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Paleostress investigation and kinematic analysis along the Telegdi Roth Fault (Bakony Mountains, western Hungary)

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Abstract: The Telegdi Roth Fault, a major WNW–ESE fault in the Transdanubian Range, western Hungary is analysed. Fault striation data suggest that the fault and its neighbourhood experienced polyphase brittle deformation from the Senonian, mainly during the Tertiary. The first phase is an Albian–Cenomanian NW–SE thrusting, generating conjugate thrust faults. Then a major sinistral shear due to E–W maximum horizontal stress direction occurred. This main sinistral shear along the Telegdi Roth Fault appears to have occurred between the Senonian and the Early Eocene. This second tectonic event was followed by a dextral strike-slip movement along the fault, due to WNW–ESE maximum horizontal stress. This third movement probably took place from the Middle Eocene to Early Miocene (Eggenburian). Later (after a possible counterclockwise rotation of the Alcapa Unit in the Ottnangian) the deformation detected in the vicinity of the Telegdi Roth Fault was connected to a tensional phase which is characterized by a WSW–ENE minimal stress axis. This movement took place probably in the late Early and early Middle Miocene (Ottnangian to middle Badenian). Related structures are normal and sinistral faults which cut across the Telegdi Roth Fault. The last, fifth identified phase is marked by WNW–ESE minimal horizontal and NNE–SSW maximum horizontal stress directions. The suggested age interval for these deformations is late Middle and Late Miocene (late Badenian to Pannonian). The topographical expression of the main fault and neotectonic observations suggest a probable Quaternary reactivation as well.

Key words: Tertiary, Transdanubian Range, kinematic evolution, microstructural analysis, strike-slip fault, Telegdi Roth Fault.

Introduction

The aim of the paper is to study the Telegdi Roth Fault, one of the most prominent fault structures of western Hungary. This fault is located in the Bakony Mts (Transdanubian Range, Figs. 1, 2), in the Alcapa (Alpine-Carpathian-Pannonian) block of the Intra-Carpathian area. It was first described by Telegdi Roth (1934) and later named after him, as a roughly WNW–ESE directed fault, accomodating major right-lateral offset (Fig. 2). Mapping has shown that this is a fault which cuts the Bakony Mts into two parts and which cuts across Triassic to Oligocene, or even younger Miocene formations (e.g. Noszky 1957; Knauer & Végh 1967; Korpás 1969; Császár 1970; Knauer 1977; Gyalog & Császár 1982; Mészáros 1983; Kókay 1996).

The paper deals with a fault microstructural study in order to reveal the polyphase history of this important fault. During the work all potential outcrops were visited along a broader zone of the fault between Ugod and Várpalota (Fig. 2). Fault-slip and joint data were collected and numerically analysed. A Digital Elevation Model (DEM) of the sector (Fig. 3), as well as published geological maps were analysed. Finally we also confronted our data with the conclusions of relevant earlier publications.

Structural features of the Telegdi Roth Fault and its neighbourhood

On a regional scale, the Telegdi Roth Fault represents an important, approximately hundred km long right-lateral fault with WNW–ESE strike (Fig. 2). There are other faults, however, which cut and offset the main fault. These will be listed as different fault trends.

Fault trend 'A': The Telegdi Roth Fault

A main WNW–ESE system of strike-slip faults is present throughout the Bakony Mts (Figs. 2 and 3) which was already observed by Telegdi Roth (1934). The main fault shows a total of 4.7 km dextral separation (e.g. Noszky 1957; Knauer & Végh 1967; Korpás 1969; Császár 1970; Knauer 1977; Gyalog & Császár 1982; Mészáros 1983; Kókay 1996). It seems to curve near its western termination (Figs. 2 and 3). Two alternative models are brought up. Either it turns south near Tevelvár–Pápavár–Hideghegy–Hajszabarna (TPHH on Fig. 2), and limits an elevated block of Triassic against Eocene and Egerian formations (Korpás 1981), or it turns north and forms a horsetail structure east of Ugod. Individual splays also limit the Egerian basin remnants there. In the former case the

