Tectonic and climatic forcing in Quaternary landscape evolution in the central Pannonian Basin: A quantitative geomorphological, geochronological and structural analysis
Ruszkiczay-Rudiger, Z.

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CHAPTER 7: NEOTECTONICS AND LANDSCAPE EVOLUTION OF THE GÖDÖLLŐ HILLS

Conclusions of the DEM-based morphotectonic-morphometric analysis of chapter 6 (Fig. 6-18, Table 6-5) were used as an initial step for this structural study. Tectonic geomorphology indicated several possible locations of structural deformation in the Gödöllő Hills. Sudden river deflections (#2, #3 and #4 on Figs. 6-13, 6-18), radial (#5, #6) and centripetal (#7) drainage networks, longitudinal valley profiles and variable degree of surface dissection enabled the recognition of possible locations of tectonic uplift and subsidence (Fig. 6-18).

In this chapter the subsurface evidences of (neo)tectonic deformation are inquired. The study of seismic reflection profiles enables to define the style, and – within certain limitations – the timing of the latest deformation phase that affected the area. Structural mapping was based on the correlation of structures observed on seismic reflection profiles, but required a basic knowledge about the structural evolution of the area. Works of Tari et al. (1992), Csontos (1995), Bada (1999), Fodor et al. (1999) provided information about regional paleo-stress orientations and fault kinematics. Structural mapping of Bada et al. (2003b) in the Southern Cserhát Hills helped structural interpretation in the NW part of the study area.

Finally, the structural analysis will be compared with possible locations of tectonic forcing on landscape evolution indicated by the morphotectonic study (chapter 6, Fig. 6-18). Results presented in this chapter are to be published by Ruszkiczay-Rüdiger et al. (2007).

7.1. Methodology and structural data sources

For the subsurface tectonic study industrial land seismic reflection profiles were used. These were shot and processed by the Hungarian Oil Company (MOL Rt), before 1997. Fig. 7-1 shows the grid of seismic reflection profiles used for the structural analysis. In the middle and upper Pannonian (late Miocene, post-rift) sediments of the Gödöllő Hills 1 ms TWT roughly corresponds to 1 m depth. The datum plane (“0” TWT) is at 50 m asl. The first imaged horizons are frequently situated 100-200 m below the “0” level of the sections. The surface of the Gödöllő Hills lies between 100 and 344 m asl, hence information about the uppermost 250-450 m, representing the sedimentary record of the last 4-6 Ma, is frequently missing. This is the most important limitation of

the timing and quantification of neotectonic deformation. The resolution of the upper imaged horizons is ~20-30 m. If the deformation remains below this limit, the youngest structures are not visualized. On the other hand, the Pannonian-Pliocene sediments are unconsolidated thus ongoing deformation is not necessarily manifested in the form of brittle faulting. A multielectrode resistivity profile (Fig. 6-3B) provided information about the deformation at the base Quaternary horizon.

Surface structural measurements in the Gödöllő Hills are hindered by poor outcrop conditions and by the thin and incomplete Quaternary sequences (see section 6.3). Under subaerial conditions original bedding is not necessarily horizontal (Photo 6-2C). An inclined loess-paleosol sequence is more probably an original feature of sedimentation on a slope than the result of tectonic tilting. Surface processes like e.g. landsliding originate outcrop scale aetectonic structures (Photo 6-3C), which have to be separated from tectonic features.

The comparison of the structural map with the geomorphic-morphometric indications of tectonic warping enabled the recognition of deformation connected to the neotectonic phase. Coincidence of structural elements and geomorphic features implies tectonic control of the landforms; where no such correspondence can be observed, no tectonic preformation on landscape evolution is suggested.

7.2. Seismic image of the main geologic formations

The uppermost imaged reflectors on seismic profiles belong to the late Miocene (Pannonian, post-rift, ~11-5.4 Ma) phase, occasionally up to the Pliocene fluvial sequences. The upper Miocene delta succession is a well reflecting formation below the Gödöllő Hills. Its characteristic layered-cake structure usually appears as continuous, gently dipping reflectors (Figs. 7-2–7-5). Deformation of these layers provide information about the neotectonic phase.

