

Late Miocene-Pliocene Shortening, Uplift and Wrench Tectonics Dominated Canyon Development along the Mid-Hungarian Mobile Belt*

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Introduction, Geologic Framework

The Pannonian Basin (Central Europe) is underlain by an orogenic collage which is built by several tectonostratigraphic terrains. The boundary of the two main terrains, the northwestern ALCAPA and the southeastern TISZA, is the Mid-Hungarian Mobile Belt (MHMB). It is the most significant neotectonic zone of the Pannonian Basin. Structural analysis was carried out on historical industry seismic sections across and along the Mid-Hungarian Mobile Belt, between the Danube and the Tisza rivers ([Figure 1](#)).

The structural analysis focusing on the upper Miocene and younger sediments was supported by sequence stratigraphic analysis. Interpretation of seismic and well log data on workstation facilitated kinematic evaluation and mapping of late Miocene-Pliocene structural elements. The aim of the paper is to evaluate the connection between late Miocene-Quaternary tectonic evolution of MHMB and canyon incision on the southern margin of the MHMB.

Late Miocene Shortening, Uplift, and Wrenching

Change of the sense of faulting is hard to determine. The structure of upper Miocene Pliocene sediments is dominated by NE–SW- or ENE–WSW-striking master faults ([Figures 2](#) and [3](#)) with significant lateral displacements, rooted in the pre-Neogene basement. The orientation of the conjugated faults seems to be controlled by the pre-Neogene – early Neogene zones of weaknesses; therefore observed geometry (e.g., flower structure) is not necessarily indicative of the sense of the last displacements, and the direction of the slip may possibly be oblique.

However, shortening features are not restricted to inverted faults. Based on seismic reflection pattern, shortening-related folding and uplifting were observed. Definition of key chronostratigraphic surfaces (sequence boundaries) and unconformities within the upper Miocene – Pliocene sediments, allowed the mapping of late Miocene anticlines ([Figure 2](#)). These folds may be connected with thrusting of the pre-Neogene basement (and accommodation of the unconsolidated cover), with fault ramps and with closure of pull-apart basins. Comparing map of late Miocene folds with late Miocene fault map ([Figure 2](#)) three structural domains could be identified. The northern domain, situated north of the Mid-Hungarian Line is characterised by dominantly ENE-WSW-oriented late Miocene faults. Paleogene – mid-Miocene structural deformation of this domain (e.g., Csontos and Nagymarosy, 1997, and Palotai and Csontos, 2010). The central domain can be found above the western continuation of the Mid-Hungarian Flysch Zone, characterised by dominantly NE-SW-oriented set of folds. The majority of late Miocene anticlines have the same orientation as the late Miocene – Pliocene faults. The southern domain seems to be only slightly folded or almost unfolded (see the southeastern part of seismic line on [Figure 2](#)). This domain is characterised by dominantly ENE-WSW-oriented faults. The central and the southern domains seem to be separated by the left-lateral Paks-Kisújszállás wrench zone (Pogácsás et al., 1989, Lőrincz et al., 2002), being active until the late Quaternary.

The overall late Miocene – Pliocene fault pattern is dominated by wide left-lateral wrench fault zones. The main wrench faults seem to be rooted in the Mesozoic-Paleozoic slices of the pre-Neogene basement. The geometry of the faults reflects action in both the major fault zones and individual faults during the several changes of the paleo stress field, and many of them were conjugate.

Shortening-related folding of the upper Miocene sediments and uplifting are conspicuous north of the Mecsek Fault Line. Fold axis distribution suggests alternation of an N-S-oriented and a NW-SE-oriented shortening. The orientations of mapped late Miocene faults are ENE-WSW and NE-SW (Pogácsás et al., 2011). Fold systems near the main strike-slip fault zones can be characterised by an en echelon folding geometry. The geometry of the faults active during the late Miocene and Quaternary is controlled by the previous, preformed fault pattern and the configuration of the hardrock basement.

Paleostress Evolution and Block Rotations

The evolution of the stress field in the study area ought to be approached in a Carpathian-Pannonian context (review in Nemčok et al., 2006), concentrating on the nearest available data on recent and paleostresses ([Figure 1](#)). The analysis of Fodor's observations from North Hungary (Márton and Fodor, 1995; Fodor et al., 2005) and from the Transdanubian Range (Márton & Fodor 2003) resulted in WNW-ESE-oriented highest principal stress from the Eocene to the Eggenburgian, NNW-SSE in the early Ottnangian – middle Badenian period and NNE-SSW from the late Badenian. Recorded deformations were generally extensional. Similar evolution (an apparent clockwise turn from E-W to N-S) was recognized in the whole West Carpathian – Pannonian area, in the north part of Transylvania (Fodor et al., 1999) and in the East and South Carpathian region (Huismans et al., 1997; Ratschbacher et al., 1993), but transpression, dominant shortening, and extension were alternating. There are local (or may be periodical) deviations from this picture in the orientation of principal stresses, the time constraints, and number of the separated phases. E-W-oriented highest principal stresses were reported from several sites of the Carpathians and East Alps

region (Peresson – Decker, 1997), also from the Bükk Mountains with horizontal shortening (Németh, 2006) from the end of the Miocene ([Figure 1](#)).

A change from N-S shortening (observed also in Pannonian sediments of the Mecsek--Csontos et al., 2002; Sebe et al., 2008; Konrád et al., 2010) to NE-SW or E-W was documented from Villány Mountains (Petrik, 2009); this may reflect the building-up of the recent stress field of the initial basin-scale shortening with generally NE-SW-oriented highest horizontal principal stress in the Mid-Hungarian Mobile Belt (Bada et al., 2007). Tertiary and Quaternary changes in the reconstructed paleostress orientations reflect partly the block rotations indicated by paleomagnetic surveys (reviews: Balla, 1987; Márton and Márton, 1989; Fodor et al., 1999; Márton 2001). The ALCAPA block, NNW from the Mid-Hungarian Mobile Belt, rotated counter-clockwise. Available data cover the Transdanubian (Márton and Fodor 2003) and the North Hungarian Range (Márton and Fodor 1995) as well ([Figure 1](#)).

The rotation occurred in three phases, in variable amounts in different regions, but with relatively well established time constraints: 30°–50° in the late Oligocene – early Karpadian, 15°–30° in the late Karpadian – early Badenian and 0°–30° in the Pliocene – Quaternary ([Figure 1](#)). This last phase is missing from the North Hungarian Range and the Western Carpathians, but present in Transdanubia, Croatia, and Slovenia (Márton and Fodor 2003), and Sarmatian volcanics of East Slovakia and East Hungary also suffered about 20°–30° counter-clockwise rotation (Márton et al., 2000). The rotated zone (with reduced amount of rotation) extends to the Carpathian Foredeep in the North (Márton et al., 2011). Considering the timing of the stress field evolution phases and the rotations, a nearly constant, N-S-oriented highest horizontal principal stress can be restored during the Tertiary to the recent inversion (Márton and Fodor 1995, 2003). Real changes began in the late Miocene only.

The Tisza block on the SSE side of the Mid-Hungarian Mobile Belt rotated clockwise according to data from the Villány Mountains (Márton and Márton, 1978; Márton, 2000), the Mecsek Mountains (Márton and Márton, 1999), the Apuseni Mountains (Patrascu et al., 1994) and Maramures (Márton et al., 2007). This rotation could have reached 90° (Fodor et al., 1999) or even more (Márton et al., 2007) from the end of the Oligocene to the late Miocene. Pannonian; younger rocks show counter-clockwise rotation (Márton 2001). Regional differences are much larger than inside the ALCAPA. In this block, where both paleomagnetic and apparent stress field rotations (Ratschbacher et al., 1993) are clockwise, restoration gives no constant orientation.

