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Wrench Tectonics Control on Neogene-Quaternary Sedimentation and Hydrocarbon Accumulation along the Mid-Hungarian Mobile Belt*

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Introduction

The Neogene-Quaternary Pannonian Basin is underlain by an orogenic collage which is built up by several Mesozoic-Paleogene continental tectonostratigraphic terrains. The largest ones are the northwestern ALCAPA (Alpine-Carpathian-Pannonian) and the southeastern Tisza (Figure 1). The continental ALCAPA and the Tisza terrains are separated by the Kriscevo, Szolnok, and Szava belt consisting of oceanic-origin ophiolites, suture zones and oceanic accretionary prisms (Ustaszewskyi et al., 2008). Each terrain experienced a complex deformation because of hinterland extension spreading toward the accretion wedge in front of the advancing orogen since the Eggenburgian. Each microplate can be characterized by frontal shortening, wrench zones along sides, and complex normal fault systems inside (Nemcok et al., 2006).

The Mid-Hungarian Mobile Belt (MHMB) is situated above the Szolnok-Sava belt and above its boundaries with the ALCAPA and Tisza terrains on the opposite side of the MHMB. It is the most significant neotectonic zone of the Pannonian Basin (Lőrincz et al., 2002). The faults of the Mid-Hungarian Mobile belt were active through the complete Neogene period, although with changing sense. MHMB recorded multiple deformations during Miocene–Quaternary, witnessing an inherited weakness zone (Fodor et al., 2005, Jarosinski et al., 2011).

Structural analysis focuses on late Miocene-Quaternary wrench faults, folds, and unconformities were supported by time and sequence stratigraphic analysis (see Figures 2, 3, and 4). Interpretation of seismic and well log data on workstation facilitated kinematic evaluation of three different late Miocene-Pliocene-Quaternary structural evolutionary stages. The aim of this article is to investigate buckling and different-order, shortening-related folds on composite seismic sections along and across the Mid-Hungarian Mobile Belt. Structural analysis was carried out on historical industry seismic sections across and along the MHMB, between the Danube and the Tisza rivers (Figure 1).

Style of Shortening in the Mid-Hungarian Mobile Belt

Shortening structures are characteristic in the upper Miocene - Pliocene sedimentary succession of the Danube - Tisza Interfluves Area (Figure 1). The structure of upper Miocene Pliocene sediments is dominated by NE–SW- or ENE–WSW-striking master faults (Pogacsas et al., 2011) 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, the 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 patterns, shortening-related folding and uplifting were observed. 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. Shortening-related folding of the upper Miocene sediments and uplifting are conspicuous north of the Mecsek Fault Line. Folds related to the base late Miocene Unconformity (base Pannonian) identified hereafter as the 10.6 Ma horizon, can be divided into two groups. Larger folds are characterized by an order of 4 to 9 kilometers wavelength and the smaller folds characterized by a shorter 1 to 2 kilometers wavelength. The smaller folds seem to be superimposed on the larger folds. The 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).

On seismic lines (Figure 5) shot parallel with the Mid-Hungarian Mobile Belt, folds connected to the 8.3 Ma horizon can be characterized by an order of 6 to 12 kilometers wavelength and 25 to 75 m amplitude. Folds on SW-NE-oriented seismic lines(# 4 and # 5 on Figure 5.) seem to be much more asymmetric than the identified folds on the NW-SE-oriented seismic lines (# 2 and # 3 on Figure 3 and on Figure 4). Fold systems near the main strike-slip fault zones can be characterized by an en-echelon folding geometry. The geometry of the faults active during the late Miocene and Quaternary is controlled by the previous, pre-formed fault pattern and the configuration of the hard-rock basement.

Discussion

Folds related to the Upper Miocene-Pliocene sedimentary rocks within the studied area of the Mid-Hungarian Mobile Belt can be divided into three groups.

1. Folds connected to the base late Miocene unconformity (Figures 6 and 7) are characterized by an order of 5 to 20 kilometers wavelength. The height of the folds of this group are between 300m and 600m at the base upper Miocene level while the buckling of the 8.3 Ma horizon shows only 25m to 200m amplitude.
2. A group of much smaller folds characterized by a shorter 1 to 2 kilometers wavelength are superimposed on the larger folds. The vertical heights of these smaller folds are between 25m and 75m.
3. Folds connected to the 6.85 Ma, 5.35 Ma, 3.6 Ma, 2.8 Ma horizons (Figures 6 and 7) at the SE side of the Mid-Hungarian Mobile Belt are characterized by much more gentle 5 to 15 km wide and 10 to 30 m high folds.

Three tectonically driven unconformities were identified on 2D historical industry seismic network in the investigated area of the Mid-

Hungarian Mobile Belt:

1. Base late Miocene Unconformity.
2. Top late Miocene Unconformity.
3. Late Pliocene Unconformity.

Within the upper Miocene-Quaternary sedimentary rocks at least two wrench faulting episodes have been observed. A seemingly wider wrench-dominated seismic pattern is localized for the upper Miocene sediments underlying the 5.89 Ma horizon (top late Miocene Unconformity). The overlying Pliocene and Quaternary sedimentary rocks which are only gently folded are displaced by usually less than one kilometer-wide Quaternary wrench fault systems. The recently seismically observed orders of wave lengths and amplitudes of shortening-related bucklings and/or folds within the Mid Hungarian Mobile Belt might be a promising new contribution to the deeper understanding of the geology of the MHMB.

