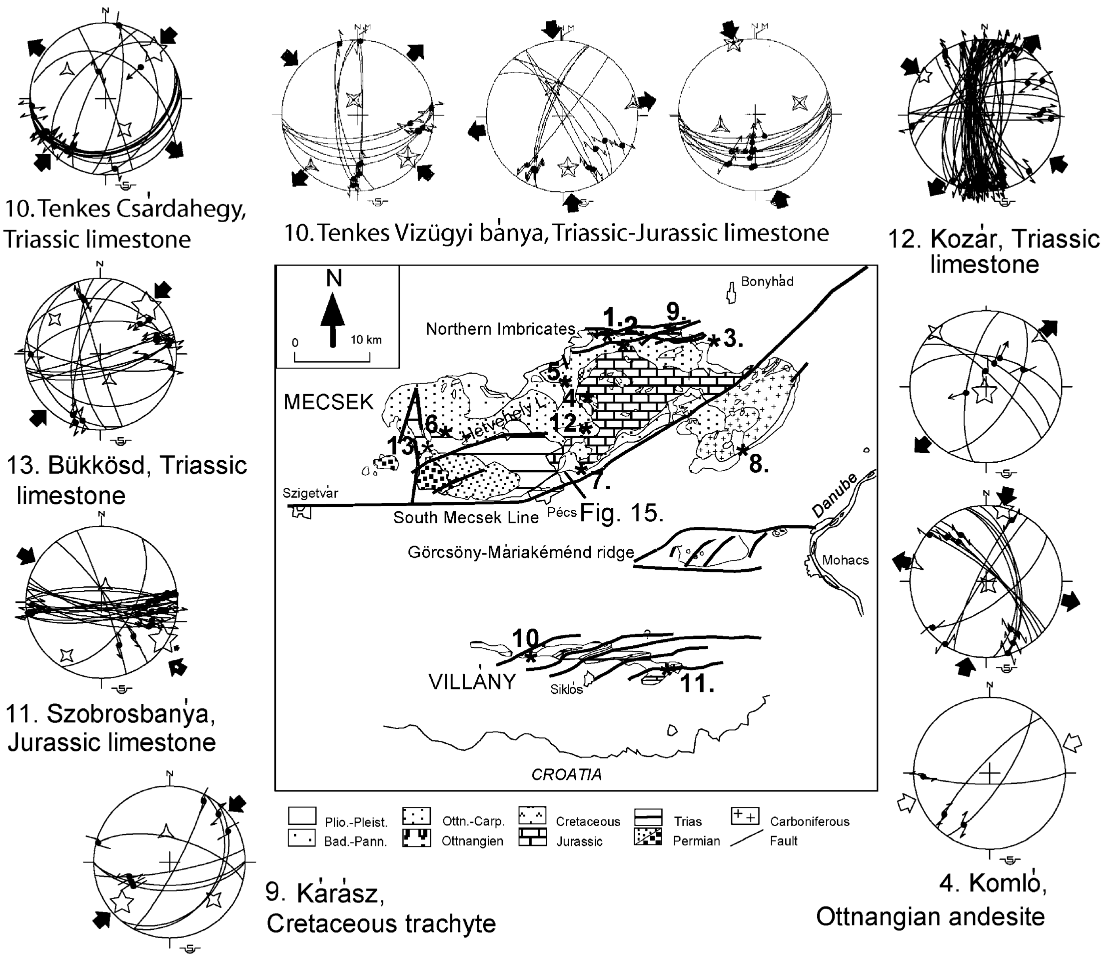


Fig. 7. Simplified geological map of the study area (after Benkovics, 1997, modified) with location of described outcrops (asterisk and number). Thick line indicates location of geologic profile in Fig. 15. Main structural zones are marked in bold. Stereographic plots: lower hemisphere, Schmidt projection (data from Bergerat and Csontos, 1988; Csontos and Bergerat, 1993; Benkovics, 1997). Faults are represented by their trace, slickensides by a dot. Small arrows mark the determined shear. Black arrows indicate computed stress directions. Star is for $\sigma_1$, diamond for $\sigma_2$ and triangle for $\sigma_3$. White arrows indicate estimated stress axes. All measurements in a site are grouped into subsets.

Table 1
Determination of some characteristic paleostress tensors in the Mecsek–Villány area

| Site | Age | *N* | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ | Fig. | Ref. |
|---|---|---|---|---|---|---|---|
| Tenkes Csárdahegy | Triassic | 13 | 045/11 | 149/51 | 306/37 | 7 | 1–2 |
| Tenkes Vizügyi bánya | Triassic–Jurassic | 11 | 130/14 | 349/13 | 224/10 | 7 | 3 |
| | | 9 | 174/33 | 342/58 | 080/4 | 7 | – |
| | | 10 | 343/3 | 076/38 | 251/50 | 7 | – |
| Kozár | Triassic | 54 | 303/5 | 153/84 | 038/3 | 7 | 2 |
| Komló | Ottnangian | 5 | 195/85 | 318/2 | 47/4 | 7 | 3 |
| | | 11 | 012/3 | 148/86 | 283/4 | 7 | – |
| Bükkösd | Triassic | 14 | 044/14 | 307/26 | 161/60 | 7 | 2 |
| Szobrosbánya | Jurassic | 22 | 123/4 | 214/10 | 011/79 | 7 | 1–2 |
| Kárász | Cretaceous | 7 | 229/19 | 131/24 | 353/58 | 7 | 2 |
| Máza I | Ottnangian | 7 | 360/15 | 168/74 | 269/3 | 8 | 1–3 |
| | | 8 | 018/17 | 229/70 | 111/10 | 8 | – |
| | | 7 | 049/23 | 215/66 | 317/5 | 8 | – |
| Máza II | Late Ottnangian–Early Karpatian | 7 | 317/4 | 217/66 | 049/24 | 9 | 3 |
| Rác-hegy | Late Pannonian | 7 | 117/18 | 340/65 | 212/16 | 10 | 3 |
| Mecsekjánosi | Early Badenian | 6 | 028/71 | 261/10 | 168/14 | 11 | 3 |
| Hetvehely | Karpatian | 5 | 345/23 | 224/46 | 091/32 | 12 | 3 |

From left to right: name of the site (see location in Fig. 7), number of faults used for the computation (*N*), trends and plunges of principal stress axes $\sigma_1$, $\sigma_2$ and $\sigma_3$ (e.g. 261/10 = azimuth 261, dip 10), number of the corresponding figure (Fig.), reference (Ref.) (1 = Bergerat and Csontos (1988); 2 = Csontos and Bergerat (1993); 3 = Benkovics (1997)).

outcrop observations and descriptions were concentrated here (Figs. 8–14; Table 1).