As the two microplates were internally deformed and segmented during their rotation, the deformation history of the contact zone between these may be more complex. Some blocks may have been detached and moved individually, or reintegrated in the other block, changing rotation pole and rotation sense. This process is reported from the NNE and the SW segments of the zone (Márton 2001; Márton et al., 2007), where outcropping rocks of various ages are accessible from the splaying Mid-Hungarian Mobile Belt. Miocene volcanoclastics north from the Mecsek show large counter-clockwise rotations, in sharp contrast with the unrotated Neogene sediments and clockwise-rotated Paleozoic rocks of the Mecsek Mountains (Márton and Márton, 1999). Rotations also affected the fault planes and could be responsible for changes in slip senses.

There is an inevitable discrepancy in the reconstruction of the stress field evolution ([Figure 1](#)). Knowledge on the recent stresses (Bada et al., 2007) comes from focal mechanism solutions and from borehole data (breakout and over-coring). The former concerns the active faults, the latter mainly the sediments of the Pannonian Basin explored for hydrocarbons in various depth ranges. These observations affect the same structures as the seismic record. The dataset for paleostress reconstructions ([Figure 1](#)), based on fault and slickenslide orientation measurements, was recorded, in contrast, mainly in hilly or mountainous areas providing abundant outcrops on the recent surface. In some cases, e.g., in the Transylvanian basin, there is no corresponding slickenslide set on any outcrops to well dated, large-scale basinal faults or vice versa (Huisman et al., 1997). Therefore, the inferred stress field cannot be directly correlated with tectonic phases of changing tectonic style separated in the basin filling sediments.

Structural Control on Groundwater Flow

Structural elements, such as fractures and faults, can both be barriers and conduits for fluid flow. It depends on several petrophysical factors, such as the permeability of the fault gouge, the permeability and relative position of the formations in the footwall and hangingwall, as well as the relative orientation of the fault planes (Caine et al., 1996). Furthermore, the fluid potential distribution and the consequent fluid-flow directions represent a dominant factor as well (Matthäi and Roberts, 1996), considering also that high-permeability faults can be acting as direction-dependent barriers for fluid flows (Czauner et al., 2009; Czauner and Mádl-Szőnyi, in press). Besides, the spatial and temporal variation of faults' hydraulic behaviour also has to be taken into account. Either as conduits or as barriers, faults are crucial factors in groundwater flow- and petroleum systems, as well. As barriers, faults can impede and distract fluid flows resulting in hydrocarbon entrapment, heat accumulation, and/or groundwater salinization. On the other hand, as usually preferred migration pathways, conduit faults can establish short-cuts between distant and/or separated aquifers, reservoirs, or flow domains.

In the study area, where two groundwater flow domains (an upper gravity-driven, and a lower, overpressured system) exist, the hydraulic role of faults is particularly essential. Faults originated in the Pre-Neogene basement usually cross-cut the Neogene strata as well, and particularly the strike-slip fault zones often approach even the land surface. As a consequence, upwelling of the saline and overpressured groundwater of the basement and deeper Neogene basin fill is possible along these faults into shallower strata, even near to the ground surface. The rate of pressure dissipation and dilution of water primarily depends on the depth of the Pre-Neogene basement, and the heterogeneity of the Neogene basin fill, which is a function of fault density as well. In the Duna-Tisza Interfluvium (DTI) where the Pre-Neogene basement is located at a relative shallow depth (about -500m asl) and the Algyő Aquitard is relatively thin and heterogeneous around-basement-originated conduit faults, highly pressured saline waters can appear even at shallow depths, while on the ground surface soil and wetland salinization can be observed. In other words, in this special geological situation of the DTI, a hydraulic short-cut can materialize across the whole Neogene succession in which, otherwise, only a slow diffuse fluid movement is possible.

Contrarily, in the Trans-Tisza Region, where the Neogene succession is far thicker (at least 2000-3000m) and more heterogeneous, not even basement faults, which approach the land surface, can cause significant anomalies in the fluid-potential field, and particularly in the

hydrochemical characteristics of groundwater (Czauner et al., 2009), simply because ascending groundwater joins with several potential flow paths (i.e. aquifers, faults) along its way in a fault zone.

Canyon Development

Recently huge erosional features were recognized on several seismic lines in the zone of the Mid-Hungarian Mobile Belt ([Figure 4](#)) and interpreted as canyon incisions in Late-Neogene (Pannonian s.l.) post-rift sediments (Juhász et al., 2007b, 2008, Juhász et al. in press). Canyon systems were incised along the southern boundary of the structurally shortened, inverted and uplifted Mid-Hungarian Mobile Belt.

They were identified in the route of one of the main sediment supply fairway approaching the Pannonian Lake from the NW direction (i.e., the “ancient Danube”), at the zone of the coeval shelf edge now found in the central part of the basin, while the incision surface is connected to the Top late Miocene Unconformity (sequence boundary SB Pa-4 6.8 Ma by Vakárcs 1997). This SB was considered to have been associated with significant base-level fall due to shortening and uplifting. The canyon systems occur at a large releasing bend and/or extensional duplex of Paks-Szolnok strike-slip system, which was active as sinistral during the late Miocene.

The canyons are considered as new evidences of intra-late Miocene-Pliocene (Pannonian) tectonic activity and connecting relative lake-level drop in the central part of the Hungarian Plain. The canyon valleys are incised several hundred metres in the pre-existing substrate; the maximum depth at the deepest part can reach 700-800 m, which is in the area of the major trunk valley. Widths of individual valleys range from 5 to 10 km, but much smaller tributaries are connected to them, representing evidence in the course of canyon development. Considering that they were formed in a lake, the size of the canyons is astonishing. This size is larger than that of active feeder channels of modern large deep sea fans. In the deepest parts of the canyon towards the canyon head, mass-transported reservoir sands can also be found.

The deepest valleys are not perpendicular to the coeval shelf edge but have an oblique strike orientation. According to the seismic profiles the study area is highly affected by intense strike-slip tectonics. The walls of the canyons are rather aligned in trend with underlying strike-slip faults ([Figures 5](#) and [6](#)).

On the seismic profiles two or more canyon valleys can be seen next to each other, either-dip or strike-oriented. The canyon walls are represented by erosional truncation of the underlying bedrock whose seismic facies is characterized by parallel, high-amplitude, high-continuity reflections as the valleys are incised into a thick succession of delta-front, delta-plain and alluvial-plain sediments. In a definite time interval the canyon systems would have served as feeder channels for the turbidites of the Makó –trough farther southeast. Based on paleomagnetic age data, from the Kaskantyú-2 well drilled by continuous coring, chronostratigraphic horizons have been correlated on seismic network, and series of time depth maps (8.3, 6.85) have been constructed. Slope gradient reveals lake-margin morphology. Southeastward lake-margin retreat relates to deposition of prograding delta/shore face system.

Strike-slip fault system coincides with flower structures on the seismic lines ([Figure 7](#)). Detailed seismic interpretation and mapping of the

non sequential Riedel faults on the Alpar canyon area in the vicinity of Nagykőrös and Kecskemét have revealed a large releasing bend and/or extensional duplex of the SW-NE-oriented Paks-Kisújszállás strike-slip zone ([Figure 8](#)). It seems to be obvious that the transtensional stress along the releasing bend of the main strike-slip fault zone initiated the canyon development in the pull-apart areas.