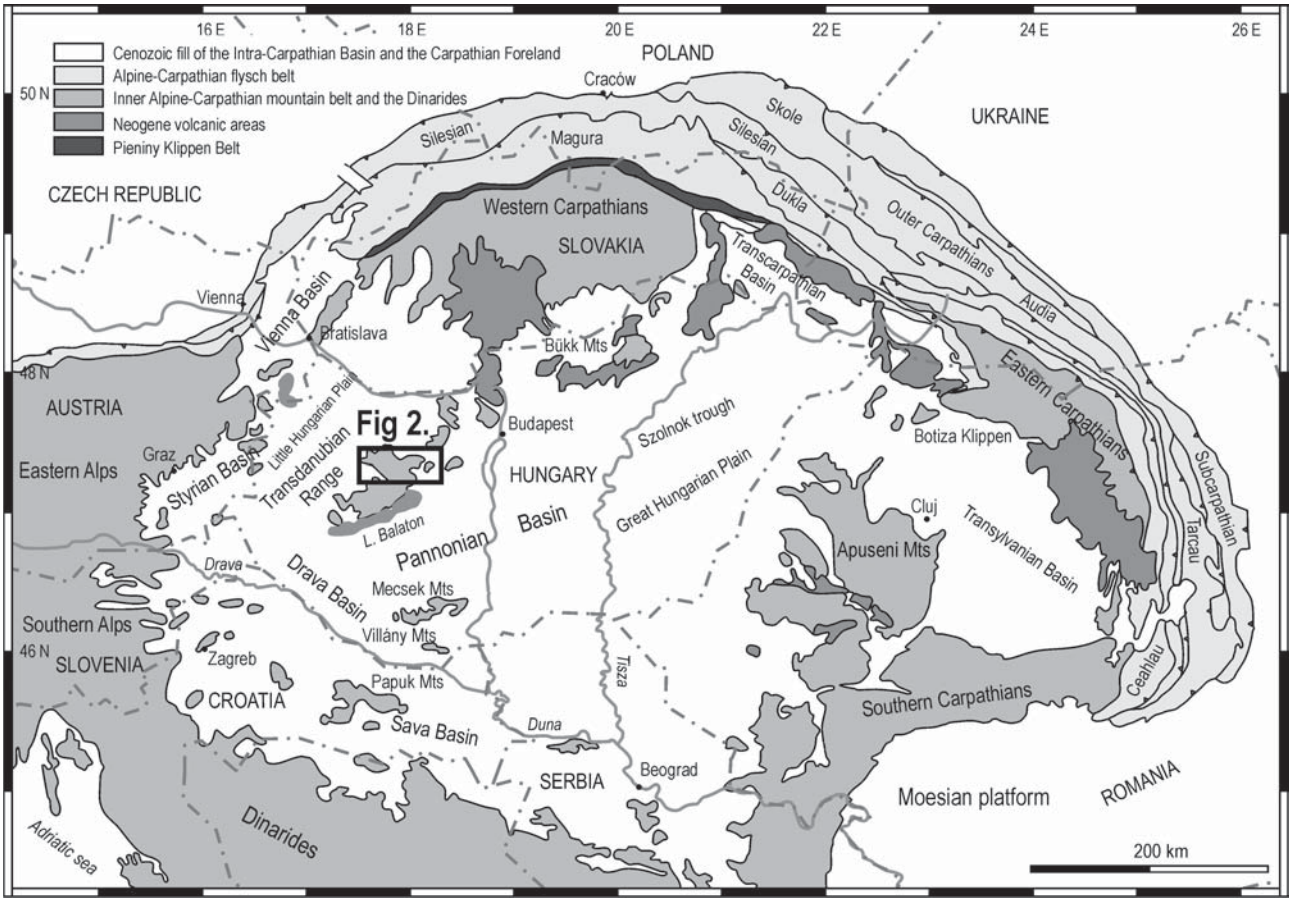

Fig. 1. Location of the studied area.

curved portions should operate as thrusts, in the latter case the faults splays should act as normal faults during the main dextral movement. It is interesting to note that on the maps of Noszky (1957) and Gyalog & Császár (1982) the western part of the fault limiting the TPHH block (Fig. 2) from the east is suggested as normal.

The main fault also gently curves at the eastern end near Várpalota, where its compressive character was demonstrated as a repetition of Miocene coal layers (Kókay 1968). The Telegdi Roth Fault can be followed as a sharp line on the Digital Elevation Model (Fig. 3). In one exposure (site 3 by the Eperkés Hill on Fig. 2) we found loess directly in tectonic contact with the Albian limestone. The loess showed several faults, not parallel but oblique to the Telegdi Roth Fault.

Fault trend 'B'

There are roughly N–S striking parallel faults east of Zirc (Figs. 2 and 3) which cut the Telegdi Roth Fault. On the DEM — see also Knauer & Végh (1967), Knauer (1977) or Gyalog & Császár (1982) — they show a clearly visible dextral offset. These faults regularly border the Egerian fluviatile deposits. The Egerian is a widespread formation (Korpás 1981), which covered the whole Transdanubian Range, so the little grabens marked by this N–S striking fault were possibly born after its deposition.

Fault trend 'C'

In some places, especially south of Zirc town, the Telegdi Roth Fault may be sinistrally offset by NW–SE striking faults (Fig. 2). Some other faults with similar orientation are well expressed in topography (Rózsa et al. 1997).

Fault measurements and analysis

Observations

During fault measurement we concentrated on outcrops along the immediate vicinity of the Telegdi Roth Fault. Mainly the Mesozoic rocks form outcrops here; the Neogene (Miocene) rocks, very important for dating, were exposed only near Várpalota-Bántapuszta (site 2 on Fig. 2). Since these Tertiary outcrops were very few, we added another Tertiary site — near Csesznek — which was somewhat more distant.

We made important observations at three outcrops. First in the Bántapuszta Basin (site 2 on Fig. 2) the Ottnangian–Karpatian gentle unconformity (Kókay 1991) was cut and

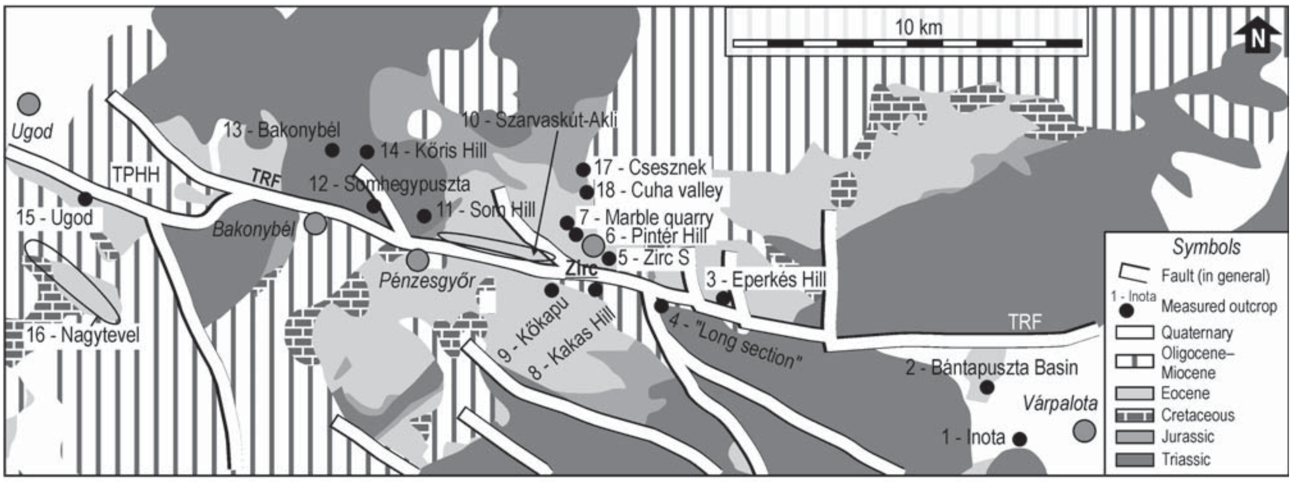

Fig. 2. Schematic geological map of the Bakony Mts with the measured outcrops, after Gyalog & Császár (1982). TPHH — Tevelvár–Pápavár–Hideghegy–Hajszabarna Hills; TRF — Telegdi Roth Fault.