### 4.1. Northern Imbricates

An Ottnangian ignimbritic–rhyolitic tuff, radiometrically dated at 19 Ma (Máthé et al., 1997) is located south of Máza village, directly south of the Northern Imbricates (no. 1 in Fig. 7). Several conjugate sets of left- and right-lateral faults grouped into three intersecting conjugate subsets (Fig. 8) were measured in the outcrop. Based on these subsets, N–S to NE–SW compression directions were calculated (Table 1). Roughly E–W sinistral strike-slip faults with their complementary dextral strike-slip faults were measured in Cretaceous magmatic rocks of the Northern Imbricates zone (see also Csontos and Bergerat, 1993).

The complex strike-slip fault patterns measured in the Early Miocene magmatic rocks seem to reflect virtual rotations of the stress field. Since major counterclockwise rotation certainly affected this outcrop in the Late Ottnangian–Early Karpatian (Márton and Márton, 1999), it seems more logical to postulate a fixed, external stress field and to rotate the respective outcrops under this stress field to produce the observed fault pattern (see a similar exercise in Csontos et al., 1991; Márton and Fodor, 1995). The subsets of Máza I can thus be interpreted as blocks rotated (and subsequently broken) under a fixed external NE–SW compression and perpendicular extension (present directions). All these data suggest that the Northern Imbricates is a long-lived strike-slip zone with rotational deformation, too.

Late Ottnangian or Early Karpatian sands of different grain size and colour lie above the ignimbritic–lower rhyolitic tuff (no. 2 in Fig. 7; Fig. 9A). Small normal faults (and a thrust fault) separate different layers of the outcrop, while the same faults are sealed by upper layers. These faults characterise a syn-depositional extension of NW–SE direction (reconstructed after back-tilting, Fig. 9B). The outcrop containing these faults is crosscut by a set of later strike-slip faults. One of these late strike-slip faults seems to offset the Pleistocene loess above the sands, so the age of this fault family is possibly Quaternary. NW-vergent thrust faults also make part of this fault family, together with some thrust-reactivated older faults. Stress tensor calculation indicates a NW–SE compression, and perpendicular NE–SW extension (Fig. 9C; Table 1).

The syn-sedimentary NW–SE extension is not overprinted by the strike-slip faults of the ignimbrites,

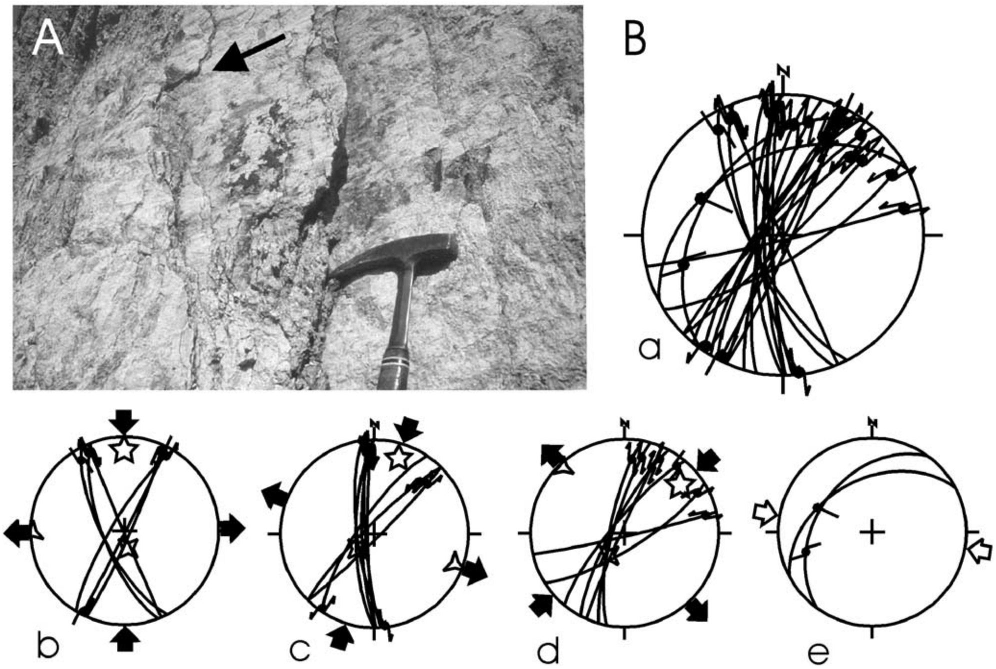


Fig. 8. Máza I (outcrop no. 1). (A) A large N–S trending right-lateral strike-slip fault (see subset c) marked by Riedel shear fractures in rhyolitic tuff. (B) Stereographic plots. Data taken from Bergerat and Csontos (1988), Csontos and Bergerat (1993) and Benkovics (1997). Same legend as in Fig. 7. The total observed fault set (a) is divided into several conjugate subsets (b, c, d, e). These define apparently rotated stress field.

so we could argue that the extension is later than these strike-slip faults. However, this extension could also work together with a NE–SW-oriented compression and related strike-slip-type deformation. The syn-sedimentary faults in the sands would fix the last increments of the Early Miocene shear event.

A smaller sandpit near the Northern Imbricates exposes Late Pannonian (ca. 6–7 Ma) sand near Mecseknádasd (Rác-hegy, no. 3 in Fig. 7; Fig. 10A). Two fault sets—a (tilted) syn-depositional conjugate normal fault set and a crosscutting strike-slip fault set—were found in this outcrop (Fig. 10B,C). Both fit a NW–SE compressional–NE–SW extensional stress field: the extension happened first and strike-slip motion occurred later, after a smaller tilt of the layers. Measured faults indicate that the E–W Northern Imbricates would play in right-lateral shear during this event.

## 4.2. Main body of the Mecsek Mountains

There is a large quarry of an Ottnangian subvolcanic body (19 Ma; Hámor, 1966) at the eastern edge of Komló (no. 4 in Fig. 7), near the termination of the Hetvehely line. Besides fissures and joints due to cooling, some fault planes exhibit slickenside fibres. The faults could be assigned to a subset of normal faults and two subsets of conjugate strike-slip faults (Fig. 7; Table 1). These later define a NNE–SSW to ENE–WSW compression with respective perpendicular extensional directions (Fig. 7). Arguments similar to those for the ignimbrites would suppose a fixed external stress field and rotating rocks in the Komló area, too. However, because of much worse defined conjugate sets, the apparently rotated stress-field pattern of the Komló andesite is not quite clear.

