Geological deformations in the Pannonian Basin during the neotectonic phase: new insights from the latest regional mapping in Hungary

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Abstract

The present paper introduces the new 1:500 000 scale map of young geological deformations in Hungary, including all important deformation structures (faults and folds) related to the neotectonic evolutionary phase (<6–8 Ma) of the Pannonian basin.

The new map is based on the interpretation of nearly 2900 2D seismic profiles and 70 3D seismic volumes, as well as on the critical evaluation of the results of published neotectonic studies. An important novelty of the map is that not only the near-surface manifestations of the neotectonic faulting, but also their roots in the underlying pre-Pannonian substratum are displayed, allowing correlation between various reactivated fault segments of longer fault zones and aiding the better understanding of the regional structural context.

The new map provides a significantly more accurate definition (actual position, extension and geometry) of the neotectonic structures and provide more details compared to previous regional studies. The prevailing (E)NE–(W)SW striking neotectonic fault pattern clearly reflects the control of identically oriented pre-Pannonian fault systems during the neotectonic deformations. Markedly different orientations in the neotectonic structures indicate important differences in the overall orientation of the underlying fault systems. These observations demonstrate that neotectonic activity is predominantly due to the reactivation of pre-existing (predominantly synrift) structures all over the Pannonian basin, as also indicated by previous studies.

Despite experiencing the largest Middle- to Late Miocene extension and the formation of the deepest depocenters in the whole Pannonian basin, SE Hungary practically lacks any observable neotectonic activity, which is a striking, but still poorly understood feature.

Detailed 3D seismic analysis of fault segment geometries indicates a consistent regional pattern: sinistral shear along (E)NE–(W)SW oriented, and dextral shear along (W)NW–(E)SE oriented fault zones, respectively. These observations — together with the E–W trending contractional/transpressional structures (folds, reverse faults, imbricates) occurring in western and southern Hungary — indicate a dominantly strike-slip stress regime with a laterally slightly rotating (from N–S to NNE–SSW) maximum horizontal stress axis (σ_1) during the neotectonic phase. Lateral displacement along major root zones amounts to a maximum of 2–3km during the neotectonic phase.

Keywords: neotectonic phase, Hungary, Pannonian basin, seismic interpretation, faults, folds

1. Introduction

The first GIS-based, regional neotectonic map of Hungary was published almost 15 years ago (Horváth et al., 2006a), and can be considered as a pioneering scientific achievement in the region. It was mainly based on the compilation, re-evaluation and correlation of structural elements depicted on numerous published and unpublished maps (e.g., Horváth and Tari, unpubl.; Pogácsás et al., 1989; Csontos, 1995; Csontos and Nagymarosy, 1998; Wórum, unpubl.; Tóth and Horváth, 1997; Detzky Lőrincz et al., 2002; Síkhegyi, 2002, Bada et al., 2003a-b, 2006; Wórum and Hámori, unpubl.; Fodor et al., 2005a-b; Windhoffer et al., 2005). However, due to the applied scale and the limited use of seismic data this new initiative basically remained a large-scale, partly model-driven overview of the most important neotectonic structures in the Pannonian basin.

Later on several modified versions of this map was published (Horváth et al., 2009, Bada et al., 2007, 2010), but the concept of the map itself did not change. Apart from these maps only one regional neotectonic overview was published (Fodor et al., 1999) based on modern, although restricted amount of data.

Despite the numerous published, local-scale neotectonic studies (for details see Section 3.) a main deficiency of the former neotectonic research activity in Hungary was the lack of integrated databases used for the neotectonic evaluation (including extensive sets of seismic surveys) and their systematic tectonic interpretation according to a uniform methodology. The main goal of this work was to construct a completely new, detailed map of young geological deformations in Hungary considering (i) as large as possible set of 2D and 3D seismic data interpreted in a systematic and consistent manner, and structurally correlated using trends emerging from interpreted seismic time horizon and geophysical maps; (ii) the results of all previous relevant neotectonic studies based both on surface and subsurface data.

The resulting new map (available at http://dx.doi.org/10.17632/dnjt9cmj87.1 and www.geomega.hu) is significantly more detailed (1:500 000) than any of its countrywide precursors and opens up a whole range of utilization purposes ranging from (neo)tectonic and geodynamic syntheses, regional- or local scale modelling studies, through strategic infrastructure developments and construction works, to the assessment of seismotectonic risks.

The main objective of this paper is to present and discuss the most important results of the new map, following the introduction of the geological background, the integrated geological-geophysical database, the key structural elements appearing on the map and the principles of the map construction.