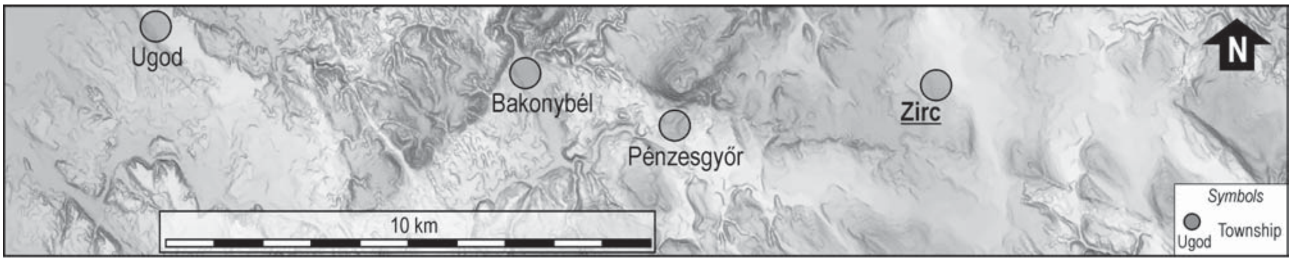

Fig. 3. Digital Elevation Model (DEM) in the vicinity of the Telegdi Roth Fault with the major townships.

dextrally offset by about 200 m. This shear zone is directly adjacent and roots in the Telegdi Roth Fault. Quarries in the same rocks yielded some strike-slip fault planes and many joints parallel to the main fault. Adjacent abandoned Middle Miocene (Badenian) coal mines also testified important lateral and thrust displacements, affecting even the Early and the Middle Miocene formations (Kókay 1968).

On the second location — an elongated area not far from Somhegypuszta (site 12 on Fig. 2), practically lying on the Telegdi Roth Fault — a chaotic mixture of rocks from the Upper Triassic to the Eocene was found. This mixture was interpreted as a fault megabreccia.

In the third important outcrop, in a quarry of Upper Triassic limestone east of Ugod (site 15 on Fig. 2), both left- and right-lateral slips (Sasvári 2003) parallel to the main fault were recorded. Dominance of the left-lateral slip contradicts all previous works and the map view and hence needs an explanation.

Analysis

In the visited outcrops all detected faults were measured. Attention was focused on planes with slickenslides, where the sense of shear and eventual superposition of striae were also noted. Unfortunately, these surfaces are relatively rare, that is why joints were also measured. In all more than 300 fault planes were measured, of which 122 carried information — slickenslides — about the direction of motion.

After application of analytical methods (mainly Angelier 1984 and the P-T method after Turner 1953) on the fault measurements, 6 stress fields were defined. As a first approach, an outcrop-by-outcrop numerical processing of fault-slip data was tried (Angelier 1984), but this failed because of lack of sufficient data. Grouping the data by age of the lithology was also meaningless (with some rare exceptions), because either the rocks giving well-constrained data were too old (Mesozoic), or data in a particular age group were too few. Finally we considered the data collected along the fault as a single data set and we processed this set by fault-slip analysis.

This data set needed separation, which was done by three methods. A full automatic separation was applied, but this gave only rough results. However, the defined 6 stress fields were practically identical to those defined with the other method. The separation process was also done in a semi-manual way by either visual analysis, or by application of the P-T method (Turner 1953). The first method chooses a fault set which might apparently work together in a Mohr or Riedel system. The latter method calculates ideal shortening and extension axes on all individual fault planes with striae, and plots them on a stereoplot. The grouping of the 'Pressure' and 'Tension' axes defines the axes of the stress field, in which the faults were capable of sliping. These faults were then entered in the Angelier software (Angelier 1984) and the stress fields were recalculated, the fit of the faults was checked. The stress axes given by the automatic separation were slightly modified by the semi-manual method. This method also gave 6 stress fields, which are different from each other within the given misfit angle which is defined by the angular difference between the measured and the calculated, 'ideal' motion on the fault plane. The misfit angle serves to check the fit of a given single fault to the stress field; its maximum value was defined as 20°.

Fault analysis results

In the following the separated 6 stress fields are described (Fig. 4). Stress field '1' is defined by relatively few faults which are characterized by NW–SE compression generating flat thrusts ($\sigma_1=313/4$; $\sigma_2=43/5$; $\sigma_3=181/83$; stress ratio: 0.43). The software could fit a left-lateral fault and a steep dip-slip reverse fault, too. We speculate, however, that the single strike-slip fault (dotted on Fig. 4) could be grouped rather to set '3' (see later), because of parallelism of faults, while the steep surface could be grouped to stress field '4'. These operations were rejected by the Angelier (1984) software (within the given relatively tight misfit angle). We still think, however, that pure compression should be separated from the strike-slip dominated stress state. Considering all faults allowed by the software to act in stress field '1' the youngest measured formation was of Ottnangian age (site 2 on Fig. 2). If we separate the steep strike-slip and oblique-slip faults from the thrust faults, the youngest formation carrying thrust faults is of Albian age (site 3 on Fig. 2). We accepted the latter solution.

The group of faults '2' ($\sigma_1=81/16$; $\sigma_2=237/72$; $\sigma_3=349/7$; stress ratio: 0.25; Fig. 4) contains mainly left-lateral slips parallel and acute to the Telegdi Roth Fault and a single conjugate right-lateral fault. The strike-slip type stress field is characterized by a roughly E–W compression and a N–S tension. Beside the strike-slip faults, two thrusts and a normal fault can act in this stress field. The youngest formation carrying these faults is of Senonian age (site 16 on Fig. 2).

The group of faults '3' can be generated by a WNW–ESE compression and perpendicular horizontal tension ($\sigma_1=291/21$; $\sigma_2=132/67$; $\sigma_3=24/8$; stress ratio: 0.80; Fig. 4). The principal axes are subhorizontal and subvertical. The main faults are N–S striking left-lateral and (W)SW–(E)NE striking right-lateral faults. Some of the latter faults are parallel to the Telegdi Roth Fault, so this stress field should be responsible for the main right-lateral offset along the fault. The number of measured right-lateral striae seems to be fewer than the left-laterals. A great number of strike-slip faults without a defined character of movement were measured at the Kőkapu exposure (site 9 on Fig. 2) which has a parallel orientation to the main trend of the Telegdi Roth Fault. If we suppose that these striae have a right-lateral character, the amount of left-lateral striae is exceeded by the right-laterals. The principal axes of stress field differ slightly from the second one, but this difference is large enough to create opposite movements along the main Telegdi Roth Fault. The youngest measured formation carrying these faults was an Ottnangian sediment (site 2 on Fig. 2).