The lower Pannonian lacustrine layers are marked with occasionally vanishing reflectors. These strata onlap the characteristic unconformity horizon at the base of the Pannonian, which appears as a well recognisable double reflector (Figs. 7-2–7-5).

Late early to middle Miocene (Ottnangian-Sarmatian, syn-rift, ~18-11 Ma) formations usually overlie an erosional surface and provide variable seismic image. The middle Miocene volcaniclastic sediments give strong but irregular reflections, thus they are difficult to follow.

The pre-rift sandstones of late Oligocene – earliest Miocene age are good reflectors. Oligocene claystones, siltstones and marls provide an irregular “pepper-and-salt” texture and, in favourable circumstances, can be differentiated from the slightly stratified overlying strata. Thin sequence of upper Eocene limestone cover unconformably the basement, which generally consists of Mesozoic, mainly upper Triassic carbonates. Both are good reflectors, thence they cannot always be distinguished from each other (Figs. 7-2–7-5).

7.3. Pre-neotectonic structural evolution

Seismic reflection profiles allow the recognition of Tertiary and Quaternary structural events. Detailed description of Tertiary structures is beyond the scope of this analysis, aiming at the reconstruction of the neotectonic deformation phase. However, syn-rift and post-rift structures are important as they indicate weakness zones for the following neotectonic deformation phase. The structural map presented in Fig. 7-6 images the pre-neotectonic – syn- and post-rift – deformation affecting the base-Pannonian unconformity. Four structural regions could be distinguished in the Gödöllő Hills: the Northwestern Area (NWA), the Northeastern Area (NEA), the Tápió–Tóalmás Zone (TaTZ) and Southern Area (SA).
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Fig. 7-2. NE-SW trending seismic reflection profile across the drainage divide between the Rákos and Felső-Tápió Creeks (Rákos Capture, #2 on Fig 6-13) (after Fodor et al. 2005b), typical of the NE Area of the Gödöllő Hills. Syn-rift block rotation and normal faulting (white arrows) and post-rift normal faulting (grey arrows) were followed by an inverse neotectonic reactivation (black arrows). These faults (dotted lines) have small reverse motion associated with folding above their tip. Note tectonic control of some landforms. Location is shown in Fig. 7-1.

Fig. 7-3. NW-SE trending seismic reflection profile across the Tápió-Tóalmás Zone. Location is shown in Fig. 7-1. Tertiary transtensional flower structure has been inverted during the neotectonic phase. Fault related folding is observed above inversely reactivated earlier normal faults. These anticlines may have diverted the Alsó-Tápió valley (#3 on Fig. 6-13). Position of the multielectrode resistivity profile of Fig. 6-3B is indicated.
Before rifting

Deformation connected to early Miocene, pre-rift (~24-18 Ma) thrust faulting of NE-SW strike is characteristic only in the SA, south of the TaTZ (Fig. 7-5 and SW part of Fig. 7-4). This thrusting could be related to the “escape” of the Alcapa Unit (~32-18 Ma; Fodor et al. 1999)

Syn-rift phase

Syn-rift extension led to NW–SE trending normal faulting in the NWA, to the west of the town of Gödöllő (Fig. 7-6). Here Pannonian–Pliocene sediments are missing, thus seismic sections do not allow to date these structures. According to structural analysis of Fodor et al. (1999), these faults mostly belong to the syn-rift I. phase (18-14 Ma).

In the NEA, extension was accommodated by a set of N-S to NNW-SSE trending high angle planar and lystric normal faults. These faults delimit rotated blocks and outline syn-sedimentary asymmetric half-grabens filled up by thickened syn-tectonic middle Miocene strata (Figs. 7-2, 7-6). Seismic profiles show that normal faulting in this area occurred during the early to middle Miocene syn-rift period (~18-11 Ma; Tari et al. 1992, Fodor et al. 1999).