2. Geological setting

The Pannonian basin surrounded by the Alpine, Carpathian and Dinaric mountain chains in Central Europe (*Fig. 1*) forms a classical back-arc basin of Miocene age (Royden, 1988) within the Alpine orogenic system. The basin floor in the Hungarian part of the basin is constituted by two Alpine orogenic megaunits (Alcapa and Tisza-Dacia; Balla, 1988; Csontos and Vörös, 2004; Schmid et al., 2008), showing markedly different paleogeographic affinity and geological evolution during the pre-Cenozoic times (e.g., Kovács et al., 2000; Haas and Péró, 2004 and references therein). These megaunits were juxtaposed along the Mid-Hungarian Fault Zone (MHFZ; *Fig. 1*) preceding the Miocene basin formation (Balla, 1984, 1988; Kázmér and Kovács, 1985; Csontos et al., 1992; Tari, unpubl.; Csontos and Nagymarosy, 1998; Fodor et al., 1998, 1999; Györfi et al., 1999; Tischler et al., 2007; Fodor, unpubl.).

In the Hungarian part, basin formation started in the Early Miocene, approximately 21 Ma ago (Horváth, 1993; Horváth et al., 2015, 2019). During the peak period of extension in the Early and Middle Miocene (the synrift phase of Royden et al., 1983) the main structural frame of the basin was established, characterized by normal and associated strike-slip faulting. Rifting took place diachronously across the basin culminating in the Early to Middle Miocene in the western and central and in the early Late Miocene in the eastern subbasins, respectively (Matenco and Radivojevic, 2012; ter Borgh et al., 2013; Balázs, et al. 2016). The continental depositional environment of the early stage (ca. 21–17 Ma, i.e., Eggenburgian–Ottnangian) changed to marine conditions from the Karpatian on due to the transgression of Central Paratethys (for a detailed overview see Horváth et al., 2015, 2018). This first period of basin evolution was also accompanied by a widespread silicic and subsequent calc-alkaline magmatic activity (Pécskay et al., 2006; Harangi and Lenkey, 2007; Lukács et al., 2018; *Fig. 1*).