Lőrinczi and Houseman (2010) recently analyzed the deformations of the ALCAPA and Tisza blocks including substantial strike-slip movements, together with shortening and possible extension across the Mid-Hungarian Line by thin viscous sheet model of the continental lithosphere in which deformation is described by a nonlinear viscous constitutive relationship. Their fairly picturesque model includes the competing influences of a NE push by the Adriatic block, a NE pull from a retreating subduction zone on the eastern Carpathians and the internal buoyancy forces arising from crustal thickness variations. Paleomagnetic studies (e.g., Márton et al., 2011) proved rotation and deformation vary across both the ALCAPA and Tisza blocks, with counter-clockwise rotation occurring in the former and clockwise rotation in the latter ones. The opposite rotations of the ALCAPA and Tisza plates led to NW–SE convergence in the space (e.g., Mid-Hungarian Mobile Belt) between them represented by a region of crustal thickening (Lőrinczi and Houseman 2010).

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, accommodating significant convergence and shear. The Miocene-Quaternary structural evolution of the study area seems to be characterized by change from the middle Miocene extension to late Miocene-Pliocene shortening accompanied by repeated rotations. Some blocks may have been detached and moved individually, or reintegrated in the other block, changing rotation pole and rotation sense. Miocene- Quaternary evolutionary history of the Mid-Hungarian Mobile Belt can be characterized by different five periods, controlling sedimentation and architecture of the basin:

1. During the early Miocene, the ALCAPA moved eastward, bounded by dextral strike-slip fault system along its contact with the Southern Alps and the Tisza terrain (most intensively 19-16.5 Ma). The Tisza unit moved northeastward over the remnant Carpathian Flysch Basin. These movements resulted in right-lateral, convergent-wide wrench along the Mid-Hungarian Mobile Belt. The ALCAPA and Tisza plates were step by step welded during the early Miocene along the Mid- Hungarian Mobile Belt, with ALCAPA thrusting over Tisza-Dacia (Csontos and Nagymarossy, 1998) The back-arc extension of the PB that took place between 20 and 14 Ma was coeval with compression at the exterior of the Carpathians (Royden et al., 1982, Jarosinski, 2011).

2. During the middle Miocene (15.5–13.6Ma), the ALCAPA collided with the European platform, and the eastward movement of the TISZA became pronounced. A long period of left-lateral strike slip began. Graben opening began, driven by the westward subduction and the eastward motion of the Tisza unit. Large displacements along listric faults have resulted in tilting of strata and formation of a regional unconformity between the middle and upper Miocene. Wrench fault-related pull-apart basins were filled by terrestrial to marine sediments.

3. During late Miocene (Sarmatian–Pannonian 13.6–6.2 Ma), the eastward motion of ALCAPA had ceased; the Tisza unit was still able to move eastward. The Tisza unit collided with the European platform (11.5–6.2 Ma), and a far-field compressional stress transmitted from the collision of the East Carpathians with the thick and buoyant part of the European foreland at 11 Ma (Matenco and Bertotti, 2000, Leever et al., 2006), have inverted and temporarily exhumed a large part of the PB (Horvath, 1995). During this time in the studied part of the Pannonian Basin the sediment supply was perpendicular to the strike of the Mid-Hungarian Mobile Belt.

4. Latest Miocene – Pliocene. At the end of late Miocene the structural style changed (Németh N. 2006), and a strong relative base-level drop occurred, driven by the shortening and uplift of the northwestern part of Danube Tisza Interfluves Area. On the area of the uplifted northwestern block a well developed angular unconformity (Top late Miocene Unconformity - TLMU) revealing erosional truncation can be seen on the industry seismic network. Below the TLMU the upper Miocene sediments are strongly folded. TLMU might be considered as a “top folded unit unconformity”. Several late Miocene wrench fault zones have been terminated upward against the TLMU. The Top late Miocene Unconformity seems to be connected to the second inversion of the Pannonian Basin (Horvath, 1995), which took place during the latest Miocene-Pliocene, affected an already locked orogenic system (Horvath and Tari,1999). This “second inversion” might have been responsible for partial exhumation and erosion of the Mid-Hungarian Mobile Belt. The beginning of the shortening event might have been related to subducting slab break off in the Carpathians which stopped roll-back mechanism of extension and caused the coupled mechanical conditions across the orogene (Nemcok et al., 1999, 2000; Jarosinski et al., 2009). The onset of inversion is considered diachronous across the Pannonian Basin system, generally migrating in time from the Adria push towards the Carpathians front (Tari et al., 1999, Fodor et al., 2005, Jarosinski et al., 2011). In areas located close to the Adria indenter (e.g., the Sava fold belt) inversion was recorded since the late Miocene (Placer, 1999). In the Pannonian Basin system the onset of inversion was estimated between 4 and 7Ma (Fodor et al., 2005). The boundary between the uplifting Mid-Hungarian Mobile Belt and the continuously subsiding southeastern block is the Paks-Szolnok wrench fault zone. An estimation of 8-10 km magnitude of late Miocene left-lateral strike slip was based on detailed seismic study on the above-mentioned wrench fault zone (Pogacsas et al 1989, Lőrincz et al 2002). The effects of the latest Miocene- Pliocene shortening are generally linked with differential vertical movements, commonly interpreted to be driven by large-scale lithospheric folding (e.g., Horvath and Cloetingh, 1996).