In the WSW-ENE trending TaTZ, in the central part of the Gödöllő Hills, a series of transtensional negative flower structures were recognised on the seismic reflection profiles (Fig. 7-3 and NE part of Fig. 7-4). In accordance with Tari et al. (1992) these structures outline a transtensional strike-slip zone developed during the syn-rift phase (Fig. 7-6). This strike-slip zone was named Tóalmás Zone by Fodor et al. (1999) and dated as middle to late Miocene. In present study this strike-slip zone is called Tápió–Tóalmás Zone (TaTZ) after its characteristic morphotectonic expression at the Alsó-Tápó valley (see below).

In the SA, to the south of the TaTZ limited amount of Neogene extension can be observed (Tari et al. 1992; Fig. 7-5 and SW part of Fig. 7-4).

During early to middle Miocene NE-SW extension of the Pannonian Basin gradually shifted to a NW-SE direction (Fodor et al. 1999). The Tápió-Tóalmás Zone is one of the ENE-WSW oriented shear zones, which acted as transfer faults by connecting areas of different magnitude and polarity of extension (Tari et al. 1992), like e.g. Northern and the Southern Areas of the Gödöllő Hills. Segments of the TaTZ shift their polarity along strike between north and south.
and are organized in en-echelon geometry (Fig. 7-6), which suggest left lateral component of shear (Fodor et al. 2005b; Ruszkićzay-Rüdiger et al. 2006).

**Post-rift phase**

During the post-rift phase (~11-6 Ma) the orientation of the stress axes was similar to the late syn-rift period (~NW-SE extension and ~NE-SW compression; Fodor et al. 1999), which allowed post-rift reactivation of earlier structures. In the NEA normal faulting continued during the post-rift phase as shown by the normal offset of several faults at the base of the Pannonian together with thickened and onlapping lower Pannonian lacustrine sediments (at 3, 5.5 and 7.5 km along section on Fig. 7-2). Amplitude of monoclinal (narrow zone of tectonically tilted strata; see at ~6 km on Fig. 7-2) related to these faults rarely exceeds 50 ms (~50 m). Slight normal offset of the upper Pannonian strata (around the resolution of the seismic sections, i.e. ~20 m; at 7.6 km on Fig. 7-2), suggests slight normal faulting up to ~4 Ma.

In the TaTZ sudden changes in thickness and syn-tectonic wedges of lacustrine lower Pannonian layers refer to rejuvenation of transtensional flower structures during the beginning of the post-rift phase (~4 km on Fig. 7-3 and ~6 km on Fig. 2-22), as recognised already by Csontos and Nagymarosy (1998). The normal offset of the negative flower structures of the TaTZ at the base of the Pannonian and syn-sedimentary thickening of the lower Pannonian strata are indicative of early Pannonian transtensional deformation, which gradually ceased in the late Pannonian (Fodor et al. 1999; Figs. 7-3, 7-4).

**7.4. Neotectonic structural evolution**

In the Gödöllő Hills deformation of the uppermost reflectors, which mainly show gentle folding with a maximum amplitude of a few hundred ms, is assumed to be associated with the neotectonic phase. Brittle faulting of these strata is rarely observed in the resolution provided by the seismic sections (Figs. 7-2–7-5). Fig. 7-7 shows the structural map of the neotectonic phase.

In the NWA, where the post-rift sedimentary suite is missing and pre-Pannonian rocks are at the surface no neotectonic structures are recognisable on the seismic profiles.
In the NEA small anticlines have appeared above the tip of the syn- to post-rift faults (at 1 and 2.7 km along section on Fig. 7-2). These drag folds are consequence of the inversion of former normal faults, their amplitude is usually \( \sim 50-150 \) ms. Reverse displacement was not sufficient to compensate the earlier normal offset at the base Pannonian discordance surface. Reverse separation is very small, distributed deformation and updoming of the upper Pannonian layers is characteristic. Bending of the layers was not induced by drape folds, as sediment-thickness above the hinge and on the flanks of the anticlines is similar. The deformation of the uppermost, lower Pliocene layers imply that neotectonic warping occurred during the last \( \sim 4 \) Ma (Fig. 7-2). Unfortunately the profiles do not allow determination of the upper time constraint of the motion.