Uncertain timing of the strike-slip event could result in another type of explanation. This would emphasise the similarities of the fault patterns of the ignimbrites and of the Komló andesites. These rocks suffered opposite rotations (Márton and Márton, 1999; Csontos et al., in press), so the similarity in this view would mean that the strike-slip event is post-rotational and the stress-field rotation indicated by the rotated

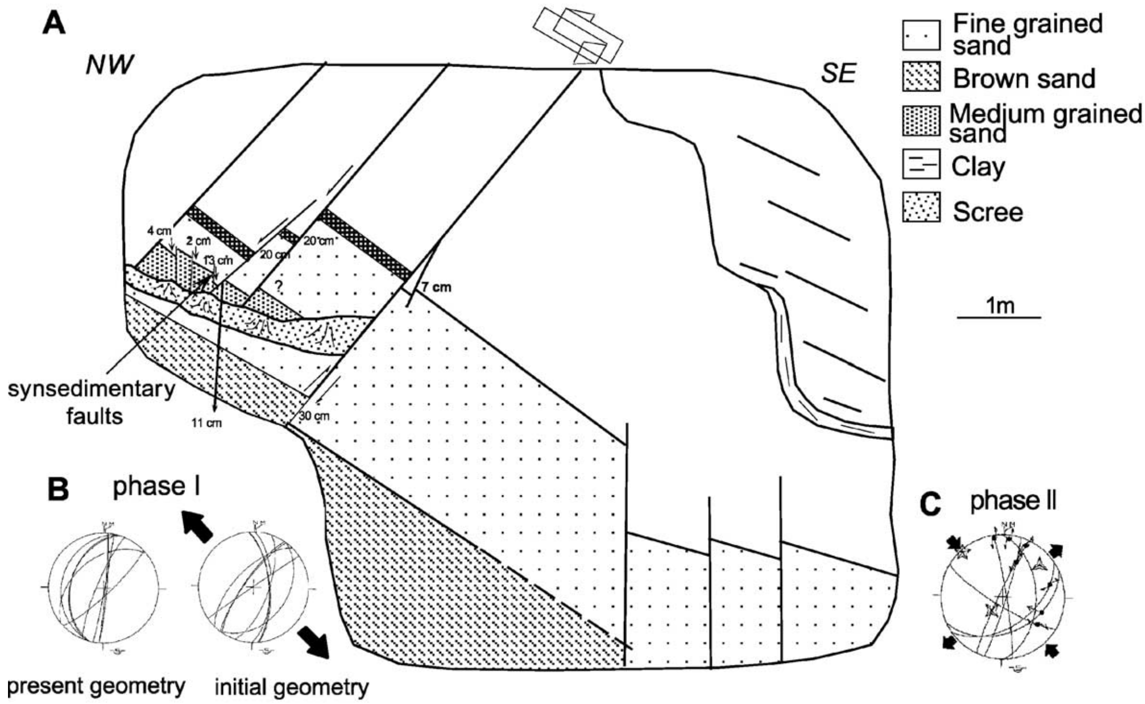


Fig. 9. Máza II (outcrop no. 2). Sketch (A) and stereographic plots (B, C). Data taken from Benkovics (1997). Same legend as in Fig. 7. Elongation directions in B are inferred after backtilting around measured bedding dip value.

conjugate strike-slip fault sets would be a real rotation of the external field. Due to the lack of observations of fault successions, we would argue for a change from Early Miocene NE–SW compression to N–S compression during the Karpatian. At the present level of knowledge, both explanations could be valid.

Near Mecsekjánosi, at the public waste disposal of Kolmó (no. 5 in Fig. 7), a fold in Early Badenian sands and silts (Fig. 11B) is evidently a later, possibly Sarmatian or Pannonian feature. The axis of this fold trends E–W. Some blind thrust faults and material flowing into hinge zones are related to folding. This site testifies the importance of shortening or transpression during Late Miocene–Pliocene. Larger folds, as the syncline to the south of the Northern Imbricates, are also oriented E–W and indicate a northerly component of shortening.

In a part of the exposure, normal faults and tilted blocks are present in the core and limbs of the fold. These normal faults (1) caused thickness changes in sand and clay layers, and (2) are sealed by upper layers (Fig. 11A). They do not seem related to the folding (not due to extension in the external part of a competent layer) and similar features were repeated elsewhere in the exposure (with uncertain sealing). These faults form a conjugate set of normal faults, which, after back-tilting, give a N–S extensional direction (Table 1).

Between the villages of Bükkösd and Hetvehely, near the railroad-station, in the neighbourhood of the Hetvehely line (no. 6 in Fig. 7), a series of small quarries are found. The Karpatian (ca. 16 Ma) sands show syn- and post-depositional transtensional faults, with strike-slip slickenside lineations (Fig. 12). The calculated stress field shows N–S compression and perpendicular E–W extension (Table 1). Based on these structures, the Hetvehely line functioned as a left-lateral normal fault during Karpatian.

There is a conflict between the Karpatian sands characterised by syn- and post-sedimentary N–S compression and E–W extension and the Early Badenian of Mecsekjánosi characterised by N–S syn-