The areal distribution of the canyons was estimated on the basis of 2D seismic survey. A fence diagram shows the confluence of several larger tributary valleys ([Figure 8](#)). These valleys are deeper and narrower in the NE part, while wider and shallower in the NW part, where signs of coeval uplifting can be observed. Their confluence and the trunk valley are located at or near the root zone of the main strike-slip fault zone. The formation of the deep canyons was presumably generated by the interaction of a relative base-level fall, the reactivation and bending/duplexing of a strike-slip system precisely in the same area, and a change in sediment supply carried by overfed rivers.

Conclusions

The canyon system is connected to SB Pa-4 (appr. 6.8 Ma after Vakarcz 1997) and can be found at a large releasing bend and/or extensional duplex of the Paks-Szolnok strike-slip system, which was active as sinistral during the late Miocene. This SB was considered to have been associated with significant base-level fall due to shortening and uplifting.

The formation of the extremely deep canyons was presumably generated by the close interaction of several factors, such as late Miocene inversion (Top late Miocene Unconformity) and uplift-related relative base-level fall, or downstep of the system, the reactivation and bending/duplexing of a strike-slip system in the same area, and in the same time, the sudden change of the sediment supply carried along by overfed rivers. The canyon area served as major feeder channels for the turbidites towards the Makó-trough during and after its formation and existence.

The canyon's importance in HC exploration and finding HC traps can be related to: a) It may act as a seal for the downdip direction, as the canyon infill in the upper part reflects lacustrine sediments; b) It can involve possible intracanyon reservoir sands at the base deposited as mass-transport sediments, but its nature and areal distribution have not been known yet; c) At upper levels possible reservoir sands could have been deposited during late lowstand.

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References

- Bada, G., F. Horváth, P. Dövényi, P. Szafián, G. Windhoffer, and S. Cloetingh, 2007, Present-day stress field and tectonic inversion in the Pannonian Basin: *Global and Planetary Change*, v. 58/1-4, p. 165-180.
- Balla, Z., 1987, Tertiary palaeomagnetic data for the Carpatho-Pannonian region in the light of Miocene rotation kinematics: *Tectonophysics*, v. 139/1-2, p. 67-98.
- Caine, J.S., J.P. Evans, and C.B. Forster, 1996, Fault zone architecture and permeability structure: *Geology*, v. 24/11, p. 1025-1028.
- Csontos L., and A. Nagymarosy, 1998, The Mid-Hungarian line: a zone of repeated tectonic inversions: *Tectonophysics*, v. 297/1-4, p. 51-71.
- Csontos L., L. Benkovics, F. Bergerat, J.L. Mansy, and G. Wórum, 2002, Tertiary deformation history from seismic section study and fault analysis in a former European Tethyan margin (the Mecsek–Villány area, SW Hungary): *Tectonophysics*, v. 357/1-4, p. 81-102.
- Czauner, B., and J. Mádl-Szőnyi, 2011, The role of faults in hydraulic hydrocarbon entrapment: theoretical considerations and a field study from the Trans-Tisza Region, Hungary: *AAPG Bulletin*, v. 95/5, p. 795-811.
- Czauner, B., J. Mádl-Szőnyi, J. Tóth, and G. Pogácsás, 2009, Hydraulic potential anomaly indicating thermal water reservoir and gas pool near Berekfürdő, Trans-Tisza Region, Hungary: *Central European Geology*, v. 51/3, p. 253-266.
- Fodor, L., G. Radócz, O. Sztanó, B. Koroknai, L. Csontos, and S. Harangi, 2005, Post-conference excursion: Tectonics, Sedimentation and Magmatism along the Darnó Zone: *Geolines*, v. 19, p. 142-162.
- Fodor, L., L. Csontos, G. Bada, I. Györfi, and L. Benkovics, 1999, Tertiary tectonic evolution of the Pannonian basin system and neighbouring orogens: a new synthesis of paleostress data *in* B. Durand, L. Jolivet, F. Horváth, and M. Séranne, (eds), *The Mediterranean Basins: Tertiary extension within the Alpine Orogen*: Geological Society of London, Special Publications, v. 156, p. 295-334.
- Huismans, R.S., G. Bertotti, D. Ciulavu, C.A.E. Sanders, S. Cloetingh, and C. Dinu, 1997, Structural evolution of the Transylvanian Basin (Romania): a sedimentary basin in the bend zone of the Carpathians: *Tectonophysics*, v. 272/2-4, p. 249-268.
- Juhász, G., G. Pogácsás, and I. Magyar, 2008, Evidences in the Pannonian Basin: giant canyon incisions in the Late-Miocene (Pannonian s.l.), connected to SB Pa-4 (), Hungary: *Geophysical Research Abstracts*, v. 10, EGU2008-A-07224, SRef-ID: 1607-7962/gra/EGU2008-A-07224, EGU General Assembly 2008.
- Juhász, G., G. Pogácsás, and I. Magyar, 2007, Óriáskanyon-rendszer szeli át a pannóniai üledékeket? (A giant canyon system incised into the

Late Neogene (Pannonian s.l.) post-rift sediments?: *Földtani Közlöny*, v. 137/3, p. 307-326.

Juhász, G., G. Pogácsás, I. Magyar, and G. Vakarcs, 2007, Tectonic vs. climatic control in the evolution of fluvio-deltaic systems in a lake basin, Eastern Pannonian Basin: *Sedimentary Geology*, v. 202, p. 72-95.

Juhász, E., L.Ó. Kovács, P. Müller, A. Tóth-Makk, L. Phillips, and M. Lantos, 1997, Climatically driven sedimentary cycles in the Late Miocene sediments of the Pannonian Basin, Hungary: *Tectonophysics*, v. 282, p. 257-276.

Juhász, G., G. Pogácsás, I. Magyar, and A. Hatalyák, (in review) The Alpar canyon system in the Pannonian Basin, Hungary – its morphology, infill and development.

Konrád, Gy, K. Sebe, A. Halász, and A. Halmai, 2010, A Délkelet-Dunántúl földtani fejlődéstörténete. (The geological evolutionary history of Southeast Transdanubia, Hungary): *Földrajzi Közlemények*, v. 134/3, p. 251-265.

Lőrincz, K.D., F. Horváth, and G. Detzky, 2002, Neotectonics and its relation to the Mid-Hungarian Mobile Belt, in S.A.P.L. Cloetingh, F. Horváth, G. Bada, and A.C. Lankreijer, (eds.), *Neotectonics and surface processes: the Pannonian Basin and Alpine/Carpathian System*: European Geosciences Union Stephan Mueller Special Publication Series, v. 3, p. 247-266.

Matthäi, S.K., and S.G. Roberts, 1996, The influence of fault permeability on single-phase fluid flow near faults and intersections: results from steady-state high resolution models of pressure-driven fluid flow: *AAPG Bulletin*, v. 80/11, p. 1763-1779.

Márton, E., A.K. Tokarski, O. Krejčí, M. Rauch, B. Olszewska, P. Tomanová Petrová, and A. Wójcik, 2011, 'Non-European' palaeomagnetic directions from the Carpathian Foredeep at the southern margin of the European plate: *Terra Nova*, v. 23/2, p. 134-144.

Márton, E., M. Tischler, L. Csontos, B. Fügenschuh, and S.M. Schmid, 2007, The contact zone between the ALCAPA and Tisza-Dacia megatectonic units of Northern Romania in the light of new paleomagnetic data: *Swiss Journal of Geosciences*, v. 100/1, p. 109-124.