In the TaTZ the uppermost reflectors above the tip of the syn- to post-rift transtensional flower structures form anticlines of \( \sim 30-250 \) ms amplitude (between 2 and 7 km on Fig. 7-3, 5-10 km on Fig. 7-4). These folds are interpreted as drag folds above the inversely reactivated fault branches. Similarly to the NEA reverse separation was small, thus these faults still show normal offset at depth (base Pannonian horizon at 3 km on Fig. 7-3, at 7.5 km on Fig. 7-4). The transpressional deformation is dated as post-Pannonian and is connected to the inversion of the earlier transtensional flower structure. According to the seismic profiles – similarly to the NEA – neotectonic inversion started in the Pliocene (\( \sim 4 \) Ma) and may be active up to present (Fodor et al. 2005b, Ruszkiczay-Rüdiger et al. 2006).

To verify late Pleistocene activity of the TaTZ, a multielectrode resistivity profile was measured N of the village of Mende (see section 6.3, Fig. 6-3B; Fodor et al. 2003b). This profile follows a SE dipping ridge-top running parallel to relevant segments of the seismic reflection profiles presented in Figs. 7-3 and 7-4 and crossing the northern branch of the TaTZ. Slight deformation of the boundary of the loessy and clayey layers visualizes five anomalies along the section (Fig. 6-3B). Four of these (at 300, 400, 550 and 700 m, black arrows) can be interpreted as consequences of structural deformation along the northern branch of the TaTZ. The fifth anomaly (at 1000 m; grey arrow) proved to be only an artefact caused by bad electrode contact at a road, perpendicular to the profile. The gently dipping base of the upper,
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7.4 Sandy-loess body is slightly warped above the TATZ suggesting that deformation continued up to late Quaternary times.

In the S4 faulting of the post-rift sediments is not observable (SE part of Fig. 7-4 and Fig. 7-5). The lower Pannonian lacustrine layers are usually thin or missing and the upper Pannonian sediments are folded. They form synclines and anticlines with 100-300 ms amplitude, and 10-20 km wavelength below the Gomba Depression and the Pánd Antiform (at ~12-30 and 20-38 km along section, respectively on Fig. 7-4 and at ~5-12 km on Fig. 7-5). Smaller anticlines and sliding are common on major fold limbs (at 13-15 km on Fig. 7-4). The warping affected the upper Pannonian layers up to the uppermost imaged reflectors and is suggested to be coeval with the ~4 Ma inversion in the NEA and with the shift from transtension to transpression along the TaTZ. Earthquakes (Zsíros, 2000) in the S4 (around Pánd), in the Jászság Basin and in the SE elongation of the TaTZ (south of Budapest, Fig. 7-7) suggest that deformation may last until the Holocene.

7.5 Neotectonic deformation pattern in the light of surface morphology

In this section connections between the youngest structures and surface morphology (based on results chapter 6; Fig. 6-18) are examined with special emphasize on the peculiarities of the drainage pattern. Joint investigation of the seismic sections, of the derived structural map and of the landforms revealed considerable similarities between the topography and the shape of the youngest imaged layers.

The NW-SE trending valley system

The northwest-southeast-trending valleys and the sharp, rectilinear southwest boundary of the Gödőllő Hills were mostly defined as structurally controlled landforms carved by fluvial erosion (e.g. Schafarzik 1918; Rozloznik 1936; Marosi and Szilárd 1981; Gábris 1987; Síkhegyi 2002) and re-shaped by mass wasting (Balla 1959; Láng 1967). Significant wind erosion along these landforms was first stressed by Strömpl (1912), Lóczy (1913), Cholnoky (1918), Rozloznik (1936) and by Pávai Vajna (1941). New investigations disprove structural control and support a deflationary origin of this valley set (e.g. Fodor et al. 2005a,b; Ruszkiczay-Rüdiger et al. 2006).