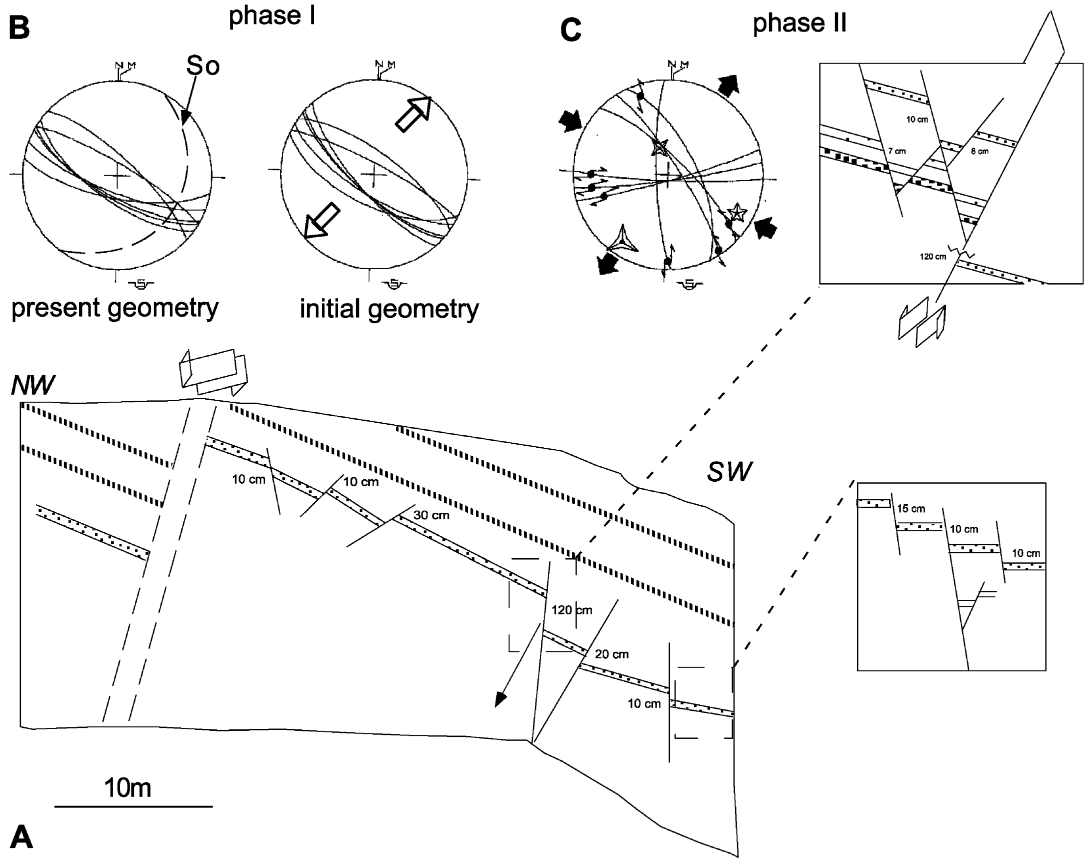


Fig. 10. Rác-hegy (outcrop no. 3). Sketch (A) and stereographic plots (B, C). Some layers are drawn to highlight the syn-sedimentary faulting. Data taken from Benkovics (1997). Same legend as in Fig. 7. Elongation directions in B are inferred after backtilting around measured bedding dip value ($S_0$). Stress field in C may be a later manifestation of B.

sedimentary extension. It is probable that the N–S extension in Early Badenian of Mecsekjánosi was only a local feature, induced by gliding along the slope of the basin. In this case, the general stress field could remain N–S compression, without any major change during the Middle Miocene.

### 4.3. South Mecsek line

A big sandpit in the eastern suburbs of Pécs, located very close to the South-Mecsek line (no. 7 in Fig. 7), exposes nearly flat-lying Upper Pannonian (ca. 7 Ma) sand, thrown into somewhat undulating, large, open folds. Another fold (Fig. 13), described by Kleb (1973), has a very steep and a flat lying limb, with some shear-related small thrust faults in its core. The direction of this fold indicates N–S shortening. It is eroded and transgressed by Late Pannonian sand. This exposure clearly indicates a Late Miocene–Pliocene shortening of northerly direction and a late reactivation of the South Mecsek line.

Another big sandpit, near the village of Hímesháza, at the SW periphery of the Morágy granite body (no. 8 in Fig. 2) shows syn-depositional tectonics. Two sets of faults are observed in coloured sands (Fig. 14). One is a tilted set of conjugate normal faults sealed by sandy upper horizons. The second set includes syn- and post-tilting faults. The small grabens are filled with Pannonian sand (10–8 Ma). Both the first set of normal faults and the layers are slightly tilted and crosscut by the second set of faults. These later faults have a normal and strike-slip

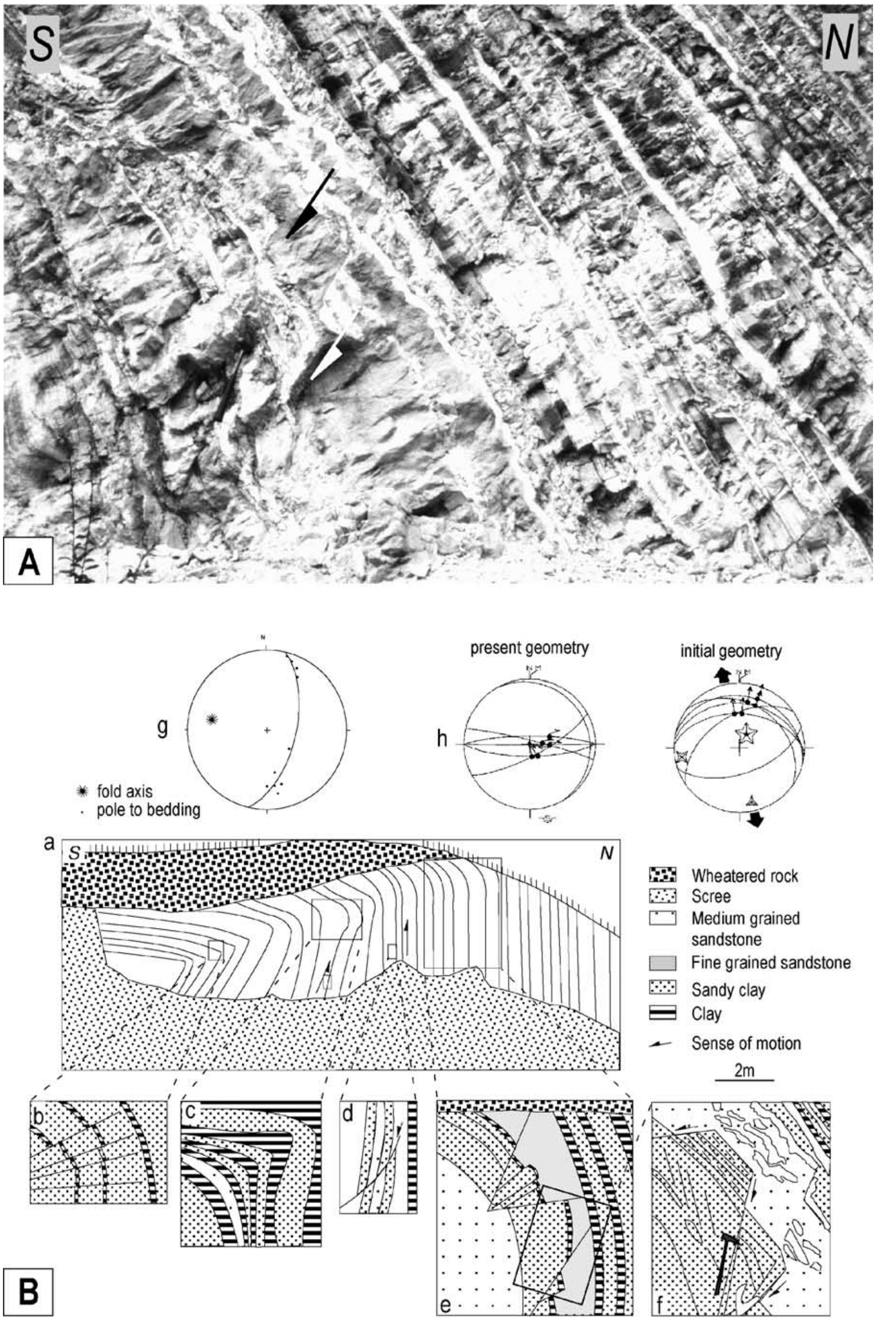


Fig. 11. Mecsekjánosi (outcrop no. 5). (A) Syn-sedimentary normal faulting in sand and clay (Early Badenian). (B) Sketch of the fold (a) and stereographic plots (g, h). Modified after Benkovics (1997). Same legend as in Fig. 7. Insets b to e show details of the fold. Detailed scheme (e) indicates syn-sedimentary normal faults (see photograph in A). All other markers are related to folding mechanism. In g, dots are poles to bedding planes, axis of fold is drawn as barbed point, girdle indicates zone circle for bedding poles. Elongation directions in h are calculated after unfolding. This stereoplot indicates syn-sedimentary extension.