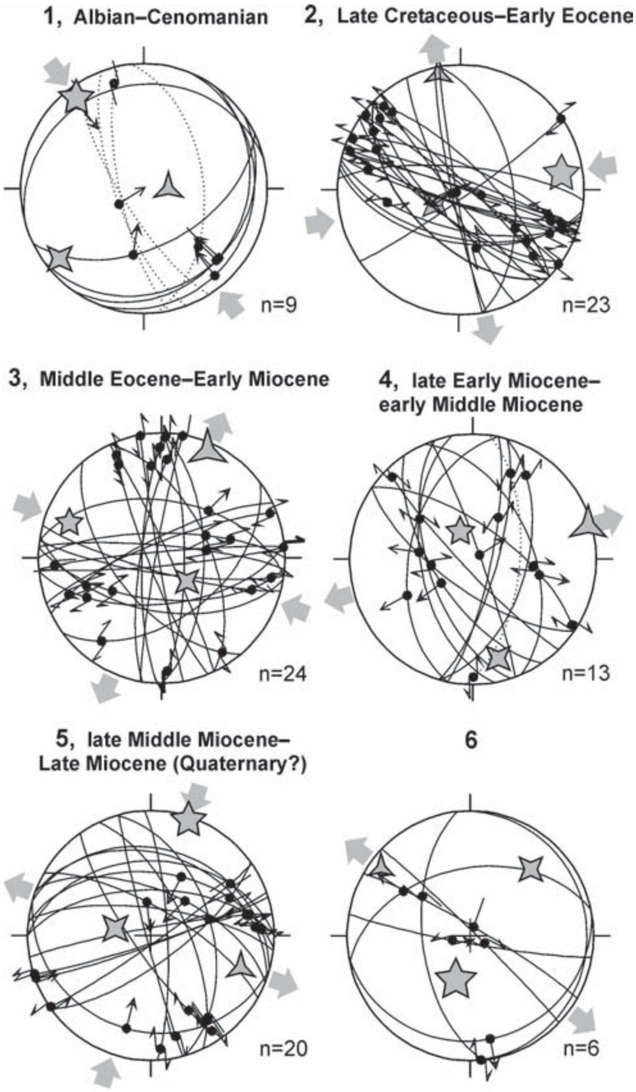

Fig. 4. Stereograms of tectonic phases (1–6) with fault planes, slickenslides and calculated stress fields on Schmidt net, lower hemisphere. $\boldsymbol{\sigma_1}$ — star; $\boldsymbol{\sigma_2}$ — diamond; $\boldsymbol{\sigma_3}$ — triangle.

The fault group '4' can be related to a roughly WSW–ENE tensional stress field ($\sigma_1=335/70$; $\sigma_2=165/20$; $\sigma_3=74/3$; stress ratio: 0.73; Fig. 4). The minimal stress axis is subhorizontal. Some NNE–SSW trending left-lateral and NW–SE trending right-lateral strike-slip faults also occur in the group. The youngest formation carrying these faults was of Senonian age (site 16 on Fig. 2).

The group of faults '5' was generated by a NNE–SSW compression and a WNW–ESE extension ($\sigma_1=18/3$; $\sigma_2=281/66$; $\sigma_3=110/24$; stress ratio: 0.72; Fig. 4). The fault set is dominated by conjugate strike-slip faults. Some rather steep reverse faults also occur in the stress field. The principal stress axes σ_1 and σ_3 are gently tilted from the ideal horizontal–vertical. The youngest formation carrying these faults was an Eocene limestone in the northern part of Bakonybél (site 13 on Fig. 2).

The last fault group '6' is also composed of few faults (Fig. 4). It is characterized by NW–SE subhorizontal extension. This stress field is highly similar to stress field '5', but the Angelier (1984) software does not allow the faults to fit in the strike-slip type stress field. With the exception of a couple of faults, this stress field contains steep faults with steep striae, which are most probably rejuvenated surfaces. That is why we do not consider the fault group '6' to be well-constrained.

All the stress fields described above had principal stresses very close to horizontal and vertical, so a visual analysis and grouping of joints could be made. Most of the joints were very steep and parallel to adjoining fault planes.

Relative dating of the fault sets

Superposition of striae was detected in three cases. In the case of a fault belonging to stress field '3' its striation is superposed by the slip working in stress field '4', therefore the latter is younger (Fig. 5A).

In another case, superposing striae were assigned by the software to the same '5' stress field. We attempted to assign the strike-slip motion to the stress field '4', but because of the narrow interval of the allowed misfit angle, this was unsuccessful. However, visual analysis could suggest that the strike-slip motion could better fit in stress field '4', therefore we do not accept the calculation of the software. According to visual analysis, stress field '5' is younger than '4' (Fig. 5B).

After the numerical analysis one of the superposed striae was found in the rejected fault group (trash). The superposing fault can, however, be assigned to the stress field '4' (not allowed by the software, but following the logic of fault mechanics). After that operation we can state that stress field '5' is younger than '4' (Fig. 5C).

An exposure more distant from the main Telegdi Roth Fault may help in relative dating. Slickenslides were measured in an outcrop near Noszlop (South Bakony Mts, not indicated on Fig. 2). The Egerian age of the deformed rock is the most relevant for dating of phase '3' (Fig. 6, taken from Kiss & Fodor 2003). Very nice conjugate sets of strike-slip faults parallel and antithetic to the Telegdi Roth Fault were observed in Egerian fluviatile beds. This means that phase '3' is synchronous or younger than Egerian.