The characteristic SE slope of the ridge-tops of the Gödőllő Hills resembles the common SE dip of the upper Pannonian reflectors (Figs. 7-3, 7-4), however usually the later is slightly steeper. Smoothed dip angle for both surface and upper Pannonian reflectors remains below 1°, usually around 0.5°. This suggests that the prominent SE slope and the consequent NW-SE valley directions are surface expressions of tilting towards the subsiding GHP. “Structural control” of the SE trending valleys means that they follow the tilt of upper Pannonian–Pliocene sediments.

Sharp NW-SE trending boundaries of the Isaszeg Channel and Úri Ridge (Figs. 3, 4) lack structural control: on seismic reflection profiles no corresponding faults cut the Pannonian sediments (Figs. 7-2, 7-5; map view on Fig. 7-6, 7-7). According to the morphometric analysis of the previous chapter, these landforms were shaped by spatial change from fluvial to wind erosion.

River deflections 1: peculiar drainage divides

Two valley-floor drainage divides have developed within the Isaszeg Channel. The watershed between the catchments nr. 5 and 6 coincides with the boundary fault of the
Pannonian sediments (“#1” on Figs. 6-18, and 7-6). Possibility of neotectonic inversion related uplift along this fault could not be excluded nor verified, as upper Miocene layers are not imaged by the seismic sections. In the Northwest Area (NWA), where Pannonian sediments are missing, lithologic control may have played an important role in landscape evolution. Slower erosion of more resistant rocks on the hanging wall could fix the drainage divide. In the west, around the town of Fót steep NW-SE slopes also reflect exhumed the pre-Pannonian faults (Fig. 7-6).

The second intra-valley drainage divide is connected to the Rákos Capture (“#2” on Figs. 6-18, and 7-7). According to the seismic reflection profiles Quaternary inversion of N(NW)-S(SE) trending syn-rift normal faults led to folding of the upper Pannonian layers with an amplitude of ~100-150 ms (Fig. 7-2). Such anticline is observable below the watershed between the Rákos and Felső-Tápió Creeks (“#2” on Fig. 7-7) suggesting considerable influence of the growing anticline on the diversion of Rákos Creek.

The relative relief of the watershed above the anticline (respective to the Rákos Creek) is ~100 m in the Úri Ridge, while it is less than 25 m within the Isaszeg Channel. This drainage divide is the highest section of the Isaszeg Channel, on its smooth surface no evidence of Quaternary alluvial sediments was found. The Pliocene cross-bedded sandstone is at the surface or covered by a wind-blown sand sheet with deflation hollows and small sand dunes (Fig. 6-4A). Above the southern continuation of this anticline, the most dissected part of the Úri Ridge is characterised by the dominance of landforms of riverine erosion (Fig. 6-4A). Both landscapes are above the uplifting hinge of the anticline visualized by the seismic reflection profiles (Figs. 7-2, 7-7). Results are in good accordance with the morphometric analysis of chapter 6 suggesting that severe deflation caused significant denudation in the Isaszeg Channel and fluvial erosion led to surface dissection with smaller denudation in the Ridges.

To the west, the incision of the Danube in the Pest Plain (Pécsi 1959b; chapters 3, 5) assisted the deflection of the Rákos Creek by increasing its gradient. The early Pleistocene terrace of the Danube (tV; min. age ~800 ka; Leél-Össy 1953, Pécsi 1959b; chapter 3) predates the incision of the Rákos Creek. The graded longitudinal profile of the Rákos Creek and its high concavity (Fig. 6-15) suggest that a longer period (i.e. several 100 ky) have elapsed since the capture. The valley evolution and loess formation model proposed in section 6-5 (Fig. 6-17) suggests that the first major phase of valley incision occurred between 450-800 ka. Accordingly, the date of the river caption is tentatively placed into the early middle Pleistocene (~0.5-0.8 Ma), more precise age determination is not possible so far. The lower time constraint of the Rákos Capture is ~4 Ma, which is the date of the onset of neotectonic inversion in the study area suggested by the seismic sections (Fig. 7-2).