Márton, E., and L. Fodor, 2003, Tertiary paleomagnetic results and structural analysis from the Transdanubian Range (Hungary): rotational disintegration of the Alcapa unit: *Tectonophysics*, v. 363/3-4, p. 201-224.

Márton, E., 2001, Tectonic implications of Tertiary paleomagnetic results from the PANCARDI area (Hungarian contribution): *Acta Geologica Hungarica*, v. 44, p. 135-144.

Márton, E., 2000, The Tisza megatectonic unit in the light of paleomagnetic data: *Acta Geologica Hungarica*, v. 43, p. 329-343.

Márton, E., D. Vass, and I. Tunyi, 2000, Counterclockwise rotations of the Neogene rocks in the East Slovak basin: *Geologica Carpathica*, v. 51/3, p. 159-168.

Márton, E., and P. Márton, 1999, Tectonic aspects of a palaeomagnetic study on the Neogene of the Mecsek Mountains: *Geophysical Transactions*, v. 42/3-4, p. 159-180.

Márton, E., and L. Fodor, 1995, Combination of paleomagnetic and stress data – a case study from North Hungary: *Tectonophysics*, v. 242, p. 99-114.

Márton, E., and P. Márton, 1989, A compilation of paleomagnetic results from Hungary: *Geophysical Transactions*, v. 35/1-2, p. 117-133.

Márton, E., and P. Márton, 1978, A Dunántúli-középhegység és a Villányi-hegység mezozoos paleopólusainak eltéréséről: *Magyar Geofizika*, v. 19/4, pp. 129-136.

Nemcok, M., G. Pogácsás, and L. Pospisil, 2006, Activity timing of the main tectonic systems in the Carpathian–Pannonian Region in relation to the rollback destruction of the lithosphere *in* J. Golonka, and F.J. Picha, (eds), *The Carpathians and their foreland: Geology and hydrocarbon resources: AAPG Memoir 84*, p. 743- 766.

Németh, N., 2006, Tertiary stress field evolution in the eastern part of the Bükk Mountains, NE Hungary: *Geolines Prague*, v. 20, p. 100-101.

Palotai, M.L., and L. Csontos, 2010, Strike-slip reactivation of a Paleogene to Miocene fold and thrust belt along the central part of the Mid-Hungarian Shear Zone: *Geologica Carpathica*, v. 61/6, p. 483-493.

Patrascu, S., C. Panaiotu, M. Seclaman, and C.E. Panaiotu, 1994, Timing and rotational motions of Apuseni Mountains, Romania: palaeomagnetic data from Tertiary magmatic rocks: *Tectonophysics*, v. 233, p. 163-176.

Peresson, H., and K. Decker, 1997, Far-field effects of Late Miocene subduction in the Eastern Carpathians. E-W compression and inversion of structures in the Alpine-Carpathian-Pannonian region: *Tectonics*, v. 16, p. 38-56.

Petrik, A.B., 2009, Interpretation of the results of microtectonic measurements performed with respect to Mesozoic formations of the Villány Hills, Hungary: *Földtani Közlöny*, v. 139/3, p. 217-236.

Pogácsás, G., G. Juhász, N. Németh, A. Dudás, J. Csizmeg, 2011, Shortening features in the late Miocene-Pliocene sediments along the central part of the Mid-Hungarian Mobile Belt: *Travaux Géophysiques*, XL, p. 62-63.

Pogácsás, G., R.E. Mattick, D.P. Elston, T. Hámor, Á. Jámor, L. Lakatos, M. Lantos, E. Simon, G. Vakarcs, L. Várkonyi, and P. Várnai, 1994, Correlation of Seismo- and Magnetostratigraphy in Southern Hungary *in* P. Teleki, J. Kókai, R.E. Mattick, (eds.), Basin analysis in petroleum exploration, a case study from the Békés basin, Hungary. Kluwer Academic Publisher, Dordrecht, Netherlands, p. 143-160.

Pogácsás, G., L. Lakatos, A. Barvitz, G. Vakarcs, and C. Farkas, 1989, Pliocene-Quaternary transcurrent faults in the Great Hungarian Plain: *General Geological Review*, v. 24, p. 149-169.

Ratschbacher, L., H.G. Linzer, F. Moser, R.O. Strusievicz, H. Bedeleian, N. Har, and P.A. Mogos, 1993, Cretaceous to Miocene thrusting and wrenching along the Central South Carpathians due to a corner effect during collision and orocline formation: *Tectonics*, v. 12/4, p. 855-873.

Sebe, K., G. Csillag, and G. Konrád, 2008, The role of neotectonics in fluvial landscape development in the Western Mecsek Mountains and related foreland basins (SE Transdanubia, Hungary) *in* P.G. Silva, F.A. Audemard, and A.E. Mather, (eds.), Impact of Active Tectonics and Uplift on Fluvial Landscapes and River Valley Development: *Geomorphology*, v. 102/1, p. 55-67.

Vakarcs, G., 1997, Sequence stratigraphy of the Cenozoic Pannonian Basins, Hungary: - PhD thesis, Rice University, Houston, Texas, 514 p.

Vakarcs G., P.R. Vail, G. Tari, G. Pogácsás, R.E. Mattick, and A. Szabó, 1994, Third-order Middle Miocene-Early Pliocene depositional sequences in the prograding delta complex of the Pannonian basin: *Tectonophysics*, v. 240, p. 81-106.