DEM analysis

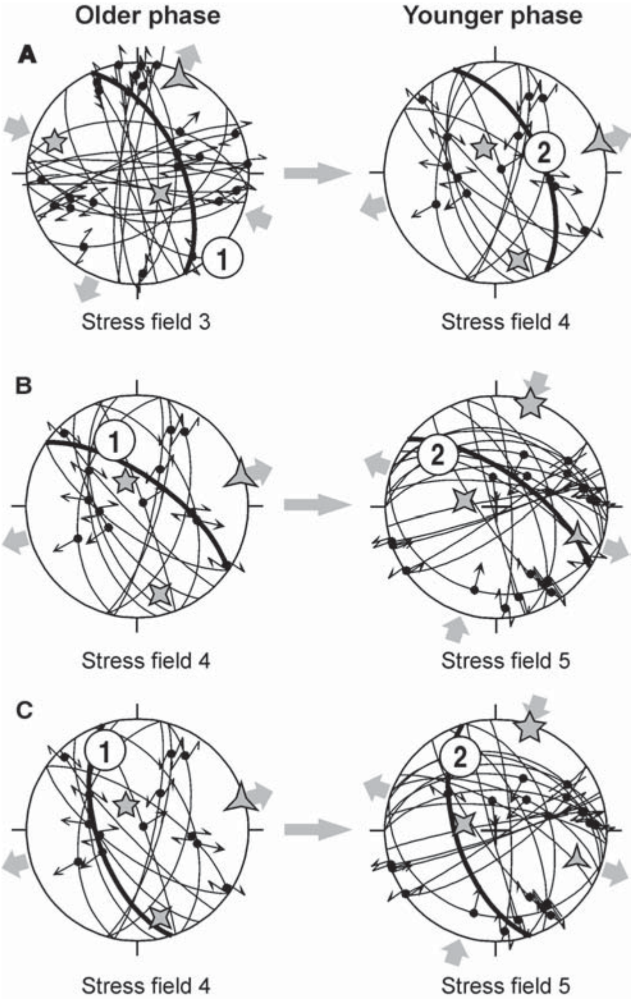

Fig. 5. Relative dating of the stress field generations; the slickenslides on main fault plane marked with bold. Same legend as for Fig. 4.

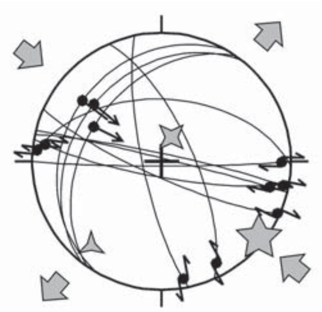

Fig. 6. Stereogram for the slickenslides observed near Noszlop, measured in the Egerian fluviatile beds indicated the phase '3'. After Kiss & Fodor (2003).

A detail of the DEM (Fig. 7) shows the main fault trend 'A' of the Telegdi Roth Fault, which could function successively under stress fields '2' and '3' (compare to stereoplots of the same figure). As previously stated, the little grabens bounded by the fault group 'B' can be formed in stress field '4' (or probably in phase '5'), later than the main right-lateral offset during phase '3'. The DEM also suggests the left-lateral offset of the main fault between Zirc and Akli (Fig. 2) by faults of the trend 'C'. These faults can be observed north of Veszprém.

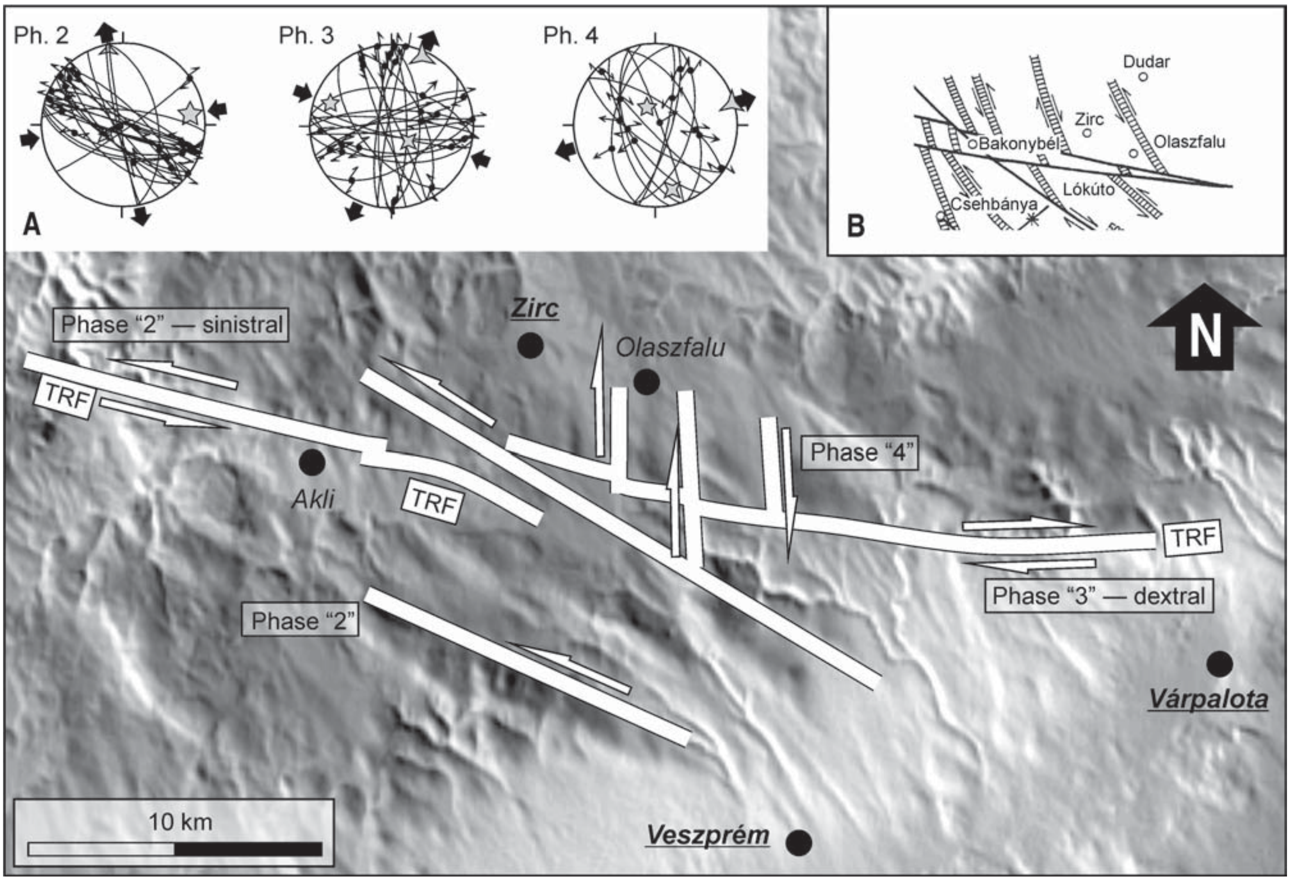

Fig. 7. Blow-up of the Digital Elevation Model and the major faults in the area of the Telegdi Roth Fault. Insert **A** — stereoplots of phases '2', '3', '4'; Insert **B** — structural sketch of Mészáros (1983).