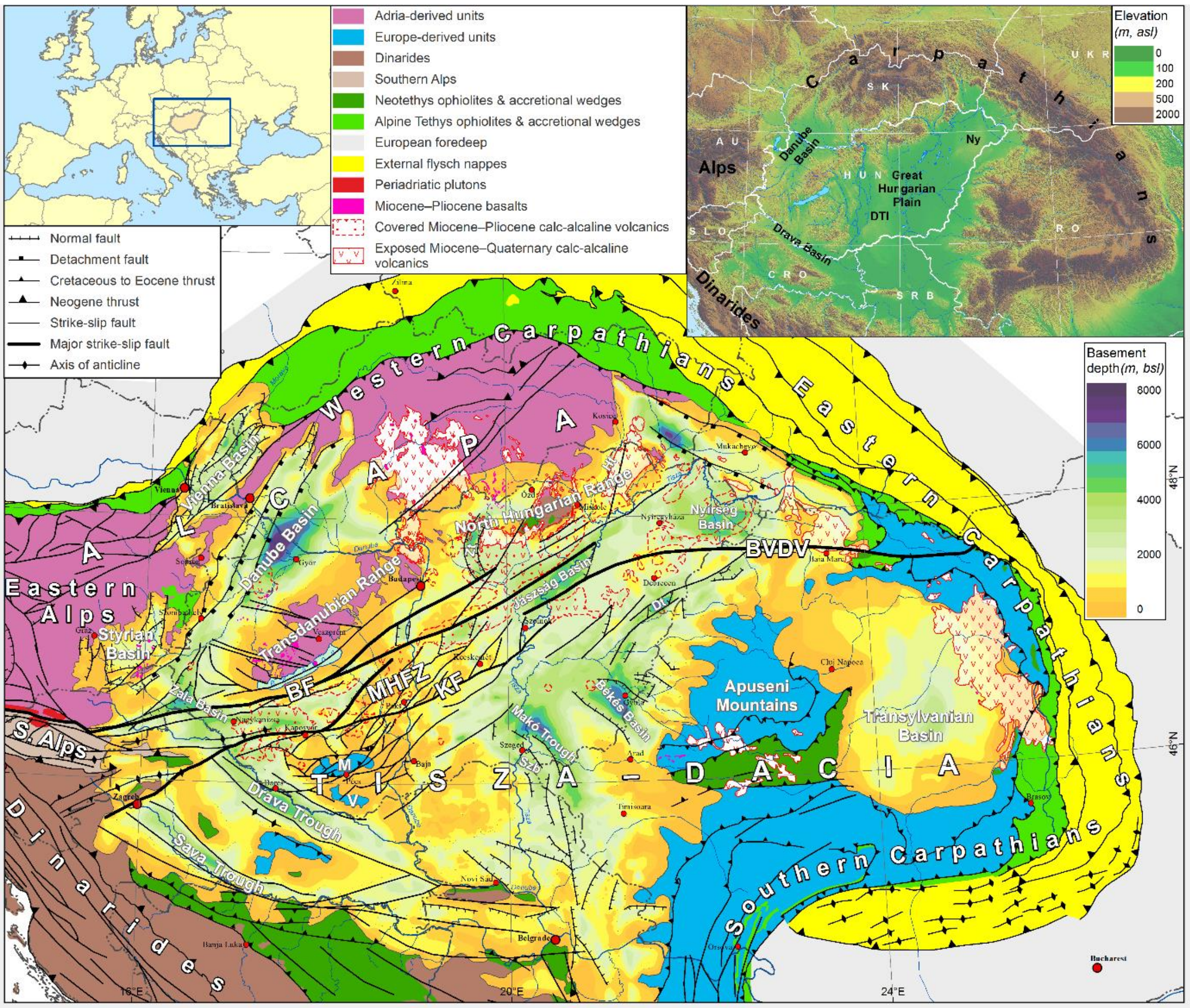


Fig. 1. Simplified overview of basement units and basin morphology in the Pannonian Basin and its surroundings with major tectonic units/elements and depth of the pre-Neogene basement (compiled after Horváth et al., 2018 and Schmid et al., 2008). Inset map shows the digital elevation model (DEM). Abbreviations: BF: Balaton fault, KF: Kapos fault, MHFZ: Mid-Hungarian Fault Zone, BVDV: Bogdan Voda - Dragos Voda fault; M, V: Mecsek and Villány Mts., Dt: Derecske trough, Szb: Szeged basin, Zt: Zagyva trough, Ht: Hernád trough; DTI: Danube-Tisza interfluve, Ny: Nyírség

From the Late Miocene on the basin became isolated due to the uplift of the surrounding mountains as well as to the sea-level fluctuations of Paratethys (ter Borgh et al., 2013). Rifting continued in the eastern subbasins in the early Late Miocene (Balázs, et al. 2016), whereas a basinwide regional thermal subsidence also occurred representing the so called post-rift phase of Horváth and Royden (1981). During the Late Miocene–Pliocene a long-lived, brackish-water lake was developed (Magyar et al., 1999) that was progressively filled up by the deposits of the Lake Pannon megasequence (Horváth et al., 2015, 2018). The boundary between the Lake Pannon megasequence and the underlying Central Paratethys megasequence is marked — except for several Transdanubian deep basins with continuous sedimentation — by a regional unconformity (*Fig. 2*) reflecting the late Middle Miocene (Sarmatian) uplift. This early inversion phase was coeval with the main collision in the East Carpathians (Horváth, 1995).

The individual elements of the Lake Pannon megasequence (*Fig. 2*), playing a fundamental role in neotectonic investigations, are discussed in details by many previous lito-, bio-, and chronostratigraphic studies having paleogeographic implications (e.g., Bérczi, 1988; Juhász, 1991, 1992; Magyar, 2010; Magyar et al., 1999, 2013, 2019; Sztanó et al., 2013a-b, 2016). The litostratigraphic units displayed in Figure 2 are by definition diachronous, as the basin was gradually filled from the northwest and northeast. This process was associated with the formation of a regional shelf-margin slope system prograding, in general, to the south-southeast in the Hungarian part of the basin between ca. 10 and 5 Ma. The total thickness of the post-rift sequence together with the Quaternary strata is strongly varying: it might reach up to 6-7 km in the deepest subbasins, whereas 1–3 km thickness occurs in areas characterized by weak to moderate post-rift subsidence (*Fig. 1*).