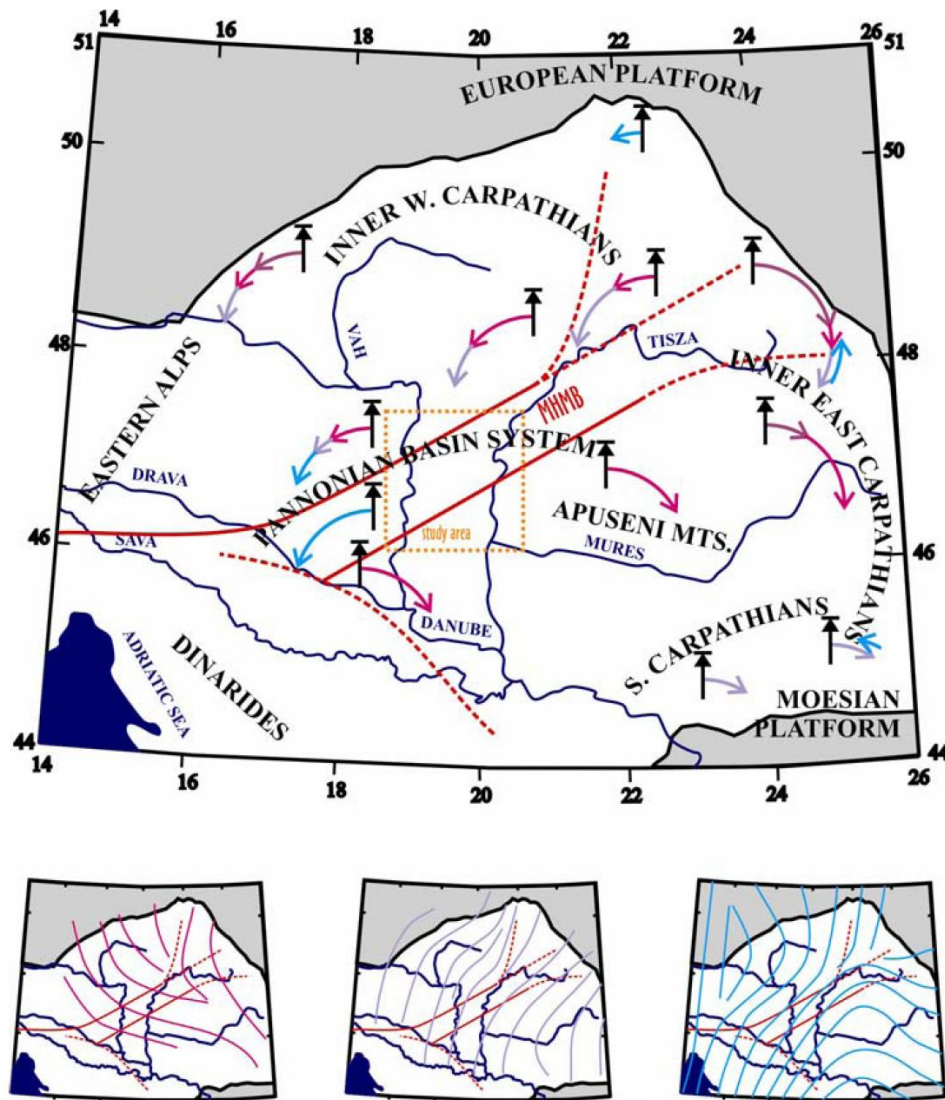


Figure 1. Block rotations indicated by paleomagnetic surveys and generalized maximum horizontal principal stress orientations in the Carpathian region, based on published data. Rotations: purple: pre-Miocene, magenta: early Miocene, pastel blue: middle-late Miocene, cyan: Pannonian - Quaternary. Stress field: magenta: late Oligocene - early Miocene, pastel blue: middle-late Miocene, cyan: recent situation.

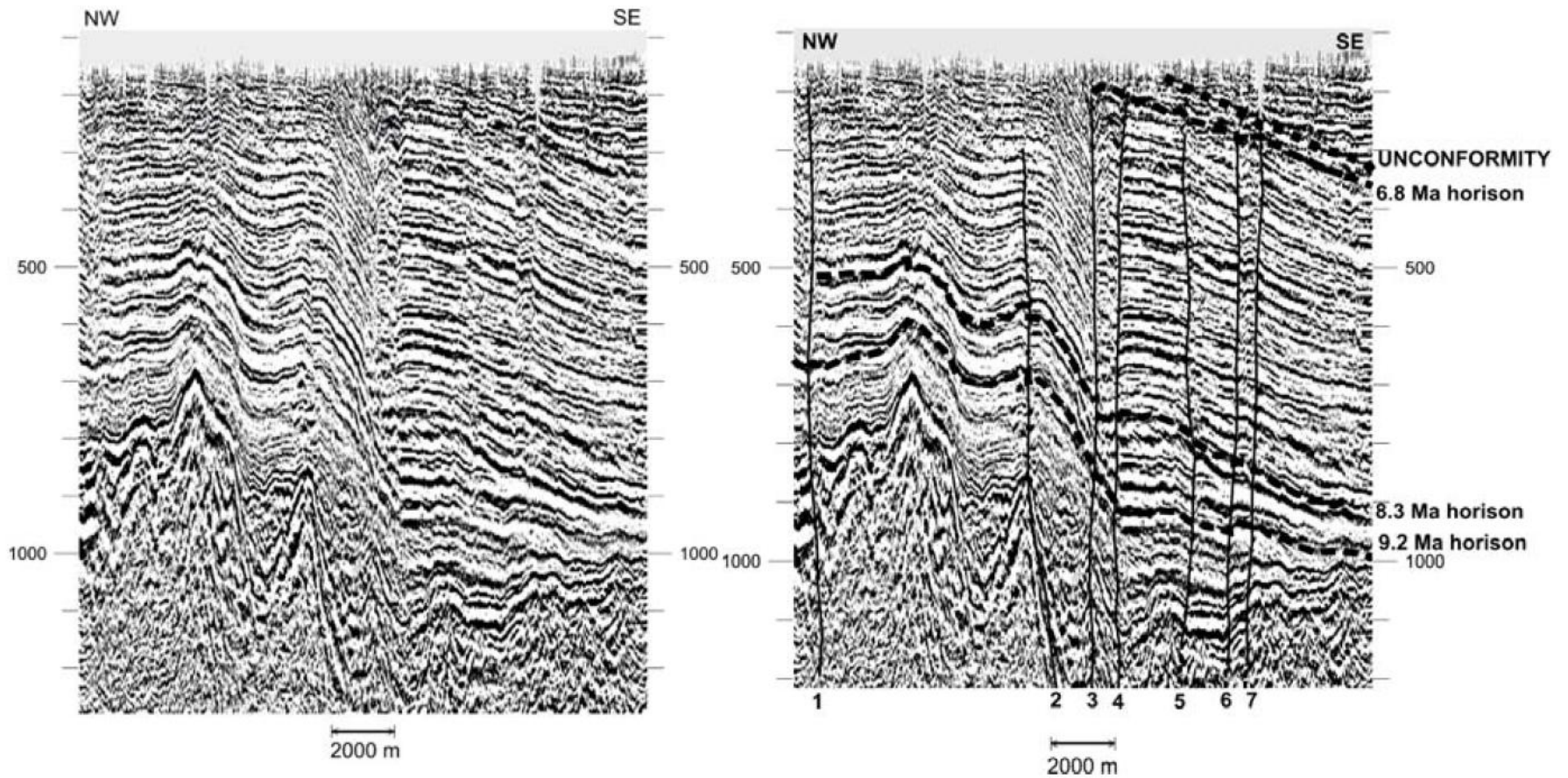


Figure 2. NW-SE-oriented seismic section. Location of the seismic line is indicated on [Figure 3](#). Age data of correlated seismic horizons (9.2 Ma, 8.3 Ma, 6.8 Ma) were based on magnetostratigraphic and radiometric (K/Ar) data from the nearby Kaskantyú-2 and Kiskunhalas-Ny-3 wells (Pogácsás et al., 1994). In the case of the Kaskantyú-2 well drilled by continuous coring, the Top Miocene Unconformity (Juhász et al 1997) represents a hiatus from 6.2 Ma to 3.9 Ma. This unconformity seems not to be affected by faults #5, #6, #7. Faults #3, #4 are strike-slip faults have been active until the late Quaternary (Pogácsás et al 1989, Juhász et al 2007). Seismic features of the nearby fault #2 indicate that faulting activity here obviously post-dated the shortening-related folding.