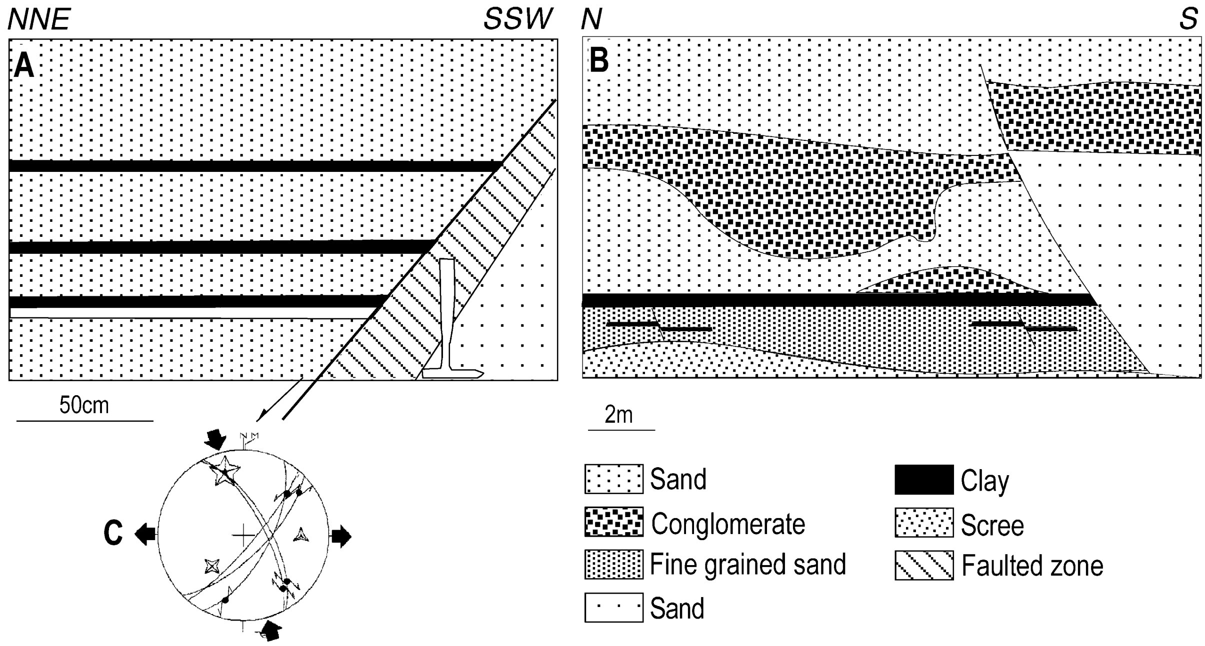


Fig. 12. Hetvehely (outcrop no. 6). Sketches (A, B) and stereographic plot (C). Data taken from Benkovics (1997). Same legend as in Fig. 7. The defined stress field is partly syn-, partly post-sedimentary.

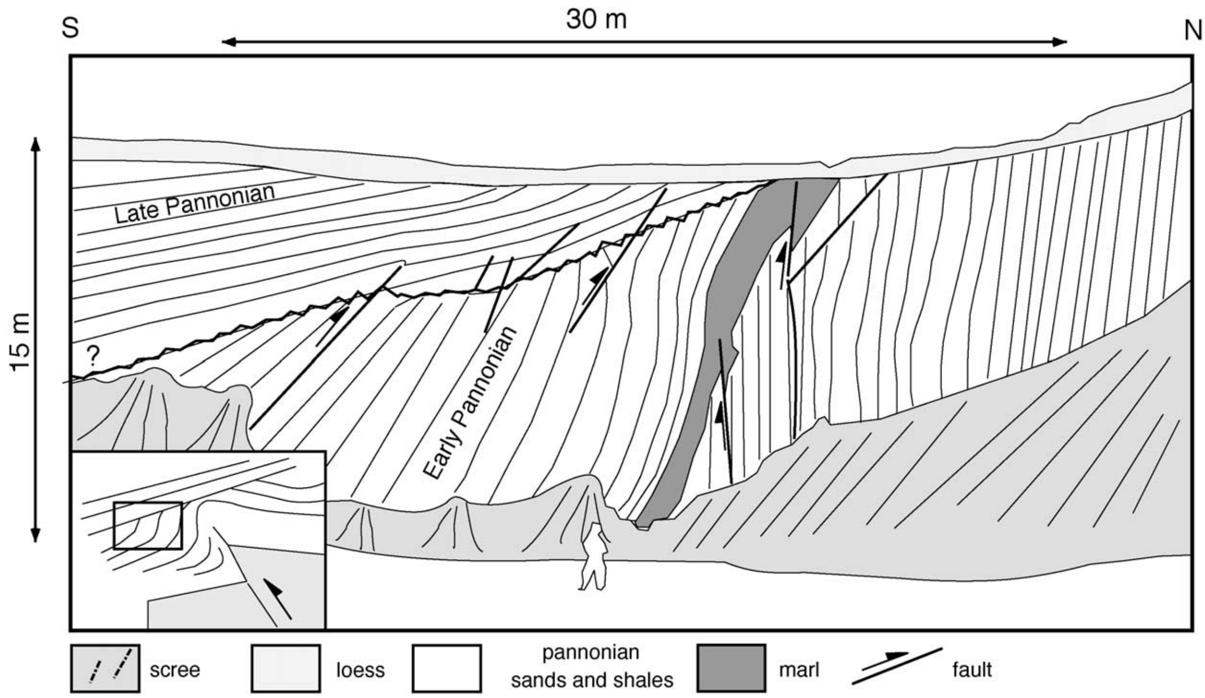


Fig. 13. Sketch of the fold at Danitzpuszta (outcrop no. 7), after a photo taken in the fifties by Mrs. Végh-Neubrandt and redrawn by Benkovics (1997).