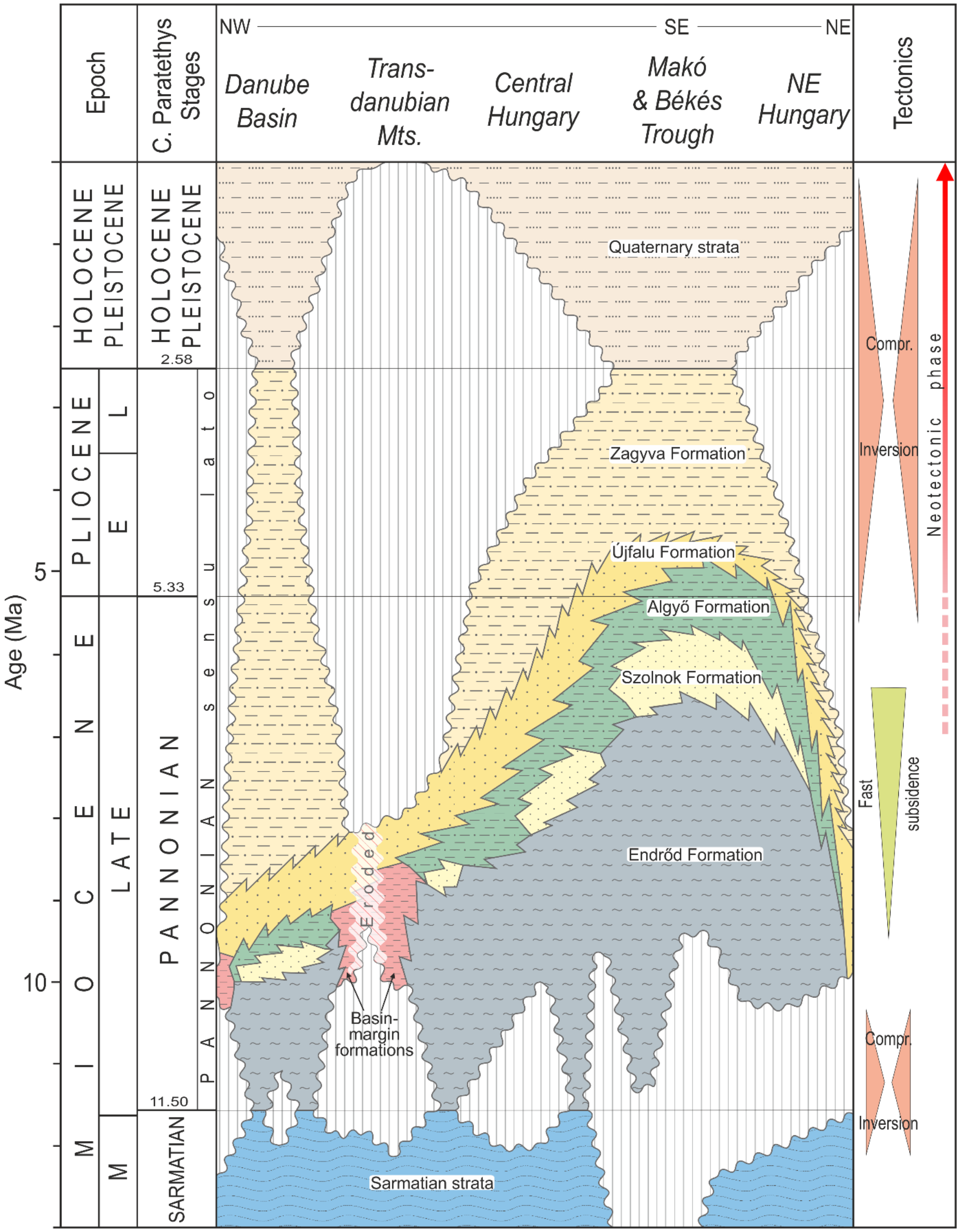


Fig. 2. Simplified stratigraphic overview of the post-rift basin fill (complied after Sztanó et al., 2013a-b, 2016; Balázs et al., 2018)

During the most recent tectonic evolutionary stage of the basin — referred to as neotectonic phase (*Fig. 2*) — inversion commenced (Tari, unpubl.; Horváth, 1995; Bada et al., 1999; Gerner et al., 1999), as the prevailing tensional/transtensional stress regime changed to compression (Horváth and Cloetingh, 1996; Fodor et al., 1999, 2005a; Csontos et al., 2002; Bada et al., 2007). The primary driving force of this change was, beside additional intraplate forces, the continuous northward indentation of the Adriatic microplate (“Adria-push”; Bada et al., 2007) and the consumption of subductible lithosphere along the East Carpathian arc (Horváth et al., 2015). Inversion took place diachronously across the basin: the first structures attributed to the neotectonic inversion were formed at ca. 8 Ma in SW Hungary (Zala subbasin; Uhrin et al., 2009), whereas initiation of neotectonic activity was definitely younger in the central (at ca. 4 Ma) and eastern part of the basin (Tari, unpubl.; Horváth, 1995; Fodor et al., 2005a-b; Ruszkiczay-Rüdiger et al 2007; Balázs et al., 2016, 2018).

On a regional scale, inversion was manifested in important differential vertical movements (i.e., subsidence of deep depocenters in the central part and uplift on the basin flanks, respectively; Rónai, 1974, 1987) interpreted as the results of large-scale folding of the lithosphere related to increased magnitude of intraplate stresses (Horváth and Cloetingh, 1996). Regional-scale folding with a wavelength being in the range of hundreds of kilometers was associated with brittle faulting in the shallow crust and intense erosion in the uplifting regions. Moreover, the basin was also interpreted as an example of irregular lithospheric folding (Cloetingh et al., 1999) with varying wavelengths being in the range from few to hundreds of kilometers. Results of analogue modelling focusing on the effect of crustal thickness variations supported this interpretation (Dombrádi et al., 2010).

On a local scale these processes were coupled with significant near surface deformations manifested in faulting and folding of the Lake Pannon megasequence. These deformations of tectonic origin were coexisting with faults and folds initiated by sedimentary (mainly compaction) processes, which together form the subject of the present study. In general, prominent contractional structures were formed in the southwest near the Adriatic microplate boundary, whereas strike-slip deformation was dominant elsewhere (e.g., Fodor et al., 2005a,b; Bada et al., 2006, 2007; Horváth et al., 2006a, 2009). These deformations affected the uppermost post-rift sediments (i.e., Zagyva/Újfalu Formations), and in some cases the overlying Quaternary strata as well (e.g., Pogácsás et al., 1989; Detzky Lőrincz 1997; Tóth and Horváth, 1997; Detzky Lőrincz et al., 2002; Magyari et al., 2005; Budai et al., 2008; Horváth et al., 2019).

3. Geological and geophysical database

The integrated database used for the project has two major constituents: an extensive seismic dataset (*Fig. 3*) and a large set of surface/subsurface-geological and tectonic maps summarizing the results of various (neo)tectonic studies as well as regional geological-geophysical overviews.