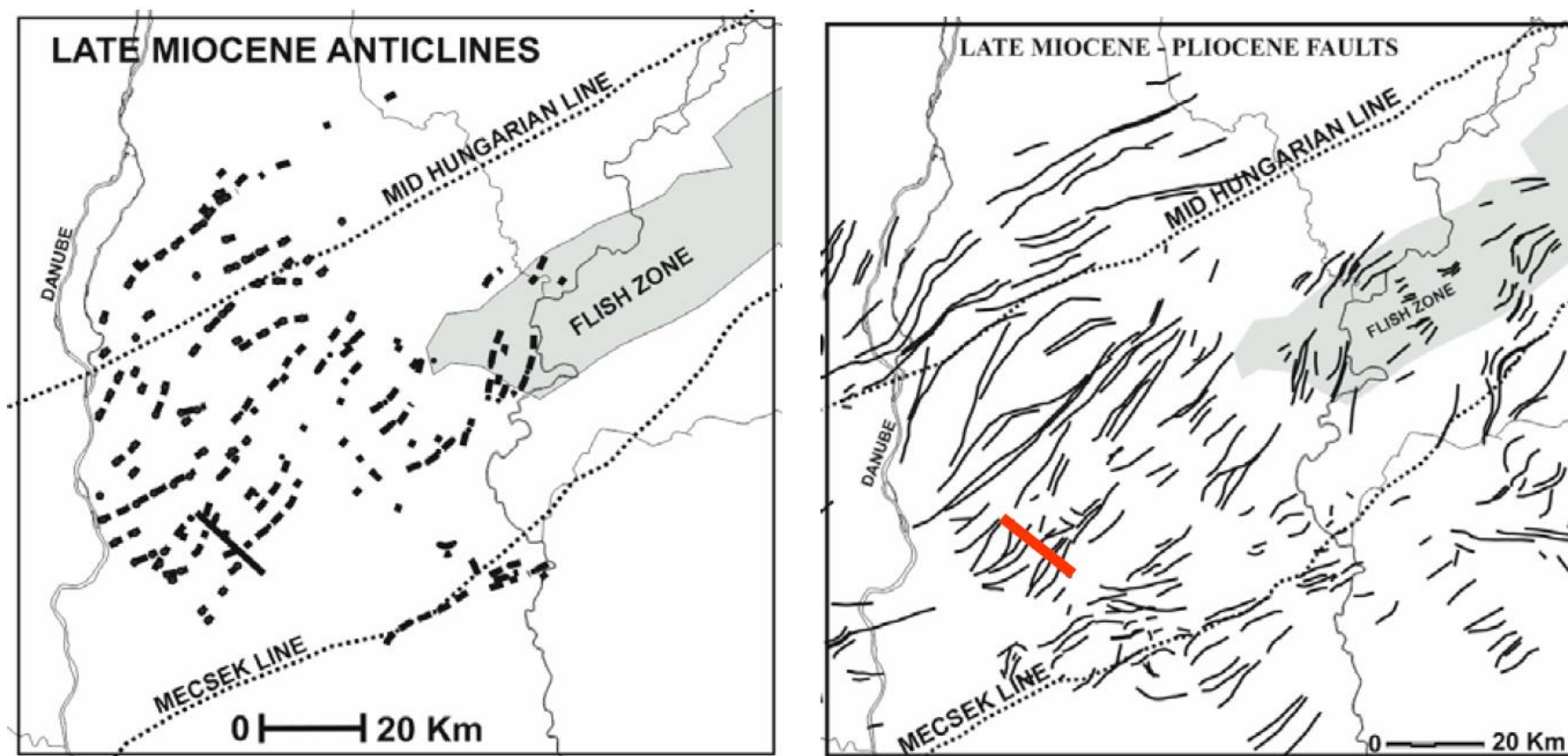


Figure 3. Correlated late Miocene folds (axis of anticlines) and correlated (assigned) post-rift (undifferentiated late Miocene-Pliocene) on seismic networks. ENE-WSW-oriented folds have been identified on seismic network along and on both sides of the Mid-Hungarian Line, e.g., above the ALCAPA and the TISZA terrains as well. The Mid-Hungarian Flysch Zone is supposed to be underlain by transitional crust, and it is considered to represent a wide zone of weakness. Seismic section presented on Figure 2 and represented by red line is perpendicular to both the Mecsek Line and the Mid-Hungarian Line.

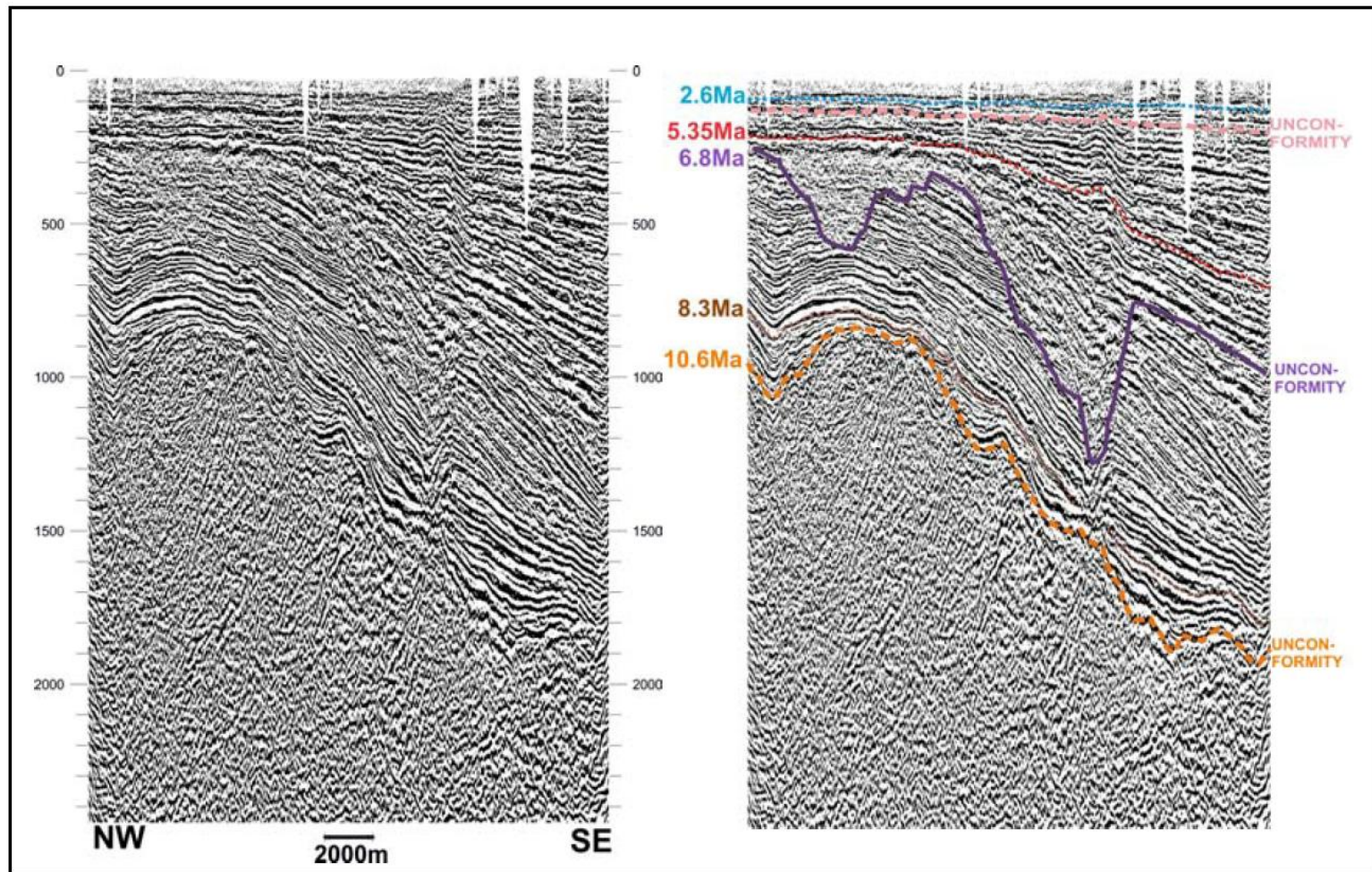


Figure 4. Seismic expressions of the three main tectonically enhanced unconformities along the southern boundary of the shortened, inverted and uplifted Mid-Hungarian Mobile Belt: Pink--late Pliocene Unconformity, Deep Blue--Top late Miocene Unconformity, Orange--Base Pannonian (Base late Miocene Unconformity), The formation of the deep canyons was presumably generated by the interaction of the late Miocene inversion (Top late Miocene Unconformity) and uplift-related relative base-level fall, the reactivation and bending/duplexing of a strike-slip system precisely in the same area, and a change in sediment supply carried by overfed rivers.