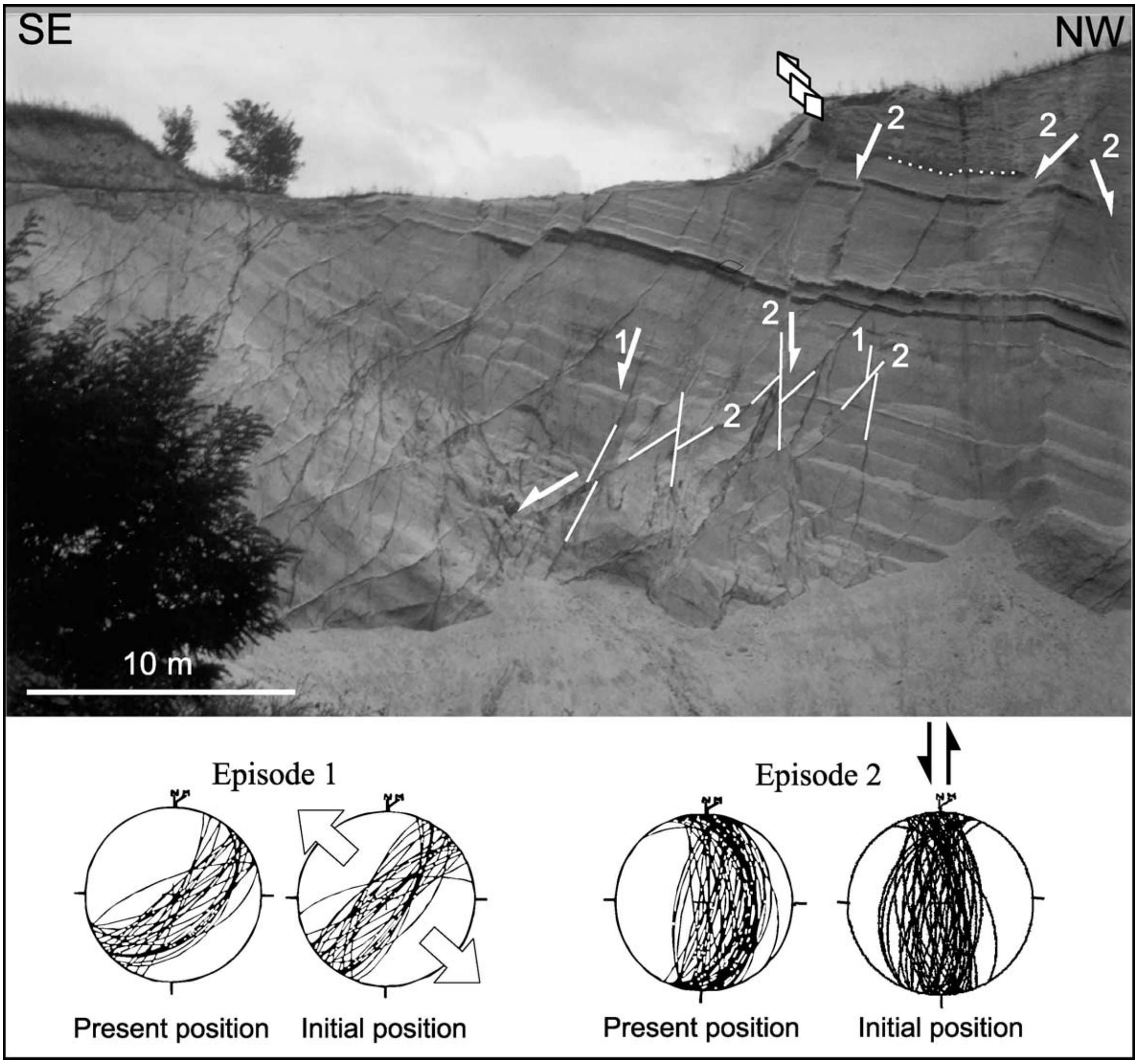


Fig. 14. Normal faulting in Pannonian sands at Himesháza (outcrop no. 8). Photograph shows the different sets of faults and stereographic plots illustrate the two faulting episodes (see detailed explanations in text). Some chronological relationships are underlined (thin white lines) as well as the upper formations non affected by normal faulting of episode 1 (dotted white line).

offset. The analysis of back-tilted first faults suggests a NW–SE extensional direction, i.e. a transtension–extension parallel to the South Mecsek zone in Late Miocene. The second set of faults fits in direction with the NNW–SSE transfer-fault termination of the granitic body. A left-lateral fault zone is inferred here from geological maps.

The observed NW–SE extension is also evidenced by a geological section across the same zone (Fig. 15; Hámor, 1966) The section is controlled by boreholes and coal mine shafts and shows syn-depositional extension during the Pannonian. Earlier Pannonian strata are folded and thrust during the Pontian–Quaternary structural event.

### 4.4. Villány Mountains

Unfortunately, no Tertiary rocks are exposed in or around the Villány Mountains. Therefore, we have to rely on Mesozoic outcrops (Bergerat and Csontos,

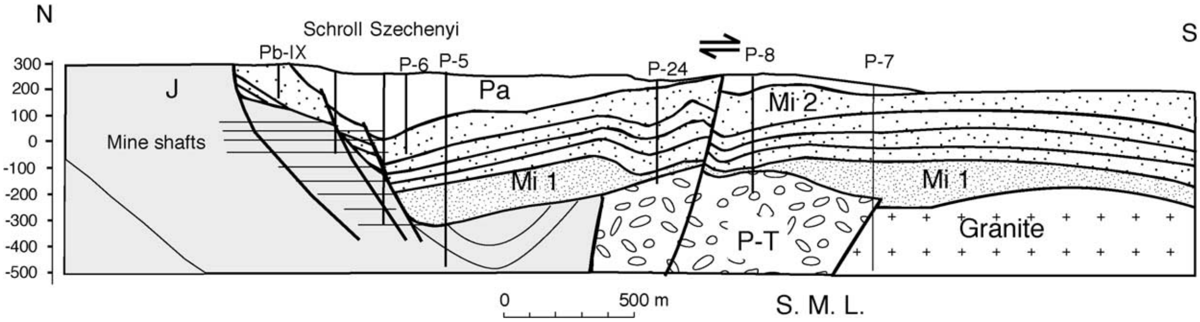


Fig. 15. Geological section at Pécsszabolcs (location of section in Fig. 7). Redrawn and slightly modified after Hámor (1966). The section was constructed after exploration wells and coal mine shafts, tunnels. J: Jurassic coal measures; P–T: Permian–Triassic; S.M.L.: South Mecsek line; Mi 1: Early Miocene; Mi 2: Middle Miocene; Pa: Pannonian, Late Miocene. A Pannonian syn-sedimentary extension and a post-Pannonian inversion, thrusting are seen on the section.

1988; Csontos and Bergerat, 1993), which contain striated fault planes. Practically, all show layer-parallel NNW-vergent thrusts, as well as layer-parallel E–W-directed left-lateral and right-lateral faults. All can be correlated to similar shears and stress fields in the neighbouring Mecsek Mountains, i.e. NE–SW compression, NNW–SSE-directed compression and NW–SE compression (nos. 10 and 11 in Fig. 7; Table 1). If these events are regarded as Tertiary, their timing could also correspond to those of the Mecsek events.