The seismic database of the project includes nearly 2900 2D seismic profiles and 70 3D seismic volumes from the seismic database of Geomega Ltd. in digital SEGY format. The 2D seismic dataset contain not only land, but also multichannel and ultrahigh resolution single channel water seismic data excellently imaging the shallow subsurface making them ideal for neotectonic investigations.

Modern 3D seismic data volumes allowing for a particularly reliable identification and correlation of neotectonic features are mostly available in the (south)eastern and southwestern part of the country (*Fig. 3*). Coherency volumes were calculated for all 3D seismic data volumes integrated into the project, and coherency time slices were subsequently used as the primary tool for identification and correlation of neotectonic faults (See also Section 5.1.).

Altogether, the available seismic dataset integrated into the project ensures — except for the mountainous areas in Transdanubia and northern Hungary (*Figs. 1, 3*) — an overall good to excellent coverage in the country providing a stable basis for the identification and correlation of neotectonic structures. In the mountainous areas the low seismic coverage was only one obstacle for the mapping of neotectonic deformations, since due to the general lack of young sedimentary cover the seismic imaging is rather poor. This necessitated the extensive use of published neotectonic studies in these areas based on surface geological, geomorphological or even remote sensing techniques.

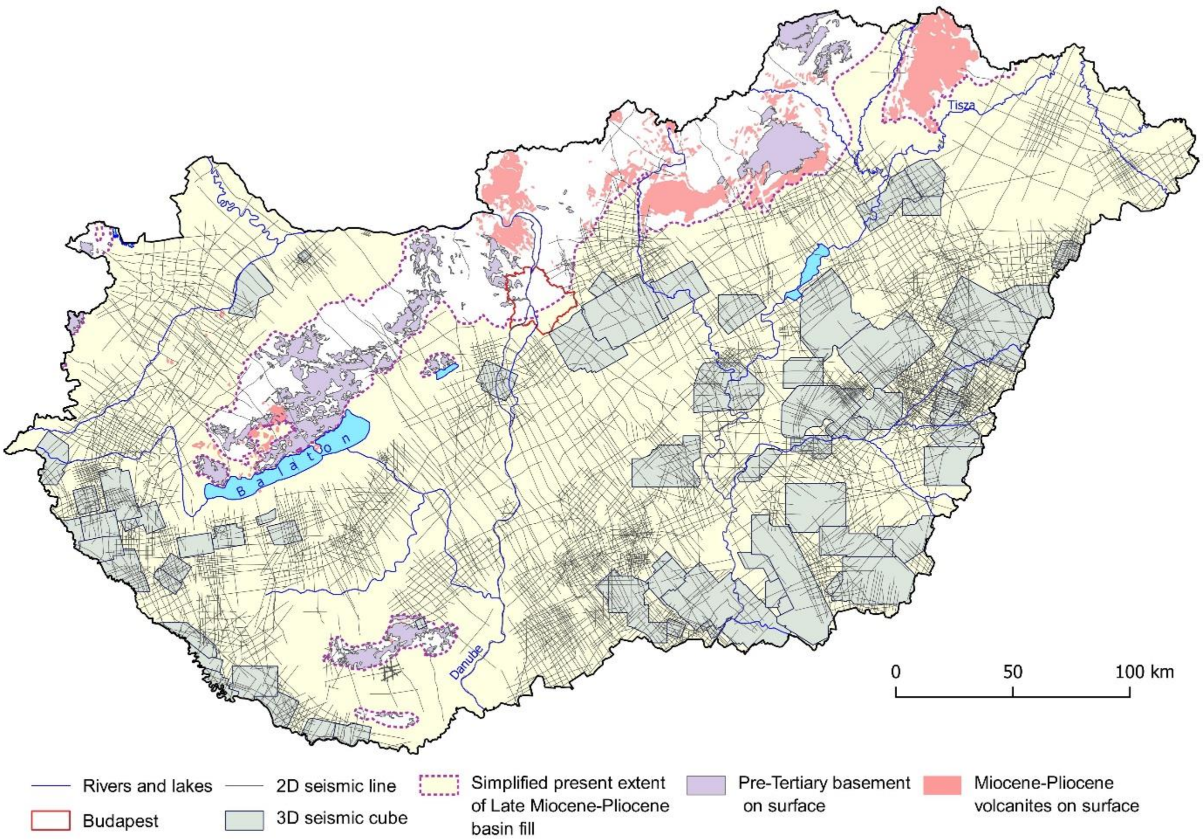


Fig. 3. Overview of the 2D and 3D seismic datasets integrated into the project

The other main constituent of the integrated database is represented by a series of georeferenced geological and geophysical maps aiding both the mapping of neotectonic deformations and the final map construction. These data include published regional neotectonic maps (Fodor et al., 1999; Horváth et al., 2006a; Horváth et al., 2009), numerous local-scale tectonic maps of neotectonic relevance (Pogácsás et al., 1989; Cserny and Corrada, 1990; Fodor et al., 1994, 2005a-b, 2013; Csontos, 1995; Detzky Lőrincz 1997; Dudko, 1997; Tóth and Horváth, 1997; Horváth et al., unpubl., 2019; Csontos and Nagymarosy, 1998; Halouzka et al., 1998; Wórum, unpubl.; Sacchi et al., 1999; Detzky Lőrincz et al., 2002; Korpás et al., 2002; Kováč et al., 2002; Lopes Cardozo et al., 2002; Síkhegyi, 2002, unpubl.; Bada et al., 2003a-b, 2006, 2010; Wórum and Hámori, unpubl.; Csontos et al., 2005; Magyari et al., 2005; Windhoffer et al., 2005; Juhász et al., 2007, 2013; Nádor et al., 2007; Ruszkiczay-Rüdiger et al., 2007, 2020; Budai et al., 2008; Székely et al., 2009; Bada et al., 2010; Konrád and Sebe, 2010; Bodor, unpubl.; Dudás, unpubl.; Nádor and Sztanó, 2011; Várkonyi, unpubl.; Várkonyi et al., 2013; Kovács et al., 2015; Visnovitz et al., 2015; Petrik, unpubl.; Loisl et al., 2018) as well as neotectonic reconstructions relying on remote sensing data (e.g., Czakó and Zelenka, 1981; Brezsnyánszky and Síkhegyi, 1987).