   The first order patterns of these vertical motions according to Jarosinski et al. (2011) can be characterized by wavelength magnitude on the order of 300–400 km, while the amplitude of vertical movements can be as high as 4 km, as observed by the differential vertical movements in the SE Carpathians and Dinarides (Horvath and Cloetingh, 1996, Leever et al., 2006, Bada et al., 2007). The second-order patterns of differential vertical movements with a wavelength of less than 100 km might have been observed in the present-day topography (Ruszkiczay-Rudiger et al., 2005). This is documented in the late-stage evolution of Sava, Drava, Békés and Danube sub-basins (Balen et al., 1999) separated by uplifted areas such as the Slavonian Mountains, Mecsek Hills and Transdanubian Central Range (Jarosinski et al., 2011). Pliocene-Quaternary folding with a 20–60 km wavelength has been described between the Drava Basin and Lake Balaton by Sacchi et al. (1999), while a 10–20 km wavelength folding system, trending E–W was presented in the area of the Zala Hills (West Hungary) by Fodor et al. (2005).

5. During the Pliocene-Quaternary tectonic-driven subsidence took place in the E and SE part of the Great Hungarian (Gabris and Nador, 2007). Quaternary was characterized by a renewed phase of left-lateral wrenching within the Mid-Hungarian Mobile Belt.

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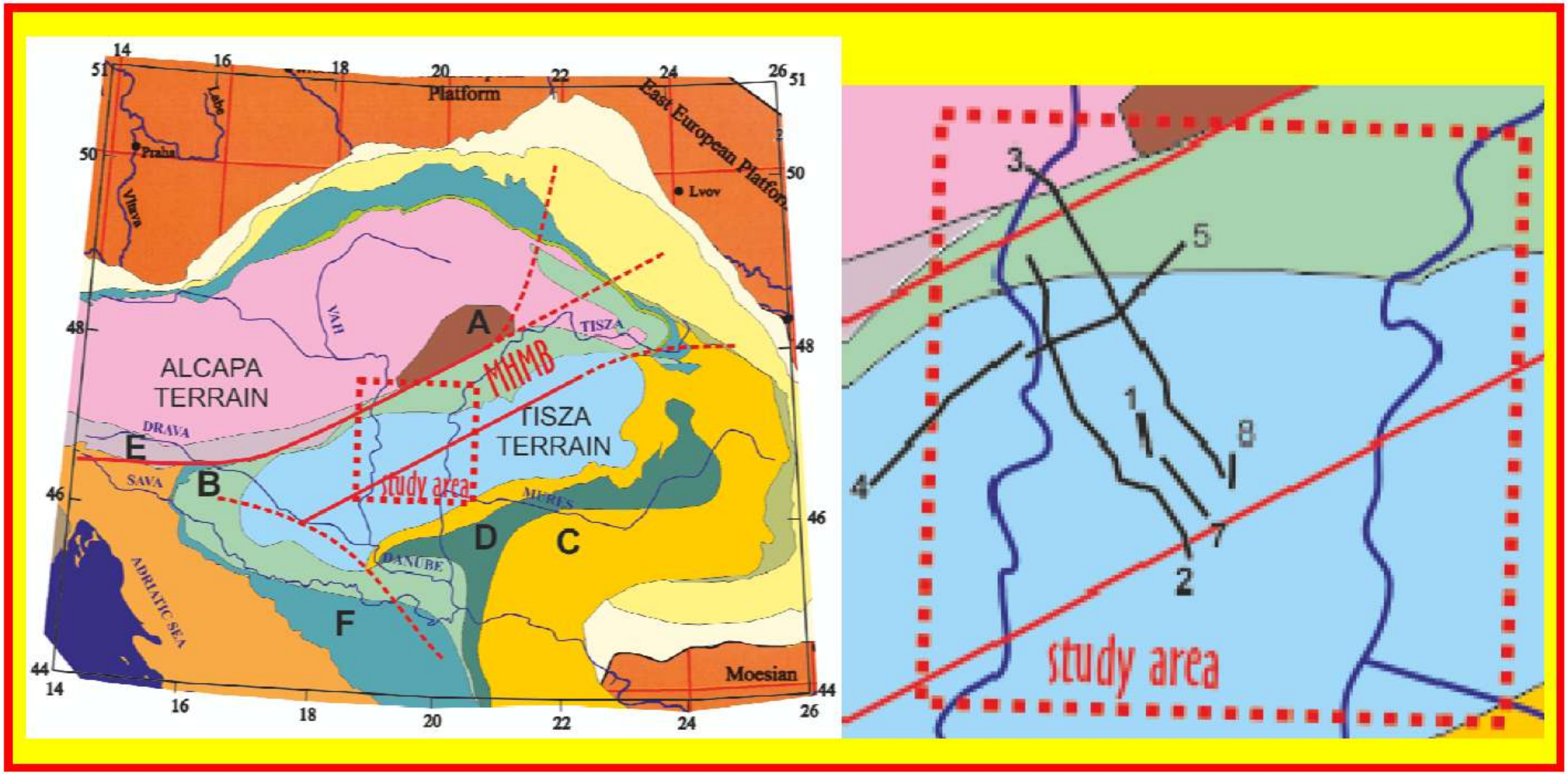

Figure 1a. Position of the study area, the Mid-Hungarian Mobile Belt and the major tectonic units. Legend: A--Bükk; B--Piemont-Liguria, Vahic, Inacovce-Kriscevo, Szolnok, Szava; C--Serbo-Macedonian, Supragetic, Subbucovinian, Bucovinian, Biharia; D--Eastern Vardar Ophiolitic unit including South Apuseni and Transylvanian ophiolites; E--Southern Alps; F--Western Vardar Ophiolitic unit (tectonic map after Schmid et al., 2008, Jarosinski et al., 2010).