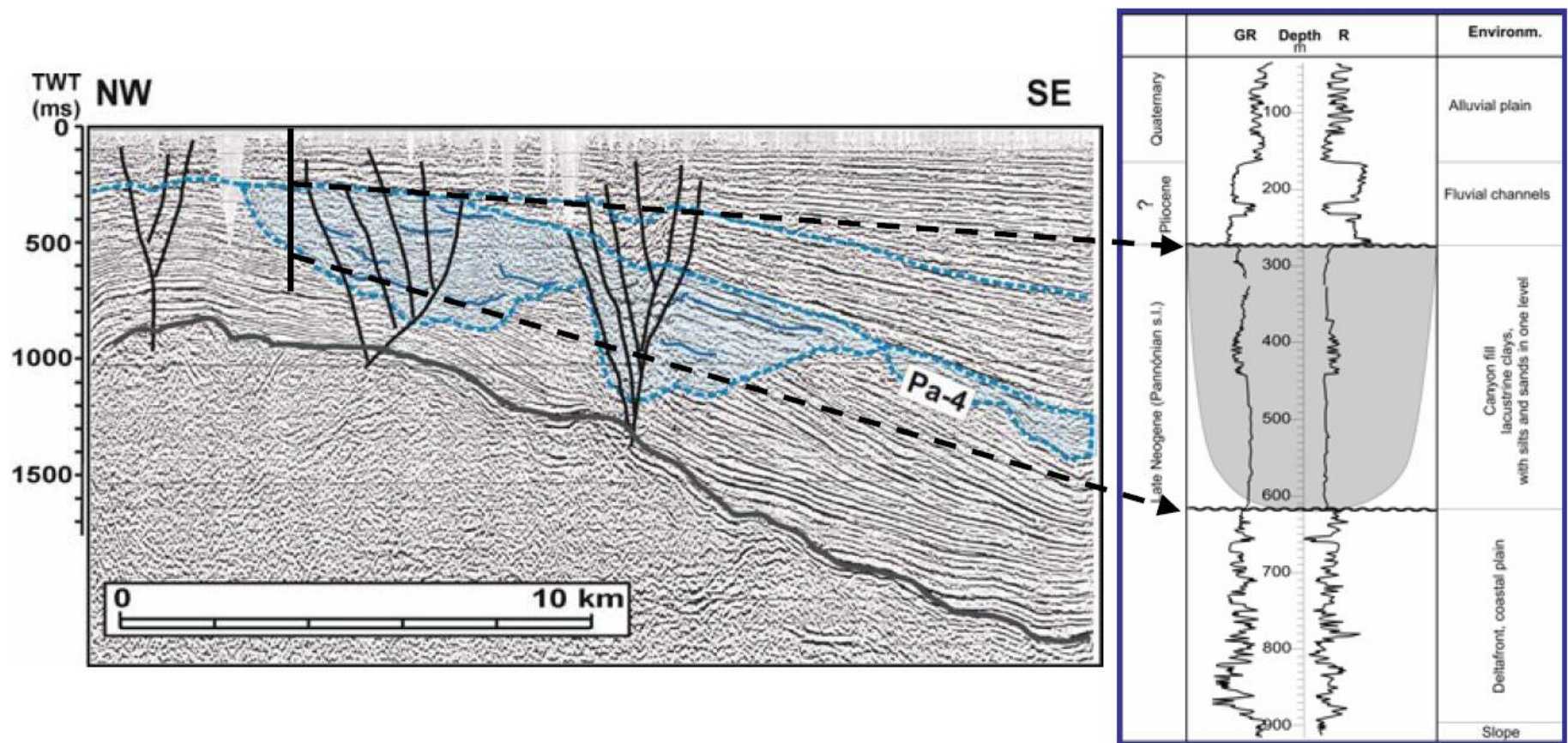
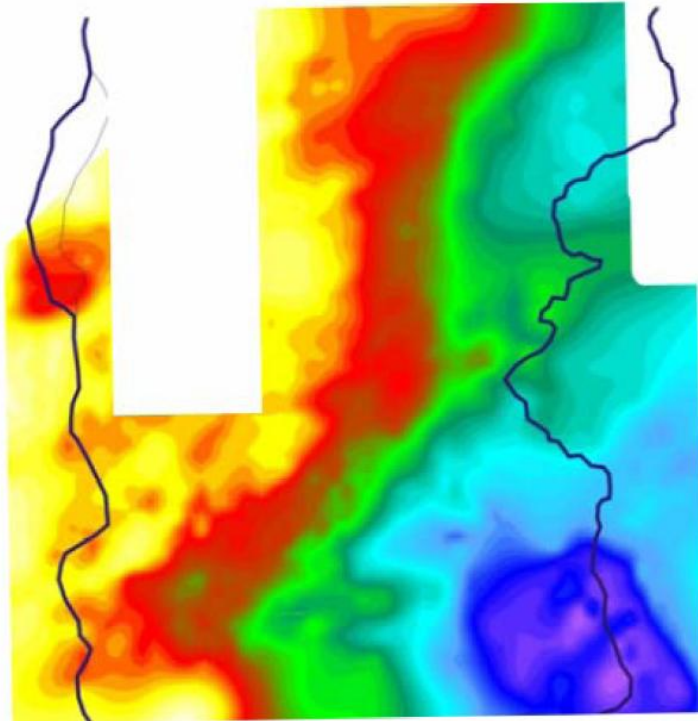


Figure 5. Seismic and well-log representation in the deeper part of the canyons. The canyon systems occur at a large releasing bend and/or extensional duplex of Paks-Szolnok strike-slip system, which was active as sinistral during the late Miocene. The canyon fill is built up by clay marls according to well logs, and it is characterized by seismically uniform, nearly transparent seismic facies, with low-continuity, low-amplitude seismic events. The infill in the shallower part of the canyon area reflects completely argillaceous lacustrine sediments, and in a few instances intercalated with some sandy succession of gravity sediments.

8.3 Ma horizon time depth map



6.85 Ma horizon time depth map

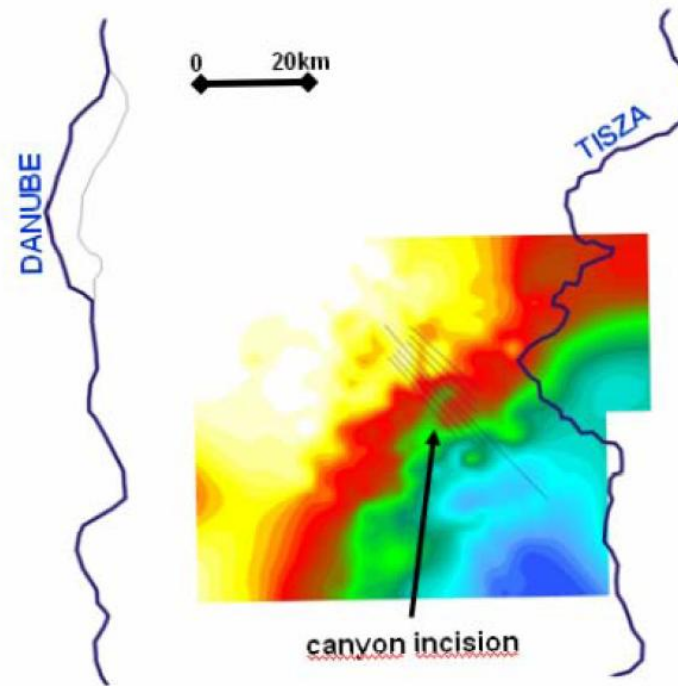


Figure 6. Large canyons incised into the upper Miocene sediments of the Pannonian Lake have been recognised in the central part of the study area (Alpár area) along several seismic lines. The canyon system has a surprisingly large size for a lacustrine setting. The incision surface is connected to Top late Miocene Unconformity (sequence boundary SB Pa-4 6.8 Ma).