These maps were complemented with a set of regional (Fülöp and Dank, 1987; Dank and Fülöp, 1990; Fodor et al., 1999; Fodor, unpubl.; Gyalog and Síkhegyi, 2005; Haas et al., 2010) and local-scale geological (Némedi Varga, 1977; Hetényi et al., 1982; Matura et al., 1998; Kiss, et al., 2001; Csontos et al., 2002; Fodor et al., 2005c, 2013; Budai et al., 2008; Palotai and Csontos, 2010; Tari and Horváth, 2010; Zámolyi et al., 2010; Palotai et al., 2012; Palotai, unpubl.; Oláh et al., 2014; Soós, unpubl.; Petrik et al., 2018; Héja et al., 2018) and geophysical maps (Kiss, 2006; Kiss and Gulyás, 2006), which provided valuable information on (sub)surface geological relationships and structural trends largely aiding fault correlations and ultimately the final map construction. Subsurface geological and tectonic maps in publicly available hydrocarbon exploration reports were also taken into account during the model construction in this project in order to have an as wide as possible scientific basis of the new regional map.

The Bouguer anomaly map of Hungary (Kiss, 2006) was vectorized, and subsequently used not only as the background image of the new map (applying a different visualization, http://dx.doi.org/10.17632/dnjt9cmj87.1), but also for the construction of a residual Bouguer anomaly map enabling the recognition of local scale trends/structures.

4. Structural elements of the new map

The newly compiled map (http://dx.doi.org/10.17632/dnjt9cmj87.1) displays all the relevant young deformation features (both tectonic and atectonic) that were mapped using the project database. The mapped structures include those faults and folds that were developed during the latest, neotectonic evolutionary phase of the Pannonian Basin (*Fig. 2*, ~ latest 6–8 Ma). From a practical, seismic interpretation point of view, those faults and folds were considered, which deform at least the Zagyva (and laterally equivalent) or younger formations (*Fig.* 2). In the oldest parts of the basin only those structures were mapped, which not only "affect", but clearly deform the entire imaged part of the Zagyva(/Újfalu) formation ensuring that the age of the deformation is younger than the mentioned 6-8 Ma. A more precise temporal definition about the formation age of these structures cannot be given using the applied method because of the (i) intense erosion of younger Late Miocene–Pliocene strata in the uplifted parts of the basin, and (ii) the poorly imaged nature of the seismic sections in the upper 200–500ms. All things considered, most of the mapped deformations probably occurred in the last 5–6 million years, locally including deformations during the Quaternary.

There are three groups of structural elements displayed on the new map:

- Fault lines displaying the near surface manifestations (i.e. mapped fault traces) of faulting affecting the Late Miocene–Pliocene or younger sediments (both tectonic and atectonic)
- Neotectonic folds affecting the Late Miocene–Pliocene or younger sediments excluding folding related exclusively to sedimentary processes such as differential compaction (e.g. drape-over anticlines)
- Pre-Pannonian faults with or without near surface neotectonic manifestation that had any influence on the sedimentation and subsequent (i. e. neotectonic) deformation of the entire post-rift sequence. These include important syn- and pre-rift faults, comprising also blind faults that cannot belong to the group of neotectonic faults defined above, because the young reactivation were not strong enough to cause visible fault offsets in the Zagyva(/Újfalu) Formation. These faults are essential — regardless

of their tectonic activity during the neotectonic phase — in the understanding of the depicted near surface deformations.

Main characteristics, their schematic genetic evolution and important differences between the mapped structures are summarized in *Fig. 4* and below.