Figure 1b Approximate location of vertical cross sections on Figures 2, 3, 4, 5, 6, and 7.

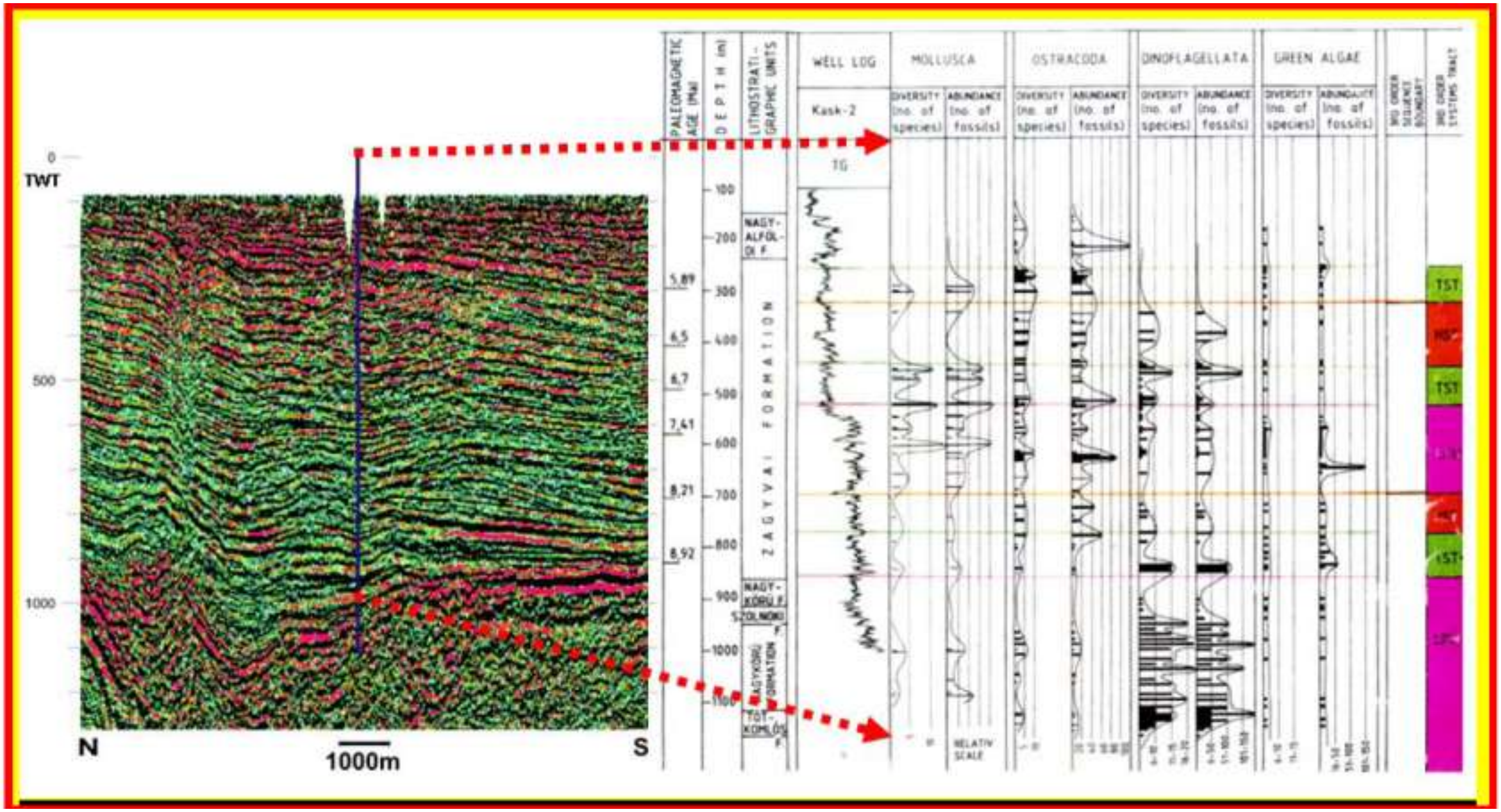

Figure 2. Results of magnetostratigraphic geological age studies on the Kaskantyu-2 well, drilled by continuous coring, have been combined with seismic time lines (Pogácsás et al., 1994) and abundance and diversity peaks of mollusks, ostracods, din flagellates, and green algae (Korpás Hódi, Sütő Szentai, Szuromi Korecz *in* Szántó, ed., 1984), with the aim of improving time-stratigraphic correlations among upper Miocene-Quaternary sedimentary rocks. Age data on the presented (composite) seismic lines are based mostly on correlated magnetostratigraphic, biostratigraphic, and radiometric (K/Ar) investigations. For location Profile (# 1) across the Kaskantyú-2 well see Figure 1b. On the # 1seismic section (left side in Figure 2) the Kaskantyú-2 well is shown to have been drilled in the southern part of a four- to five-kilometers-wide strike-slip fault zone characterized by strongly folded and faulted seismic reflection pattern. The wide-wrench-dominated seismic pattern is localized for the upper Miocene sediments underlying the 5.89 Ma horizon (Top late Miocene Unconformity).The overlying Pliocene sedimentary rocks are only very gently folded. A less-than-one-kilometer-wide Quaternary wrench fault zone can be seen on seismic section #1, three kilometers away from the Kaskantyú-2 well. The high-continuity, high-amplitude southward-dipping Pliocene aggradational unit is topped by the late- Pliocene Unconformity overlain by terrestrial Quaternary sediments.