## 5. Tertiary deformation history

The Mecsek–Villány area, a part of the former European Tethyan margin, suffered a very complicated Tertiary tectonic history, dominated by transpression (Figs. 16 and 17). The Cretaceous structures were characterised by a major, south-tilted half-graben (Mecsek), folded (Benkovics et al., 1997), partly inverted and eroded during Cretaceous Alpine tectogenesis (Wein, 1967; Némedi-Varga, 1983). It was overthrust by the Villány nappe and the tectonic contact was sealed by Late Cretaceous (Fig. 16).

The first Cenozoic tectonic episode began in Late Paleogene, when a south-vergent (present direction) thrusting or transpression along the South Mecsek basal thrust put the Mecsek half-graben upon its southern foreland and created a small basin. Since Late Paleogene deposits are not exposed and generally lacking, the extent of this tectonic phase remains unknown and this event is known from seismic sections. However, the age of main thrusting–wrenching can be inferred from the sedimentary record. Thick terrestrial clastics appeared in the Early Miocene and were sourced from a mountain belt developed in the south. Analysis of the clastic material (Wéber, 1982; Barabás, 1995) indicates that large quantities of crystalline schists were eroded from a source area near the Görcsöny metamorphics. There is however a change in clastic material from granitic in the lowest Miocene to crystalline schist-dominated source in the Ottnangian. This suggests that, first, the Mecsek granite was thrust on Paleogene in the latest Paleogene–earliest Miocene, and then, in the Ottnangian, a more southerly thrust elevated the Görcsöny crystalline above erosion level. The huge amount of clastic material (and also some seismic sections) may indicate that the transpression, or shortening, possibly did not terminate after the first, Late Paleogene–earliest Miocene event, but continued during the Early Miocene (Fig. 16). Early Miocene depocenters in the northern Mecsek area were possibly created by, and subsequently deformed by, a very important wrench zone: the Northern Imbricates. Transpressional wrenching, seen on seismic lines, was left-lateral (Fig. 16; see also Tari, 1993) and possibly produced local block rotations. The whole Tisza Unit suffered major clockwise rotations during that time (Fig. 17A; Márton and Márton, 1999; Csontos et al., in press).

A similar tectonic pattern with probably reduced tectonic activity prevailed during the Late Karpatian–Middle Miocene. Smaller north–south convergence

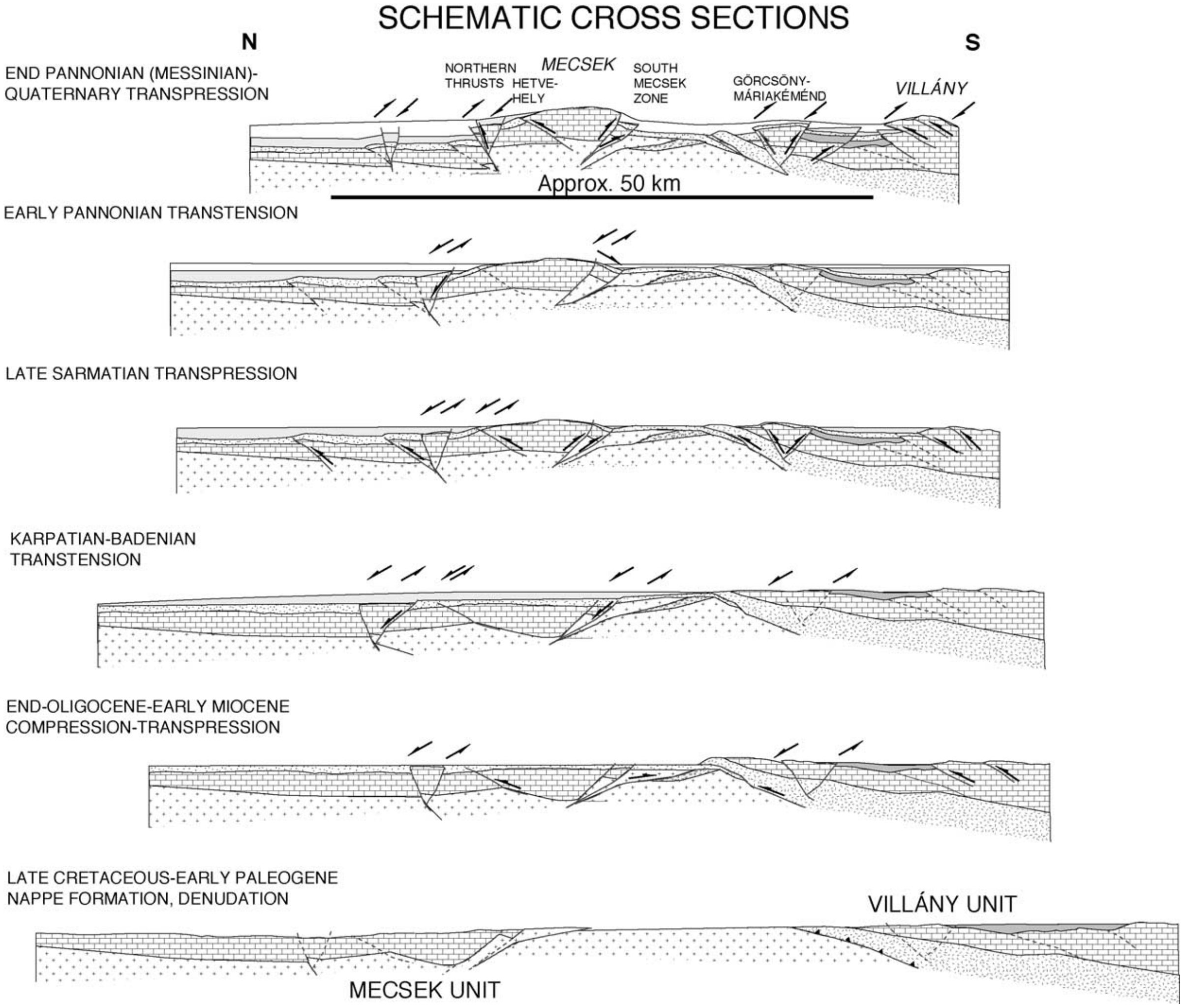


Fig. 16. Structural evolution of the Mecsek–Villány area. Schematic cross sections are roughly balanced sections for the main Tertiary deformation episodes (basic requirements are not met because of large strike-slip motions). Crosses: Mecsek basement. Small dots: Villány basement. Tiles: Mesozoic cover. Coarse dots: Paleogene. Light shading: Early Miocene. Grey shading: Middle Miocene. White: Late Miocene–Pliocene (Pannonian s.l.).

created strike-slip faults in the generally subsiding Mecsek area. Basin formation was possibly enhanced by the reactivation of earlier NNW–SSE transfer faults as normal faults.