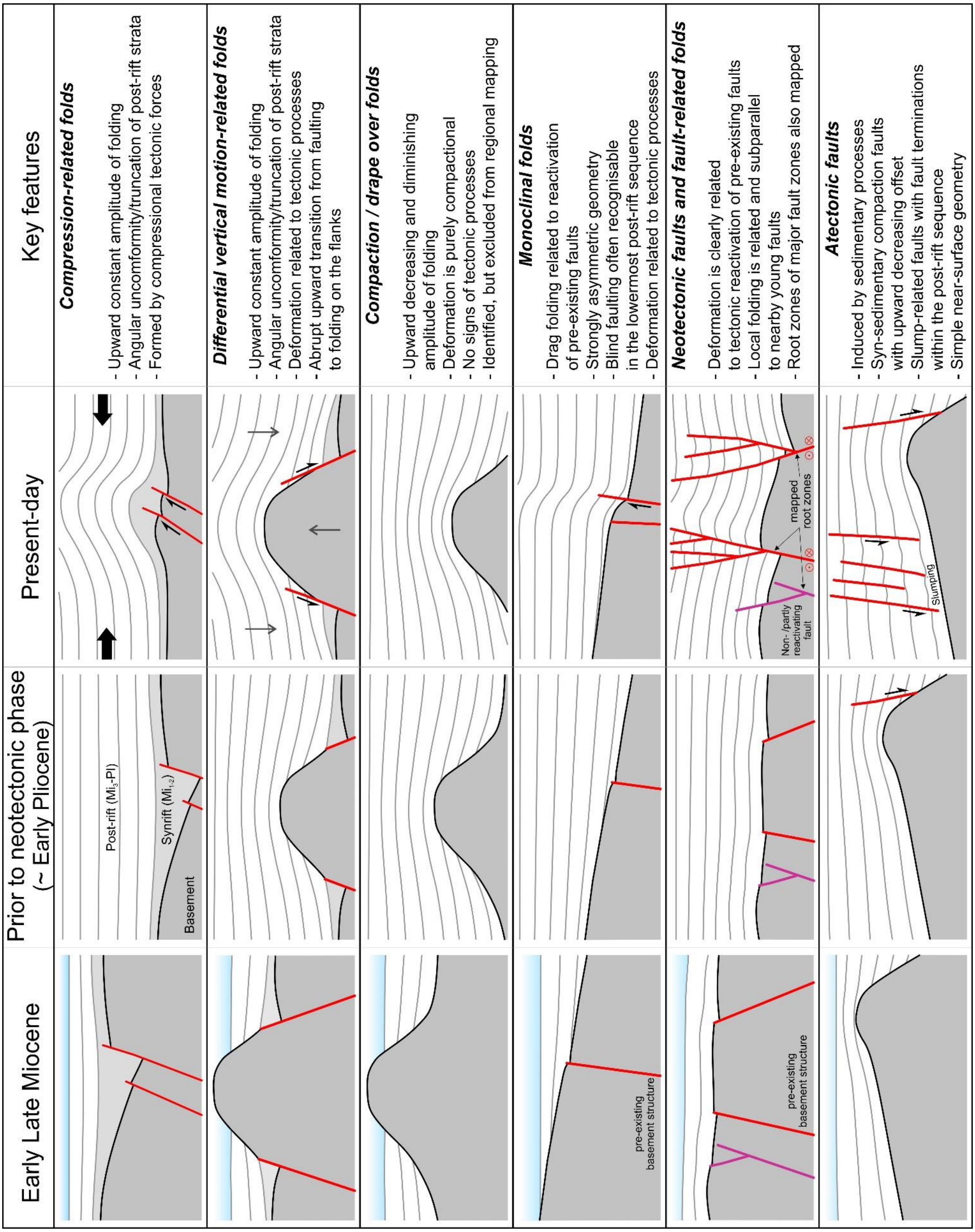


Fig. 4. Overview of the mapped structures and their schematic genetic evolution

4.1. Faults

According to origin, the brittle deformations (i.e. faulting) identified within the Late Miocene–Pliocene or younger sediments were classified into three main categories (*Fig. 4*):

- tectonic faults related to the reactivation of pre-existing faults (i.e. neotectonic faults by definition)
- atectonic faults whose formation is not (or only indirectly) associated with pre-existing fracture systems (e.g. related to atectonic sedimentary processes such as compaction and slumping).
- Several fault zones were mapped, where the tectonic or atectonic origin could not be determined unambiguously, or there exist different views in the literature on their interpretation. These faults were classified as "faults with uncertain/debated origin". They typically occur above basement highs and disappear basinwards along strike (signs of atectonic origin), but display characteristic flower structure in seismic profiles (sign of tectonic origin).

Tectonic faults related to the reactivation of pre-existing faults

These faults inherit their characteristics from the "parent" fault systems in the basement and can be considered as "classical" neotectonic faults. In these cases the "parent" fault (i.e., the primary displacement zone, PDZ) can be often directly identified on the seismic data, and/or the characteristics of the fault zone developed in the young sedimentary pile are the same as those of the well-documented tectonic fault reactivations (e.g. flower structures, en-echelon fault planes connecting to a single root, etc.; *Fig. 4*).