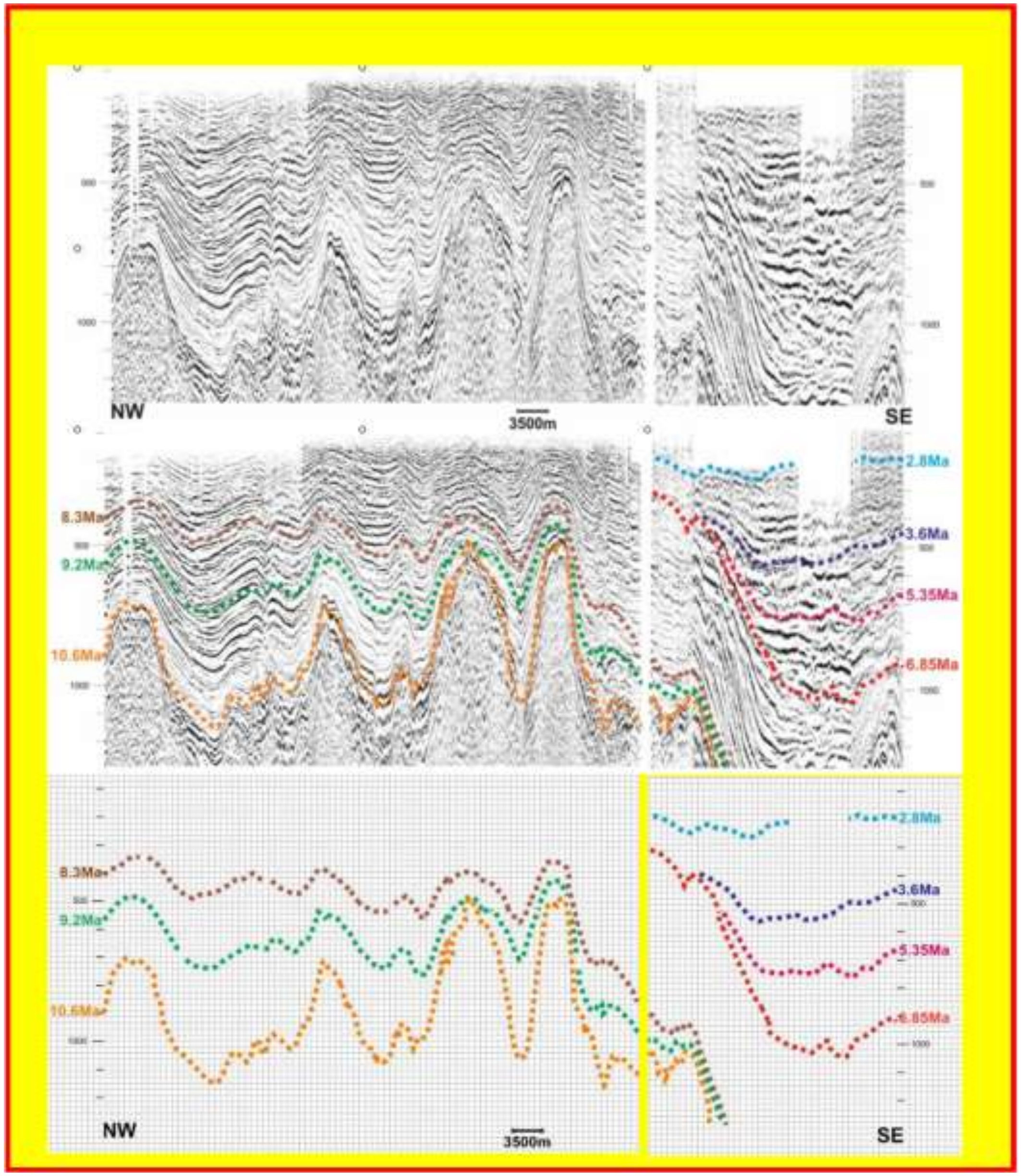

Figure 3. NW-SE-oriented composite seismic profile #2. See the approximate location of profile # 2 on Figure 1b. The 80-km-long vertical cross section is almost perpendicular to the Mid-Hungarian Mobile Belt. Figure 3a and 3b. Uninterpreted and chronostratigraphically interpreted seismic section, vertical exaggeration is 25x. Several vertical wrench fault systems can be seen on the northwestern (left) uplifted and shortened part of the cross section. Figure 3c. Folds related to the base late Miocene Unconformity (10.6 Ma horizon) can be divided into two groups. Four folds are characterized by an order of 4 to 9 kilometers wavelength, and ten much smaller folds characterized by a shorter (1 to 2 kilometers) wavelength are superimposed on the larger folds. The vertical heights of the four large folds are between 300m and 600m while the heights of the smaller folds are between 25m and 75m. The 8.3 Ma horizon shows only eight folds; order of their wavelengths is 3 to 10 kilometers. The height of the eight folds varies between 25m and 200m.