Conclusions on the dating of stress fields

Pure NW–SE compression was recorded in Aptian sediments (stress field '1', see Fig. 4). This phase was probably taking place either in the Albian, or in the Cenomanian (see also Tari 1995; Kiss 1999; Albert 2000; Budai et al. 2005; Fig. 8). The main thrust movements and related folding in the Transdanubian Range must have taken place before the Senonian, because these sediments are unconformably overlying older formations and their position is subhorizontal (e.g. Haas et al. 1984; Tari 1994).

Phase '2' was only recorded in the Senonian formations, so it may be younger than these sediments, probably Paleogene. This is also suggested by the lack of similar slip traces in Eocene or younger formations. This strike-slip type stress field created left-lateral offsets along the Telegdi Roth Fault (Sasvári 2003). The proposed age of this striae-generation is from Late Cretaceous to Early Eocene (Bada 1999; Bíró 2003; Fig. 8).

A similar, clearly strike-slip type stress field ('3') with observed traces in Eocene and Ottnangian sediments was responsible for the right-lateral motion of the Telegdi Roth Fault. This stress field was active from the Middle Eocene to the Early Miocene (Eggenburgian–Ottnangian; Bada 1994, 1999; Fodor et al. 1994; Bada et al. 1996; Fodor et al. 1999; Kiss 1999; Bíró 2003; Márton & Fodor 2003; Budai et al. 2005; Fig. 8).

Kun Jáger et al. (1994) studied the Iharkút conglomerate, a peculiar coarse clastic formation of Late Eocene to Early Oligocene age (Korpás 1981; Kun Jáger et al. 1994). They stated that the clasts were derived from local material, the sedimentary transport directions were towards the south and the conglomerate occurred only south of the Telegdi Roth Fault, even at places where the Eocene is preserved north of the fault. All this suggests that the Telegdi Roth Fault was already active in the Late Eocene–Early Oligocene and created paleotopographic changes during its activity. We propose that this activity could be the right-lateral motion. This conclusion was also supported by Magyari (pers. com.) and by Sztanó (pers. com.).

This phase might gradually change to the extensional phase '4', probably during the late Early and the early Middle Miocene (Ottnangian to Badenian age, Fodor et al. 1994; Bada 1999; Kiss 1999; Kiss et al. 2001; Bíró 2003; Márton & Fodor 2003; Budai et al. 2005; Fig. 8). The chronological order of these phases was established on superimposed fault-slips (Fig. 5A). In the absence of younger sediments the activity of these phases is only inferred from the general trend of stress field evolution of the Pannonian Basin (Csontos et al. 1991; Fodor et al. 1999).

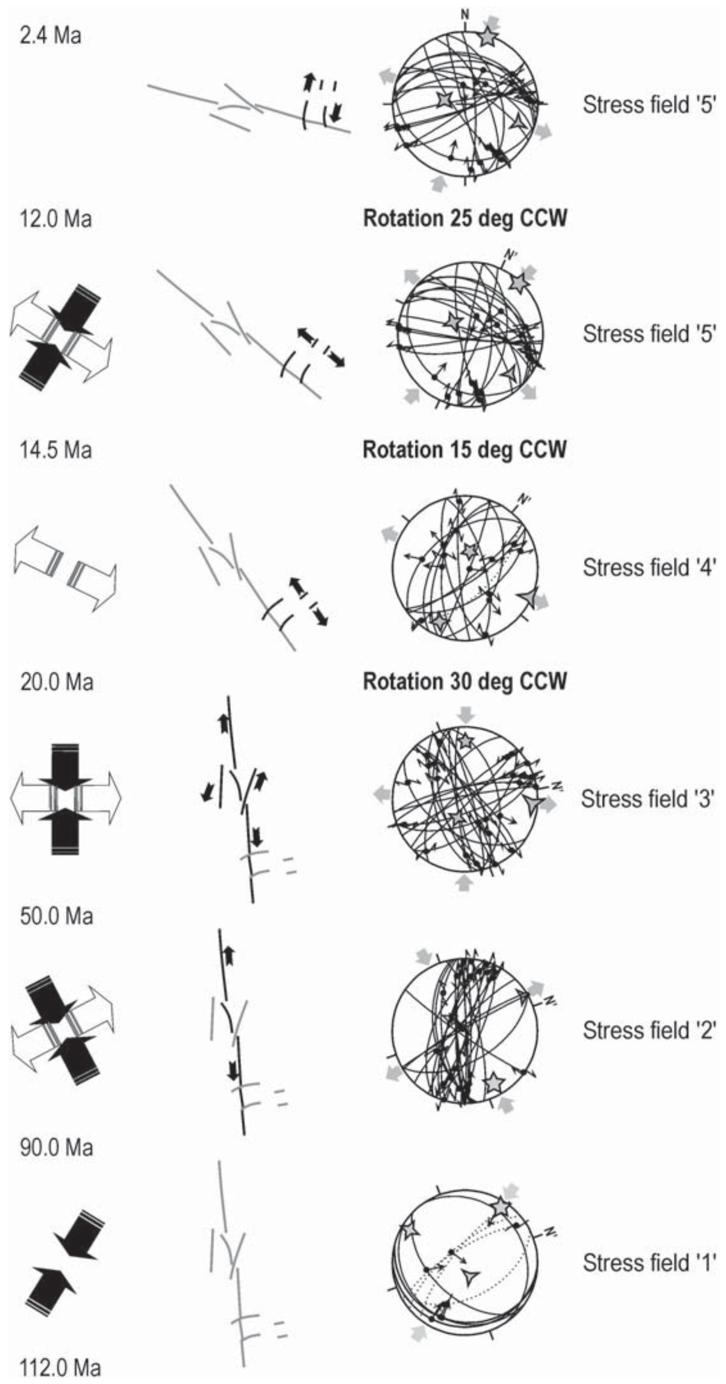

Fig. 8. Proposed stress field and structural evolution of the palinspastic Telegdi Roth Fault and its neighbourhood, with rotations taken from Márton & Fodor (2003). 'N' shows present-day north direction. Thick lines indicate the active faults.