**River deflections 2: the Tápió-Tőalmás Zone**

The upper and lower sections of the Alső-Tápió and Kókai Creeks flow consequently to the southeast (e.g. Figs. 6-13, 7-6). However, their WSW-ENE trending middle reaches are deflected (“#3” and “#4” on Figs. 6-13, 6-18). These asymmetric valley sections developed in front of the raising anticline above the S branch of the Tápió-Tőalmás Zone (TaTZ; Fig. 7-7). The fold amplitude along the fault branches regularly decreases towards the east, hence it is the highest at the sites of river deflection; i.e. at the bending of the Alső-Tápió and Kókai Creeks (“#3” and “#4”). The maximal fold amplitude reaches 250 ms but the relative relief of the surface does not exceed ~70-80 m. Eastwards, the morphologic expression of the TaTZ decreases because of the smaller amplitude of the structures and the proximity of the subsiding Jázság Basin. The lowered anticlines permit both streams turning again to the SE and leave the TaTZ. Seismic sections suggest that structural inversion is younger than ~4 Ma (Figs. 7-3, 7-4). Chronostratigraphy of the loess-paleosoil sequence in the Alső-Tápió valley at Mende
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River deflections 3: radial and centripetal valley networks

The geomorphologic-morphometric investigation demonstrated that in the Gödöllő Hills the drainage network is radial at two locations (section 6.4.4). At the first site, to the north of the Rákos Capture ("#5" on Figs. 6-13, 7-7) the neotectonic deformation is expressed as a set of NNW-SSE trending anticlines above the inversely reactivated syn-rift normal faults (Figs. 7-2, 7-7). The folding of the upper Pannonian sediments diverted the Besnyői (nr. 1b on Fig. 6-18), Nagy (nr. 2) and Sósi (nr. 3) Creeks from the consequent SE flow-direction. As this is the northern continuation of the structure below the Rákos Capture, their age is suggested to be similar. The structural deformation is are younger ~4 Ma (Fig. 7-7) and the river deflection can tentatively placed to the middle Pleistocene (~0.5-0.8 Ma; see section 6.5 and Fig. 6-17). High surface roughness (e.g. Fig. 6-6, 6-9, 6-14, Table 6-5) of this part of the Valkó Ridge and low concavity of streams incised into the anticlines are indicative of the dominance of fluvial incision probably enhanced by young activity of this deformation (Fig. 6-18).

The second site, where radial valley network have developed is the so-called Pánd Antiform ("#6" on Fig. 7-7). Seismic reflection profiles demonstrated that the smoothed envelope surface of the Pánd Antiform coincides with an anticline of the upper Pannonian layers (Figs. 7-4, 7-5, 7-7). Morphometric parameters reflected considerable dissection of this area, in spite of its low elevation and position at the SE tongue of the Úri Ridge (Fig. 6-18, Table 6-5). Accordingly, radial valley-pattern most probably mirrors the neotectonic deformation of the area.

Between the TaTZ and the Pánd Antiform a surface depression, the so-called Gomba Depression has a centripetal drainage network, which is typical of subsiding areas ("#7" on Fig. 7-7). In the subsurface of this landform the upper Pannonian layers are folded with 100-300 m amplitude (Figs. 7-4, 7-7), whereas the topography reflects 60-70 m difference in elevation. In the centre of the depression the Gombai Creek has a wide alluvial plain indicating sediment accumulation within the actively deforming syncline.

Earthquakes clustering around the Gomba Depression and Pánd Antiform (Zsíros 2000, Fig. 7-7) suggest ongoing blind thrusting at depth (at ~25 km along section on Fig. 7-04) leading to the folding of the Pannonian-Pliocene strata (Fodor et al. 2005b). Accordingly, the age of folding is younger than ~4 Ma and probably lasts until present day.