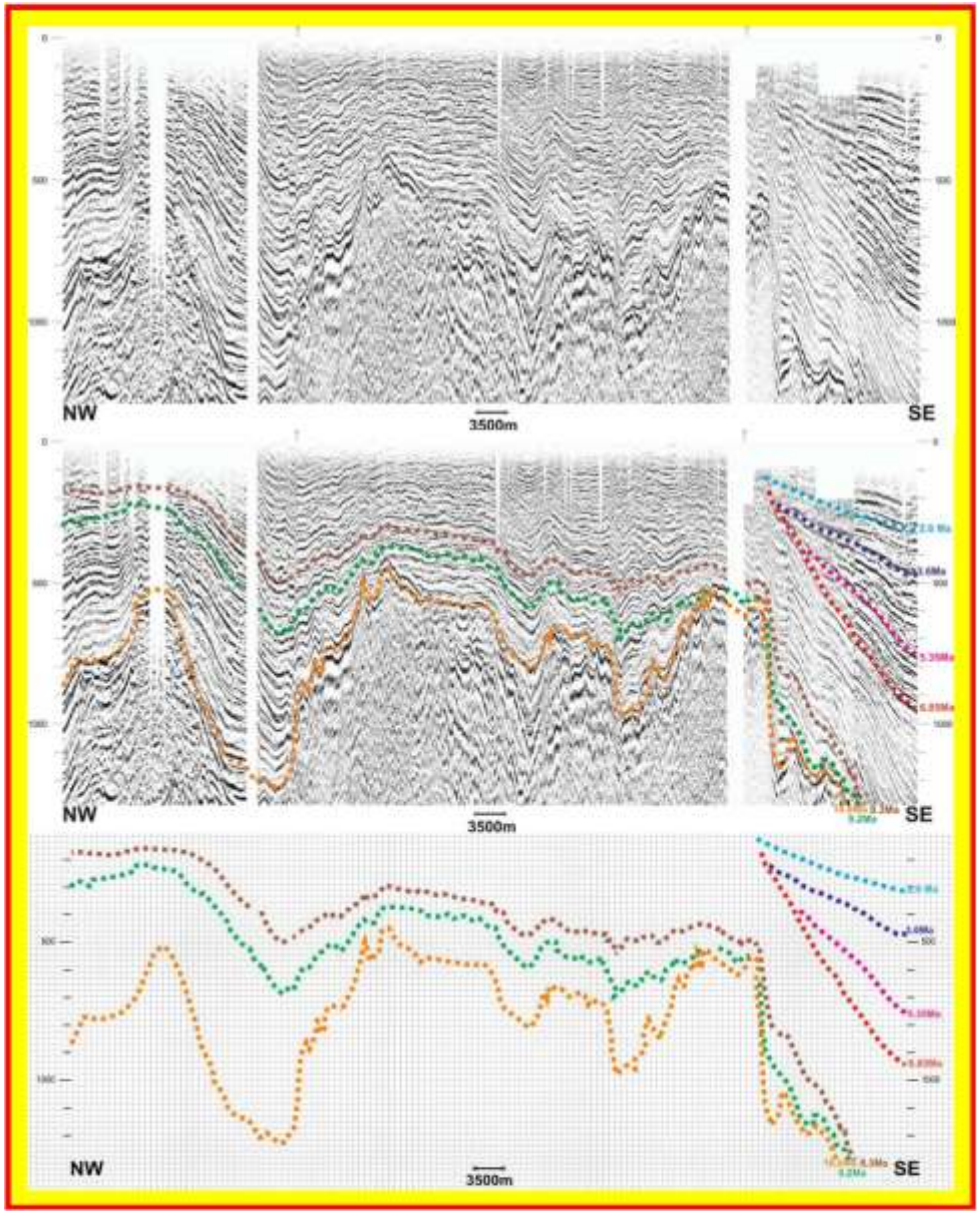

Figure 4. NW-SE-oriented composite uninterpreted and chronostratigraphically interpreted seismic profile #3. For location see Figure 1b. The 100-km-long vertical cross section is almost perpendicular to the Mid-Hungarian Mobile Belt. Vertical exaggeration is 25x. The horizontal magnitude of the shortening related larger folds in the case of the base late Miocene Unconformity (10.6 Ma horizon) is between 10 and 20 km, while several smaller size folds characterized by much shorter (1 to 2 km) wavelength are superimposed on the larger size folds. The largest fold connected to the 8.3 Ma horizon is 20 km wide and 150 m high. Folds connected to the 6.85 Ma, 5.35Ma, 3.6Ma, and 2.8Ma horizons on the SE part of the cross section are characterized by much more gentle 5- to 15-km-wide and 10- to 30-m-high folds. On the northwestern (left) uplifted and shortened part of the cross section several vertical wrench faults can be seen.