Probably, the last stage of the tectonic evolution is phase '5', which is a combined strike-slip and extensional event. A Middle to Late Miocene time (late Badenian to Pannonian) is proposed for the activity of this stress field (Palotás 1991; Bada et al. 1996; Bada 1999; Kiss et al. 2001; Fig. 8). The thrust of older formations onto the Badenian coal (e.g. Kókay 1996) might be also caused by this stress field. After unpublished observations of Kókay (pers. com.) the Quaternary–recent activity can also be supposed. Phase '5' would agree with observations on the recent stress field (e.g. Gerner 1994; Gerner et al. 1999; Windhoffer et al. 2001; 2005).

Comparison with the earlier results

In this chapter our data and interpretations are compared to earlier works by Mészáros (1983), Fodor et al. (1999), Kiss et al. (2001) and Márton & Fodor (2003). The map of Mészáros (1983) (Fig. 7B) was based on long field mapping and mining experience. However, many of the faults on his map are seen neither on earlier, nor later maps (Noszky 1957; Knauer & Végh 1967; Korpás 1969; Császár 1970; Knauer 1977; Gyalog & Császár 1982), nor on the Digital Elevation Model (Fig. 7A). On the contrary, some faults which are qualified as right-lateral on his map, appear to be left-lateral or normal after the map and DEM analysis. This is the case with the WNW–ESE trending fault south of Zirc, which is left-lateral or normal, instead of the right-lateral offset proposed by Mészáros. Additionally, the main Telegdi Roth Fault seems to diverge on his map southeast of Olaszfalu (Fig. 7B). This divergence is not really seen on any geological maps. Of the roughly N–S striking parallel faults east of Olaszfalu (Fig. 7A) only one is shown by Mészáros (1983) with sinistral movement (Fig. 7B), differing from its clearly visible dextral nature on the map and the DEM. According to Mészáros (1983) this fault generation is cross-cut by the Telegdi Roth Fault, which contradicts the analysis of the fault slip data as well as that of the DEM and other geological maps (Gyalog & Császár 1982). The E–W striking dextral fault east of Akli (Fig. 7A) which is clearly visible on the DEM and detectable on the geological map, does not appear in Mészáros's (1983) work (Fig. 7B).

Following Mészáros (1983), Tari (1991) suggested that the Transdanubian Range is cut up by a series of WNW–ESE to NNW–SSE striking right-lateral faults. In his model the WNW–ESE striking first generation is followed by NW–SE, then NNW–SSE strike-slip faults (see Fig. 7B). Some older NW–SE faults were supposed to be as old as middle Cretaceous (Mészáros 1983), but the bulk of the subsequent right-lateral shears were supposed to be Middle Miocene (Sarmatian). We do not think that the bulk of deformation was so late — in contrast, according to the proposed fault chronology (Fig. 4), we suggest that the main movements were earlier, probably in the Middle Eocene to Early Miocene (Eggenburgian); we propose that the older faults could have been reactivated in the Middle Miocene (Sarmatian), or later.

Fodor et al. (1999) show a mainly compressional stress state with (W)NW–(E)SE shortening directions from the Early Eocene to the Early Miocene (Ottnangian) valid for the Bakony Mts. The presented stress properties are in good agreement with the observed stress field '3'. For the late Early and early Middle Miocene (Karpatian–Badenian) Fodor et al. (1999) present a stress field similar to the former one, but characterized by strike-slip faulting. This is in good agreement with our stress field '4'. Following that, an extensional phase with NW–SE minimal horizontal stress axis for the Transdanubian Range is presented by Fodor et al. (1999). Conjugate normal microfaults with NE–SW strike belong to this phase in the late Badenian to the Pannonian (from the late Middle Miocene to the Late Miocene) interval. This could correspond to our phase '5'. The latest Miocene to Quaternary stress field can be characterized by WNW–ESE minimal horizontal stress axis in the Bakony Mts (Fodor et al. 1999). The main microstructures are NNW–SSE striking normal faults and strike-slip faults. We could not demonstrate this deformational stage, but normal faults of the stress field '5' can be reactivated at that time.

Kiss et al. (2001) dealt with striae sets in the northern part of the Bakony Mts. Their work was concentrated on the area around Csesznek, where a complex strike-slip corridor is visible. This corridor, parallel to the Telegdi Roth Fault, is also dextral and affects Eocene to Egerian beds. The first stress field described by Kiss et al. (2001) is a compressional one with NW–SE shortening and perpendicular extension directions. Their proposed middle Cretaceous age is in agreement with our observations and dating. The authors also present two other stages of the structural evolution in the studied area: the second stage acting from the Early to the Middle Miocene (Ottnangian to Sarmatian) is characterized by a NNW–SSE shortening direction (Kiss et al. 2001). The third tectonic phase of Late Miocene (Pannonian) age is a pure (W)NW–(E)SE tension (Kiss et al. 2001). It is to be noted that their second deformation is very similar to our phase '4', and the third to our phase '5'; but our stress fields show tensional and strike-slip properties, respectively.

Márton & Fodor (2003) compared the structural results to the paleomagnectic rotations of the Transdanubian Range showing 4 (or even 5) stages of the structural evolution. The first described stress field characterized by NW–SE compression and perpendicular tension could have acted from the Middle or Late Eocene to the earliest Miocene (Ottnangian) which is in good agreement with our stress field '3'. The second tensional and third strike-slip stress field can be characterized by NE–SW tension and NNW–SSE compression (Márton & Fodor 2003) which acted from the late Early to early Middle and the late Middle Miocene, respectively. Our stress field '4' could be a combination of these.