Near the end of Sarmatian (Fig. 17B), a stronger deformation phase affected the area. This is indicated by folded and eroded beds north of the Mecsek Mountains and also by similar truncation north of the Villány Mountains (Figs. 4, 16 and 17B). There might be a Middle Miocene thrusting or folding near the Northern Imbricates or near the Hetvehely line as well. The intensity of this tectonic phase remains debated (Vadász, 1935; Hámor, 1966; Wein, 1967). Late Sarmatian inversion is widespread in SW Hungary and elsewhere in the Intra-Carpathian basin (Csontos, 1995; Csontos and Nagymarosy, 1998; Fodor et al., 1999).

The next important tectonic phase was a NW–SE transtension (Figs. 14 and 17C), which is evidenced mainly in the South Mecsek zone. This event is not

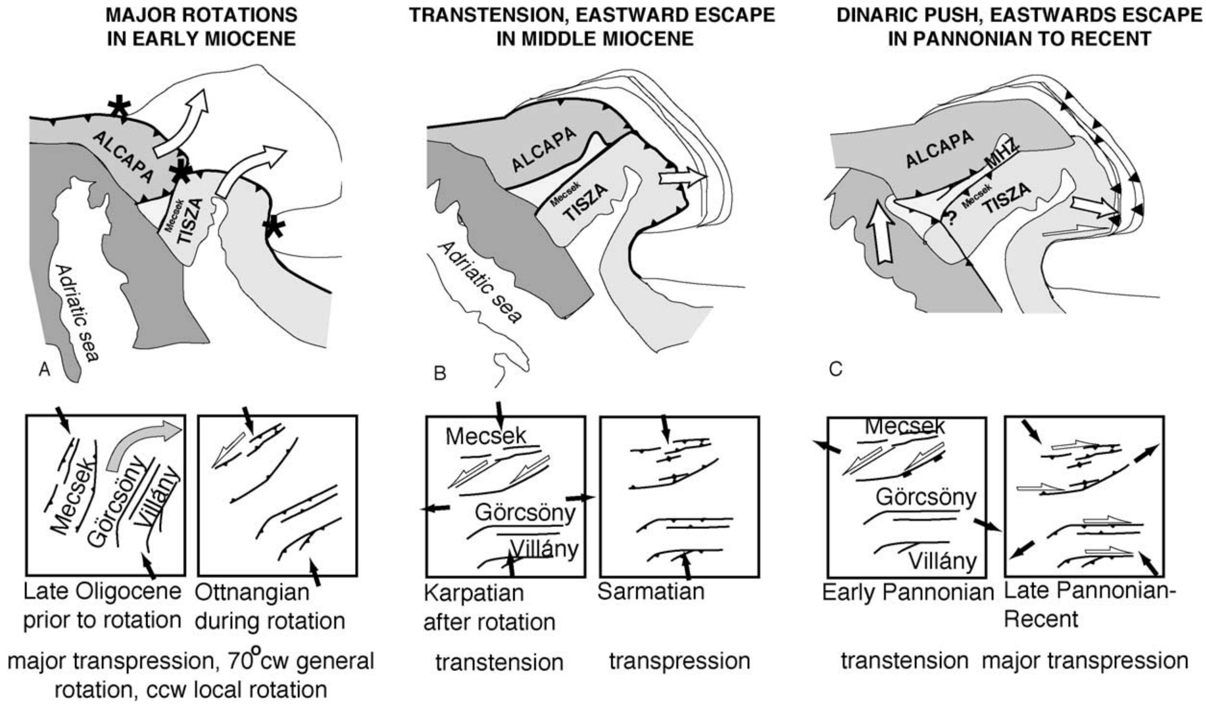


Fig. 17. Structural evolution of the study area in a Carpathian frame (partly after Csontos, 1995). A, B, C, indicate three major steps in the Tertiary evolution of SW Hungary. Stars in A indicate axes of rotation. White arrows on maps indicate major movements. Schematic figures in small boxes indicate structures of the Mecsek–Villány area active during the different deformation phases. Black arrows indicate inferred shortening and elongation directions. Grey arrow indicate rotation.

clearly seen on seismic lines, though small-offset young normal faults are evidently present. An Early Pannonian basin formed here (Figs. 15 and 16) along a NE–SW-oriented, possibly left-lateral wrench corridor. Early Pannonian NW–SE extension may be the consequence of a large scale ENE–WSW left-lateral transtensional wrenching, which is observed elsewhere in the Pannonian Basin, too (Fig. 17C; Csontos, 1995; Csontos and Nagymarosy, 1998; Fodor et al., 1999).

The last, and possibly one of the most important tectonic phase, started in Late Pannonian (ca. 7 Ma, Messinian crisis; Figs. 16 and 17C). Major inversion and uplift was controlled by NW–SE compression and perpendicular extension. The dominant deformational style was that of E–W-directed right-lateral transpressive wedges. In fact, the whole Mecsek Mountains comprised between the Northern Imbricates and the South Mecsek zone, as well as the Görcsöny–Máriakéménd ridge and the Villány Mountains can be interpreted as major pop-ups in this wrench system (Figs. 16 and 17C). Mesozoic sites in both mountain areas show slickensides parallel to those measured in Late Tertiary rocks. So we speculate that this late event caused widespread shear in the whole rock mass of the area. Differential movements along the major transpressive faults created or reactivated transfer faults perpendicular to the main trend (Fig. 17C). The Mecsek Mountains were folded along E–W structural zones and affected by uplift during this event. Structural arguments suggest that this transpressive tectonic phase is still active.

## 6. Conclusion

The inselbergs in the SW Hungarian part of the Pannonian basin show more similarities to the structural evolution of inselbergs in Croatia (Prelogovic et al., 1998; Tomljenović and Csontos, 2001), at the northern margin of the Dinarides, than to other parts of the basin (e.g. Csontos, 1995; Fodor et al., 1999). It is therefore believed that the tectonic events around the Adriatic have a deeper impact on this area, i.e. the driving forces for the complex Tertiary motions should come from the generally northerly progression of the Adriatic plate.

The outlined very complex Tertiary deformation history is a kind of warning for the quick interpretation of Tethyan margins around or inside the Alpine–Carpathian system. The Mecsek–Villány area is one of the best preserved segments of the north Tethyan margin inside the Alpine–Carpathian chain. However, this margin, when involved in the mountain system, could undergo very complicated structural evolution. Although Cretaceous tectonics is proven in the study area, the effects of Tertiary deformation could drastically modify the former structures. Therefore, study of younger deformation seems vital in understanding the older ones and is more effective, when several different methods of structural investigations are combined.

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