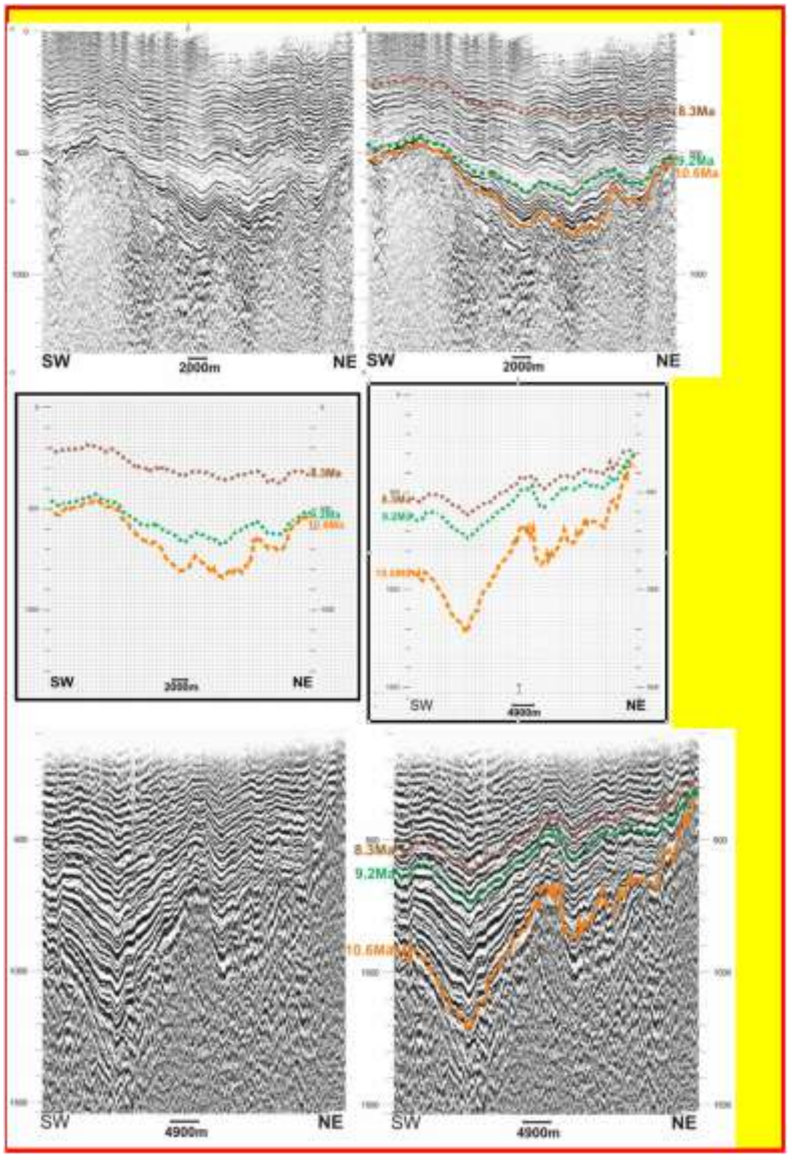

Figure 5. SW-NE-oriented cross section consisting of two seismic lines. Uninterpreted and interpreted version of seismic line # 4 can be seen on the upper part while seismic line # 5 can be seen below it.