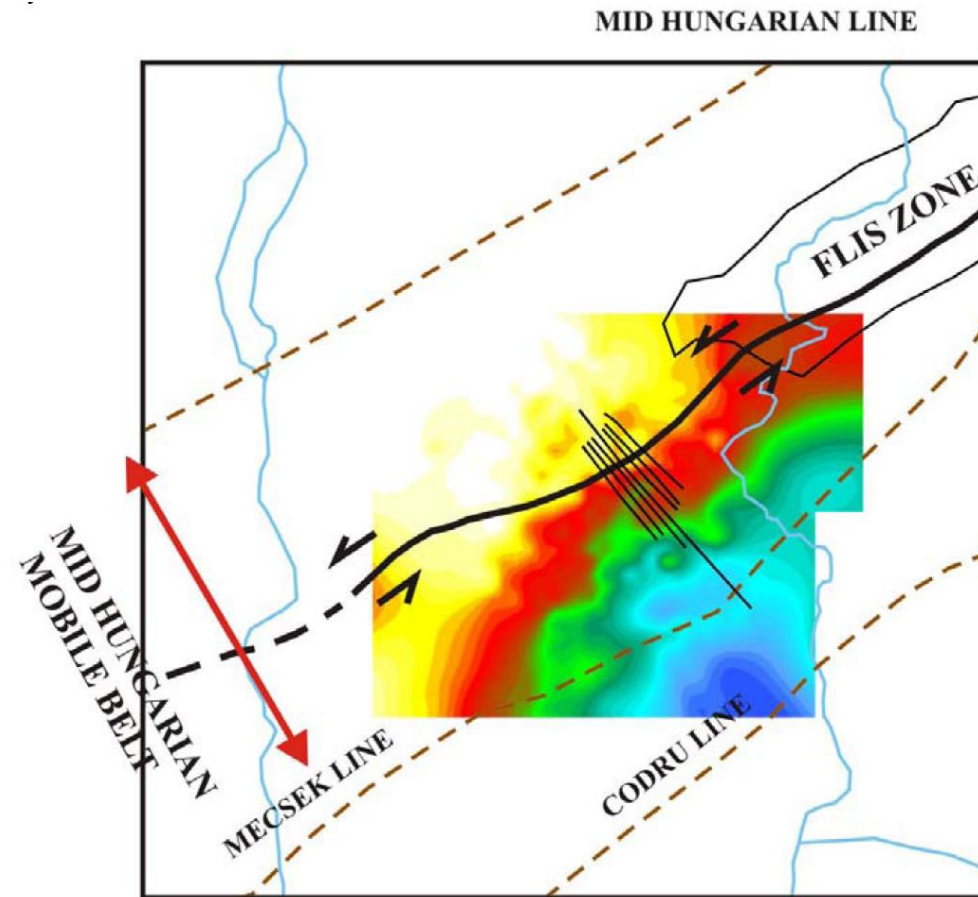


Figure 7. Releasing bend of the Paks-Szolnok sinistral strike slip zone coincided with the shelf break zone of the Pannonian Lake 6.85 My ago. Canyon incision was triggered by tectonic uplift and strike-slip-related extensional stress field at releasing bend of supposed wrench fault zone. The formation of the deep canyons was presumably generated by the interaction of a relative base-level fall, the reactivation and bending/duplexing of a strike-slip system precisely in the same area, and a change in sediment supply carried by overfed rivers.

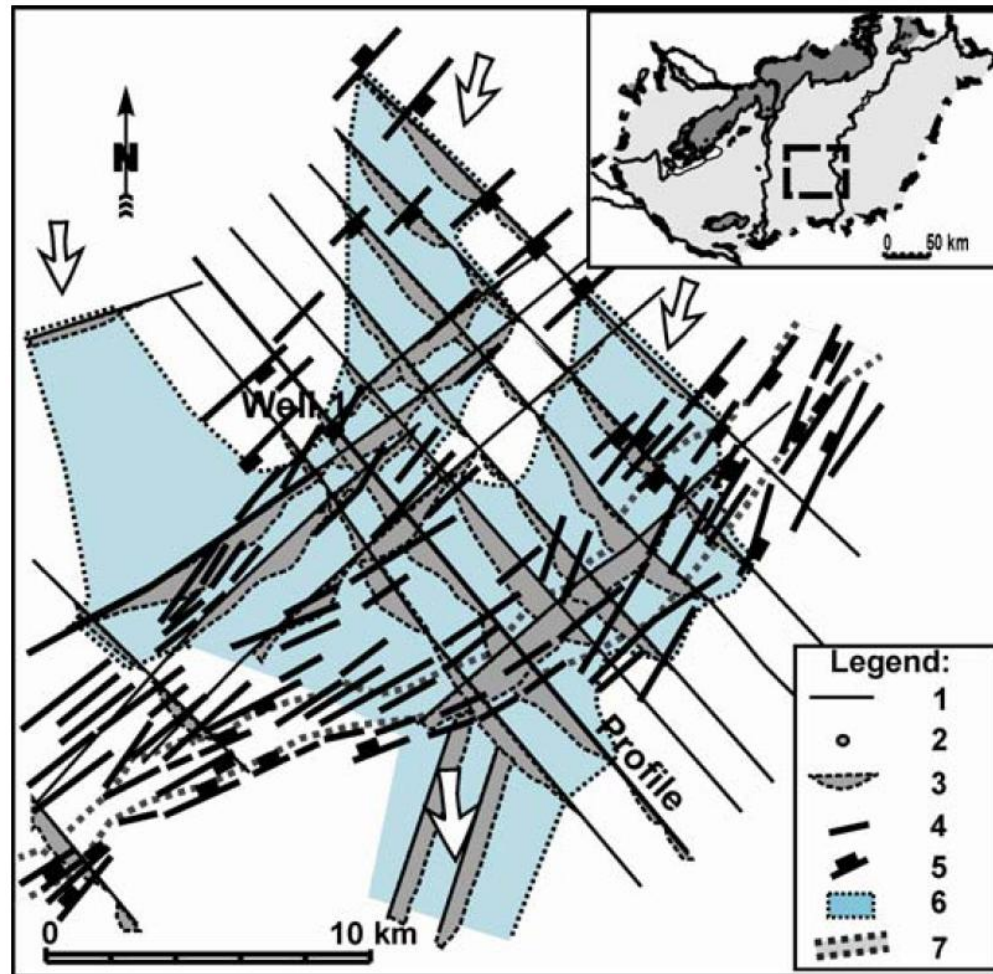


Figure 8. Large canyons incised into the upper Miocene sediments of Pannonian Lake have been recognised in the central part of the study area (Alpár area) along several seismic lines. Fence diagram and areal distribution of the canyon system and tectonic interpretation of the area (modified after Juhász et al., 2007). Legend: 1. seismic line, 2. well, 3. incised canyon, 4. normal fault, 5. Riedel fault, 6. canyon zone, 7. root zone.