7.6. Conclusions: Quaternary landscape evolution of the Gödöllő Hills

According to this study both neotectonic deformation and climate-related surface processes played an important role in the landscape evolution of the Gödöllő Hills. The termination of alluvial sedimentation and truncation of the Pliocene sandstone occurred when the overall subsidence of the Gödöllő Hills paused. This period coincided with a warm, semiarid – late Pliocene - earliest Pleistocene – climate spell, which was favourable for pediment formation. During early Pleistocene times the climate oscillations increased and the temperature decreased.

Independent geomorphic evolution and connected dissection of the landscape started with the incision of the Paleo-Danube separating the study area from the TR. The onset of the incision of the Danube can be placed, as earliest, into the early Pleistocene, which is the
assumed “traditional” age of the highest terrace (tV) of Danube in the area (Pécsi 1959b, chapter 3). Increased amount of volcanic minerals in the tIV with respect to the tV in the Pest Plain (Szabóné Drubina 1981) suggests that incision of the Danube into the tV in the Pest Plain coincided with its carving into the volcanic rocks of the Danube Bend. $^3$He exposure age dating of strath terraces suggest middle to late Pleistocene downcutting into the volcanic rocks in the Danube Bend (chapter 5), which is the earliest suggested age of the dissection of the Gödöllő Hills. Quaternary evolution of the study area is shown in a 3D model (Fig. 7-8), which was
compiled using subsurface structural, surface geomorphological and outcrop data (after Fodor et al. 2003a).

Fig. 7-7. Neotectonic structures of the Gödöllő Hills (deformation of the uppermost imaged reflectors; ~4-0 Ma; modified after Fodor et al. 2005b, Ruszkiczay-Rüdiger et al. 2006). Stress axes after Gerner et al. (1999) and Tóth et al. (2002). Earthquakes after Zsíros (2000). Locations of river deflections triggered by neotectonic warping are indicated according to Fig. 6-13. Small inset shows the drainage basins of the area. Abbreviations as in Fig. 7-6.

Surface features with no corresponding structure

Seismic reflection profiles and structural mapping proved that no structural elements are reconcilable with the NW-SE trending linear boundaries of the Isaszeg Channel and Úri Ridge (Figs. 7-5, 7-7).
Significant influence of wind erosion has been suggested by the geomorphologic study of chapter 6, in shaping the macro-scale landforms of the Gödöllő Hills (Figs. 6-4, 6-18). Spatial and temporal variation of deflation, fluvial erosion and sediment accumulation led to the development of the Valkó and Úri Ridges, separated by a wind channel, the Isaszeg Channel. The Ridges evolved in relatively wind-shielded position and climate oscillations led to several phases of eolian dust deposition and fluvial incision (Fig. 6-17). The valleys typically follow a NW-SE strike in accordance with the structural tilt of area towards the subsiding GHP. Accordingly, in the Gödöllő Hills fluvial erosion and deflation acted in similar direction, which led to the development of landforms of complex origin.

According to this study (together with Fodor et al. 2005a,b, and Ruszkiczay-Rüdiger et al. 2006), the Isaszeg Channel is the easternmost member of the fan-shaped “meridional” valley-set, which has been cut from the Transdanubian area by the incision of the Danube. Our results are in accordance with earlier authors suggesting mainly eolian origin of the Transdanubian “meridional” valleys (Lóczy 1913, Cholnoky 1918, Jámbor 2002, Bada et al. 2003a, 2005a,b, Fodor et al. 2003a,b 2005a,b).

![3D model of the structural and landscape evolution of the Gödöllő Hills](after Fodor et al. 2003a). The model is based on field observations, geomorphology, outcrop data, DEM analysis, seismic reflection profiles and structural mapping. #3, 4, 7 refer to drainage anomalies (Fig. 7-7).