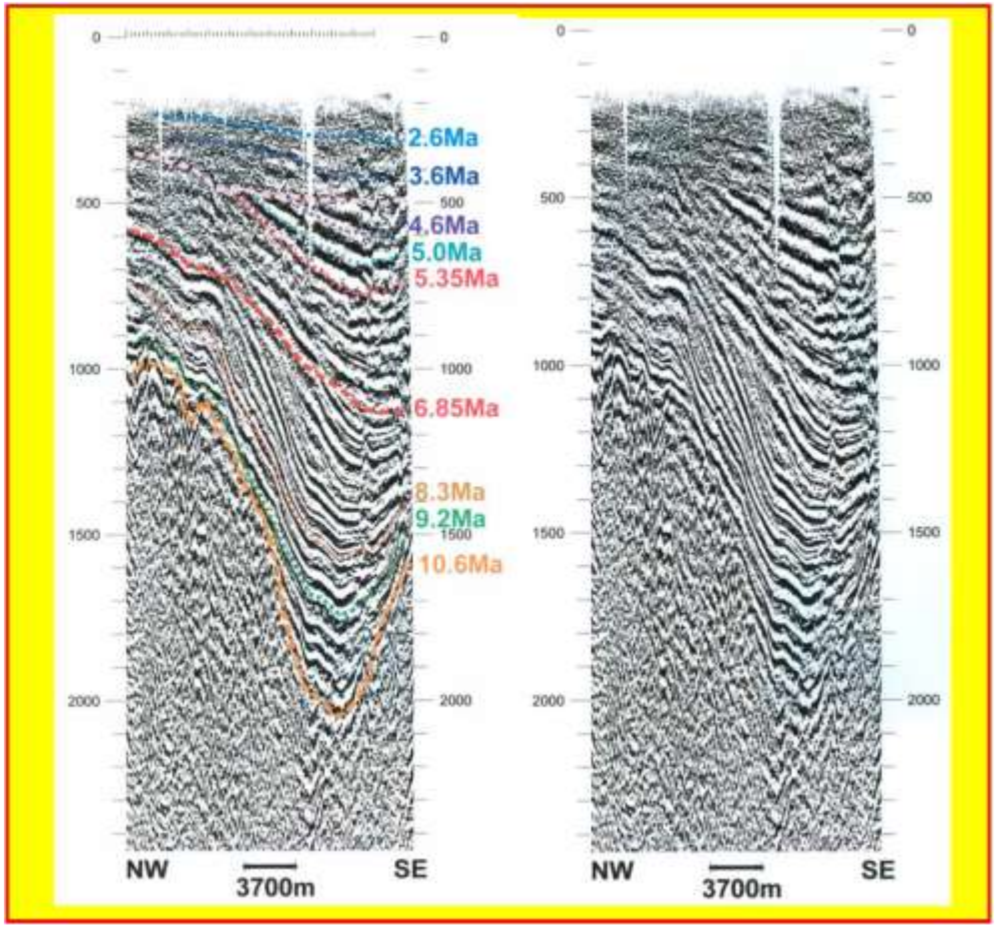

Figure 6. Uninterpreted and chronostratigraphically interpreted version of the NW-SE-oriented # 7 seismic line. Vertical exaggeration is 25x. For location see Figure 1b. Age data of correlated seismic horizons (10.6Ma, 9.2 Ma, 8.3 Ma, 6.85 Ma, 5.35Ma, 3.6Ma, 2.8Ma) were based on magnetostratigraphic and radiometric (K/Ar) data from the nearby Kaskantyú-2 and Kisk-Ny-3 wells (Pogácsás et al., 1994). The three tectonically driven unconformity are as follows:1. Base late Miocene Unconformity (identified as 10.6 Ma horizon); 2. Top late Miocene Unconformity (identified as 6.85 Ma); 3. Late Pliocene Unconformity above the 4.6 Ma horizon. Age dating of horizons younger than 5.9 Ma are more uncertain because of the questions concerning the duration of hiatuses represented by the younger unconformities. Juhász et al. (1997) also identified 2 unconformities based on sedimentological analysis and the expected duration of the hiatus from 6.2 Ma to 3.9 Ma in the case of lower and from 3.2 to 1.8 in the case of the upper unconformity. Two nearly vertical wrench fault zones can be identified on both sides of the almost 2000-msec-deep asymmetric trough. Sedimentary layers bounded by the Top late Miocene Unconformity and the late Pliocene Unconformity were affected by both nearly vertical wrench fault zones.

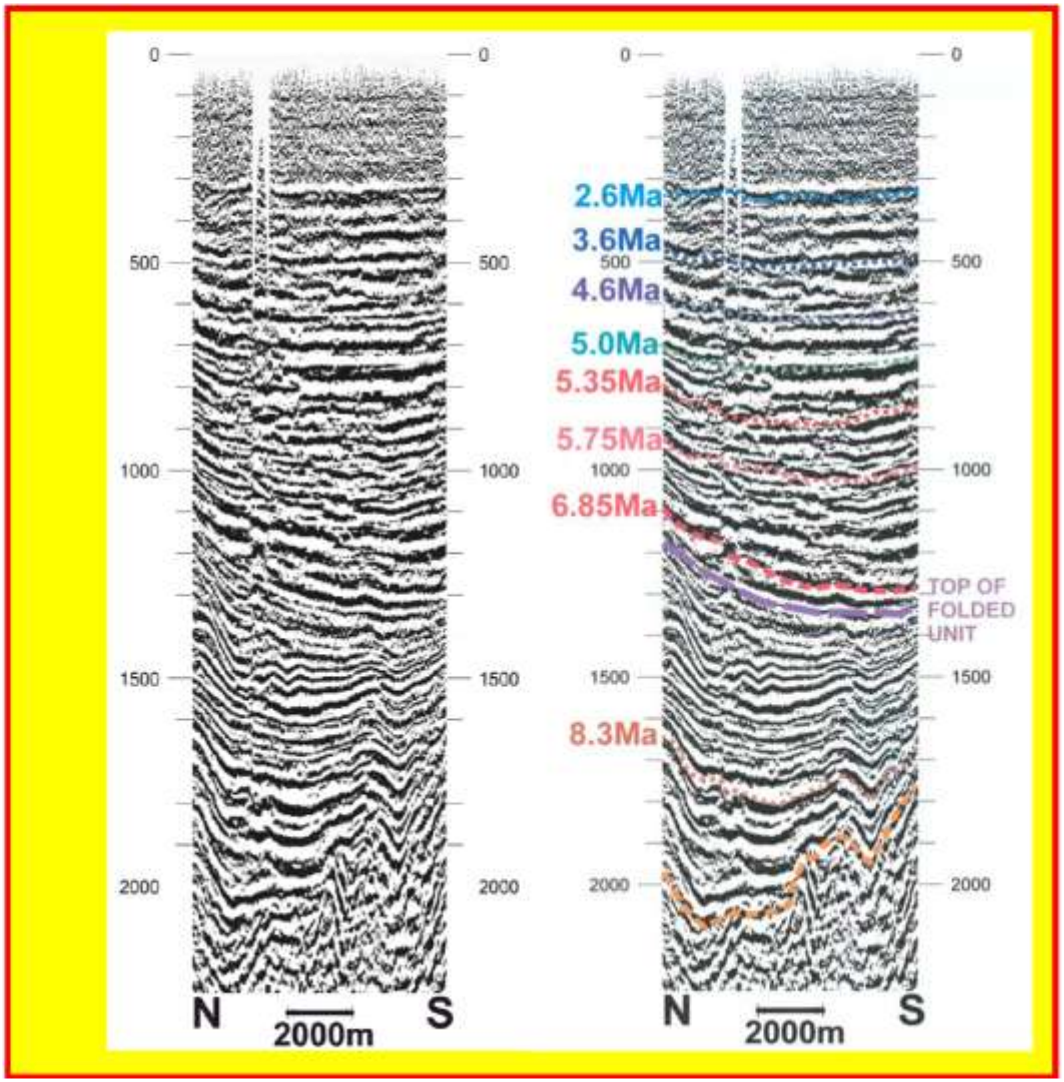

Figure 7. Uninterpreted and chronostratigraphically interpreted version of the NW-SE-oriented # 8 seismic line. Vertical exaggeration is 25x. For location see Figire 1b. Late Miocene sedimentary rocks below the Top late Miocene Unconformity are much more folded and/or shortened than the overlying younger than 6.8 Ma sediments. Age data of correlated seismic horizons (10.6Ma, 9.2 Ma, 8.3 Ma, 6.85 Ma, 5.75 Ma, 5.35 Ma, 5.0Ma, 4.6 Ma, 3.6Ma, 2.8Ma) were based on magnetostratigraphic and radiometric (K/Ar) data from the nearby Kaskantyú-2 and Kisk-Ny-3 wells (Pogácsás et al., 1994, Toth Makk 2007, Magyar 2010).