Márton & Fodor (2003) also proposed two extensional faulting events marked by approximately E–W and ESE–WNW tension for the Late Miocene–Quaternary period, respectively. Our stress field '5' could be equivalent to a combination of these. The main idea of Márton & Fodor (2003) was to link this stress-field evolution and their observed apparent rotation of the principal stress field directions to the measured paleomagnetic rotations. In their model 'A' they propose a first 30° counterclockwise rotation in the Early Miocene (Ottnangian) followed by a second 15° counterclockwise rotation in the Middle Miocene (Badenian). Finally a last 25° counterclockwise rotation is proposed in the Pliocene. Model 'B' of Márton & Fodor (2003) differs from the first one by suggesting that the time of first rotation was the Late Eocene instead of Early Miocene. If these rotations are reconstructed, the principal stress directions remain constant (N–S compression) for most of the Tertiary and the external stress field changes direction only in the Late Miocene (Márton & Fodor 2003, their Fig. 10).

We have also observed a change in the apparent principal stress directions from phases '2' to '5'. This observation can also be explained by the rotation models briefly discussed above (Fig. 8). The angular difference between our stress fields '2' and '3' equals about 30°, which is identical to the first rotation of Márton & Fodor (2003). We proposed that '2' acted prior to Late Eocene and '3' acted in the Late Eocene–Ottnangian. Therefore the rotational model 'B' would perfectly explain the difference between these stress fields. Similarly, there is about 30° difference between our stress fields '3' and '4', which might be explained by the rotational model 'A'. Naturally both cannot be applied, but according to our data we cannot discriminate between rotational models of Márton & Fodor (2003). Finally, the angular difference between our stress fields '4' and '5' equal about 15°, which is identical to the second rotation of Márton & Fodor (2003). It seems that the last, Pliocene rotation does not appear in our data set. However, because of the robust paleomagnetic data presented in the cited work, we applied this last rotation to our data set (Fig. 8).

Regional framework

The northern part of the Pannonian Basin, named Alcapa, suffered extrusion from the Alpine sector (e.g. Balla 1984; Kázmér & Kovács 1985; Balla & Dudko 1989; Ratschbacher et al. 1991; Fodor et al. 1999; Sperner et al. 2002). Extrusion can be separated into a phase of major right-lateral shear along the Periadriatic fault (and its continuation, the Balaton fault) in the Late Eocene to the Oligocene–earliest Miocene (Eggenburgian); followed by a 90–60° counterclockwise rotation, extension in W–E and compression in N–S directions in the Early Miocene (Kázmér & Kovács 1985; Balla & Dudko 1989; Csontos 1995; Márton & Fodor 1995; Fodor et al. 1994; Fodor et al. 1999; Csontos & Vörös 2004). During this later phase the right-lateral shear component along the southern periphery of Alcapa still prevailed. Rotation placed Alcapa into the Carpathian embayment, where it was possibly pulled eastwards by the subducting European slab (Horváth & Royden 1988; Csontos 1995). This centripetal pull created a complex back-arc type basin. The initiation (rifting) of the individual little basins happened in the late Early Miocene and their merging into a big back-arc basin took place in the Middle Miocene (Fodor et al. 1999). During the Late Miocene the gentle but very effective thermal subsidence (Horváth & Royden 1988) was interrupted by smaller transtensional and transpressional, eventually rotation events (Csontos 1995; Horváth 1995; Fodor et al. 1999).

Conclusions

The brittle fault data measured around the Telegdi Roth Fault, a major, map-scale fault in the Transdanubian Range enabled us to differentiate 5 tectonic events, all characterized by different fault sets and related stress fields presented with their retro-rotated stress directions.

The first, compressional tectonic event (stress field '1' on Figs. 4 and 8) NE–SW pure compression generating flat thrusts. This tectonic phase fits well into the Aptian–Albian tectonic evolution of the Alcapa block (Tari 1995). The second tectonic phase (stress field '2' on Figs. 4 and 8) with NW–SE compression and perpendicular extension direction was responsible for the sinistral shear along the Telegdi Roth Fault; the supposed age of this tectonic phase is Late Cretaceous–Early Eocene. The main dextral movement of the fault is generated by the third tectonic event (stress field '3' on Figs. 4 and 8) characterized by N–S compression and E–W extension direction. This tectonic phase could have been active from the Middle Eocene to the Early Miocene (Ottnangian). Divergence of the stress axes in the Albian–Early Miocene (Ottnangian) period should be considered normal because of the major age gap. However, the 30° angular difference between stress fields '2' and '3' could be induced by a 30° CCW rotation of Alcapa in the Late Eocene, postulated by Márton & Fodor (2003, their model 'B'). If the general behaviour of Alcapa is taken into account (Balla 1984; Márton & Fodor 1995; Csontos & Vörös 2004) it is more probable that a major rotation occurred in the Early Miocene (Model 'A' of Márton & Fodor 2003). Therefore we rather suggest that a 30° change of the external stress field took place in the early Paleogene and this change controlled the left and right lateral slips along the Telegdi Roth Fault.

The next differentiated stress field of our study is '4', characterized by ENE–WSW extension (stress field '4' on Figs. 4 and 8). This tectonic phase created the roughly N–S striking parallel faults east of Zirc (Figs. 2 and 3) which cut the Telegdi Roth Fault. The apparent 30° angular difference between the phases '3' and '4' can be perfectly explained by the 30° counterclockwise rotation (model 'A') of the Transdanubian Range proposed by Márton & Fodor (2003) for the Early Miocene (Ottnangian). Since this is the age when most major rotations took place in the Intra-Carpathian area (op. cit.) we think this model is valid for our area as well. The late Middle Miocene–Late Miocene period is marked by a strike-slip stress field with NNE–SSW compression directions (stress field '5' on Figs. 4 and 8). Between the early Middle and the late Middle Miocene (Badenian) — in good accordance with the model of Márton & Fodor (2003) — we can also suppose a 15° counterclockwise rotation.

The character of the stress field changed from pure tensional to transtensional (Figs. 4, 8). The overthrusts observed in the Badenian coal may be generated by an even younger, Quaternary stress regime. The Pliocene 25° counterclockwise rotation of the stress directions presented by Márton & Fodor (2003) cannot be observed in our study area because of lack of data.

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