**Structural deformation**

Quaternary structural deformation in the Gödöllő Hills has been documented in form of inversion of earlier normal faults and transpressive reactivation of the transtensional Tápió-Tőalmás Zone (TaTZ). The neotectonic inversion is expressed by the folding of the uppermost imaged horizons above inversely reactivated Neogene normal faults.
Slight normal offset of some faults in the early Pliocene layers (Fig. 7-2) suggest that post-rift extensional-transpressional deformation of the Gödöllő Hills ended only ca. 4 Ma ago. This delay with respect to the onset of the neotectonic phase at ~6 Ma in S Transdanubia (Fodor et al. 2005b, Bada et al. 2005a) indicates a significantly later (i.e. ~4 Ma) onset of the neotectonic phase in the Central Pannonian Basin and led to only moderate deformation of the Gödöllő Hills with respect to S Transdanubia (Bada et al. 2005a; Fodor et al. 2005b; Fig. 2-2).

Most prominent expressions of the neotectonic deformation are the river deflections, (section 6.4). The capture of the Rákos Creek ("#2" on Fig. 7-7) was triggered by a growing anticline above an inversely reactivated normal fault (Figs. 6-18, 7-2, 7-6, 7-7). The same deformation may account for the high surface roughness of the Ridges to the N and S of the Rákos Capture (e.g. Figs 6-5, 6-6, Table 6-5), for the radial drainage network in the central part of the Valkó Ridge ("#5" on Fig. 7-7) and also for the immature long profiles of streams 1a and 1b (Fig. 6-15). This anticline controlled locally the position of the Danube-Tisza drainage divide (Fig. 7-7).

The ENE-WSW trending middle reaches of the Alsó-Tápió and Kókai Creeks follow segments of the TaTZ (Fig. 7-7, 7-8). En echelon arrangement of the faults and related folds suggest sinistral motion and transpressional character of this strike-slip zone. According to this study, these deflected valleys are the continuation of the Transdanubian “longitudinal” valley set, where structural studies of Magyari et al. (2005) and Csontos et al. (2005) also suggested neotectonic reverse and strike-slip faulting mostly along reactivated earlier faults.

Reverse reactivation of NNW-SSE normal faults in the Northeastern Area (NEA) and the above described deformation pattern along the TaTZ refer to NE-SW compressional-transpressional stress field for the neotectonic phase (Fig. 7-7), which is well reconciled with recent stress field data (Gerner et al. 1999; Tóth et al. 2002).

The Gomba Depression ("#7" on Figs. 7-7, 7-8) developed above the hinge of a wide syncline of the post-rift layers. Southwards, the Pánd Antiform ("#6" on Fig. 7-7) has developed above an anticline of the post-rift sequence. There, deformation is mirrored by the radial drainage pattern and increased surface roughness (Fig. 6-18). Based on earthquake distribution data Balla (1959) suggested the presence of an active fault zone through this area and the Járszáig Depression. According to seismic reflection profiles these earthquakes are most probably connected to neotectonic folding of the Pannonian strata possibly related to a blind reverse fault at depth (Fodor et al. 2005b).

Typically minor amplitude of surface undulations (~30-100 m) respective to the amplitude of folding of the upper Pannonian layers (~50-300 m) indicates that erosion smoothed the deforming topography. In the Ridges fluvial erosion dissected the surface and the overall lowering was smaller compared to the Isaszeg Channel where deflation resulted in strong areal denudation (sections 6.3, 6.4, Figs. 6-5, 6-6, 6-4, 7-2, 6-18, 7-8).

According to the time constraints provided by the available data sets, there is a significant time lag between the onset of the neotectonic deformation and the appearance of its surface expression. Seismic reflection profiles suggest ~4 Ma for the onset of the inversion, while development of related geomorphological features – e.g. river deflections (e.g. Rákos, Alsó-Tápió Creeks) above growing anticlines – was tentatively placed to the middle Pleistocene, ~450-800 ka on the basis of geomorphology and loess stratigraphy (see chapter 6.5, Fig. 6-17).

Two equally important reasons can account for this delay. Firstly, the denudation processes were stronger during Pliocene - early Pleistocene times, thus they were able to obliterate surface expressions of the deformation. Secondly, the deformation in the first period of the neotectonic phase was slower and structural motions have been accelerating towards present. This is in agreement with terrace studies along the Danube River (chapters 3, 5) also documenting an acceleration of vertical motions.