Atectonic faults related to compaction or slumping

Faults related to compaction or slumping are considered as atectonic features *(Fig. 4)* in the Late Miocene–Pliocene sedimentary pile. Slumping frequently occurred in the unconsolidated post-rift sedimentary pile of the Pannonian Basin, especially in areas characterized by uneven basement morphology and large thickness variations. *Slump-related faults* are typically encapsulated into the young sedimentary sequence: they generally start in the upper portion of the post-rift sequence affecting the Zagyva, Újfalu and Algyő formations, and terminate (or detach) before reaching the base-Pannonian unconformity (*Fig. 5*). Although such faults do not have pre-Pannonian roots, they are many times associated with (triggered by?) nearby "real" neotectonic faults (see faults (in violet) at the Biharkeresztes-Komádi high in the eastern Great Hungarian Plain, http://dx.doi.org/10.17632/dnjt9cmj87.1).

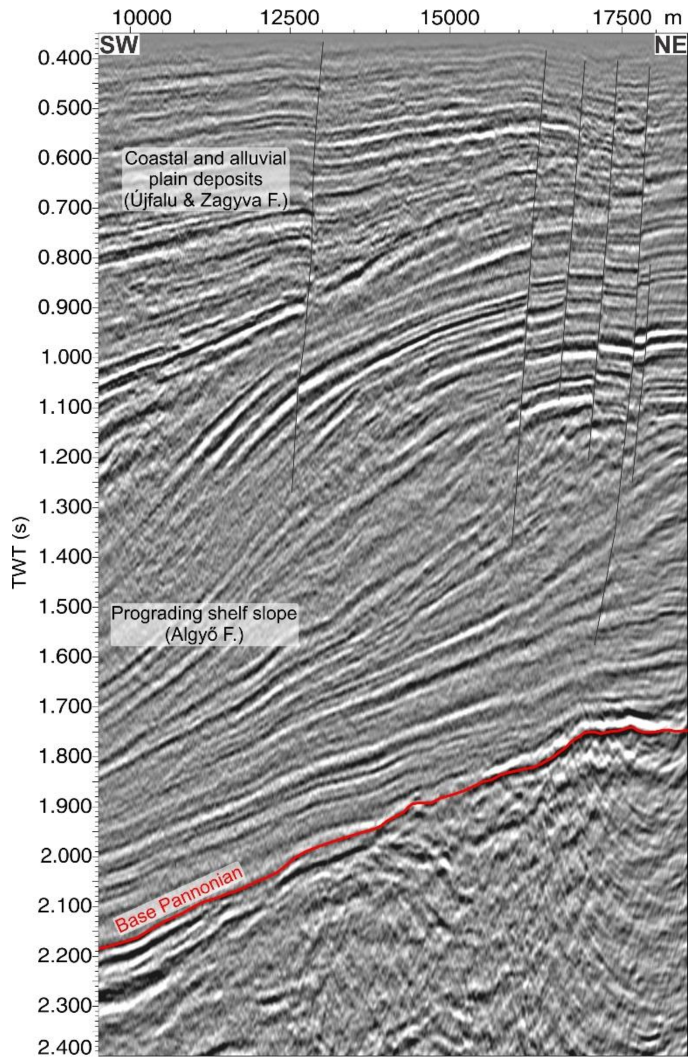


Fig. 5. Example of slump-related faulting above the Komádi basement high (eastern Great Hungarian Plain). Note that all faults terminate within the prograding shelf slope (Algyő F.). For location see Figure 17b

Compaction faults are gravity-driven features formed due to the differential compaction of young sediments with laterally strongly varying thickness. Compaction faults develop continuously during sedimentation with increasing overburden (*Fig. 4*) and has similar characteristics as classical syn-sedimentary normal faults. Compaction faults, considered previously as "classical" neotectonic faults (e.g., Horváth et al., 2006a, 2009; Nádor et al., 2007), have been recently described from the eastern part of the Great Hungarian Plain (Balázs et al., 2016, 2018). Distinction between pure compaction (atectonic) and post-depositional tectonic faults in the Pannonian Basin is quite challenging occasionally as discussed later (see Section 6.4.). The faults mapped at the southwestern flank of the Algyő high (http://dx.doi.org/10.17632/dnjt9cmj87.1) are considered as the most typical examples of compaction faults forming standalone, relatively short features developed above the steep southwestern flank of the high (see also Balázs et al., 2016).

4.2. Neotectonic folds

The axis of folds within the post-rift sequence displayed on the new map represent synclines and anticlines formed by tectonic processes. Considering a generally flat sedimentary surface at all times during the sedimentation, anticlines and synclines developed above the uneven basement topography by the process of differential compaction were identified by their upward decreasing (and diminishing) fold amplitudes and were excluded from the mapping (see *Fig. 4*). This feature is in contrast with that of (post-sedimentary) tectonic folds, where the fold amplitude is nearly constant upward within the sequence (i.e. formation occurred after the deposition of the post-rift sequence, *Fig. 6*).

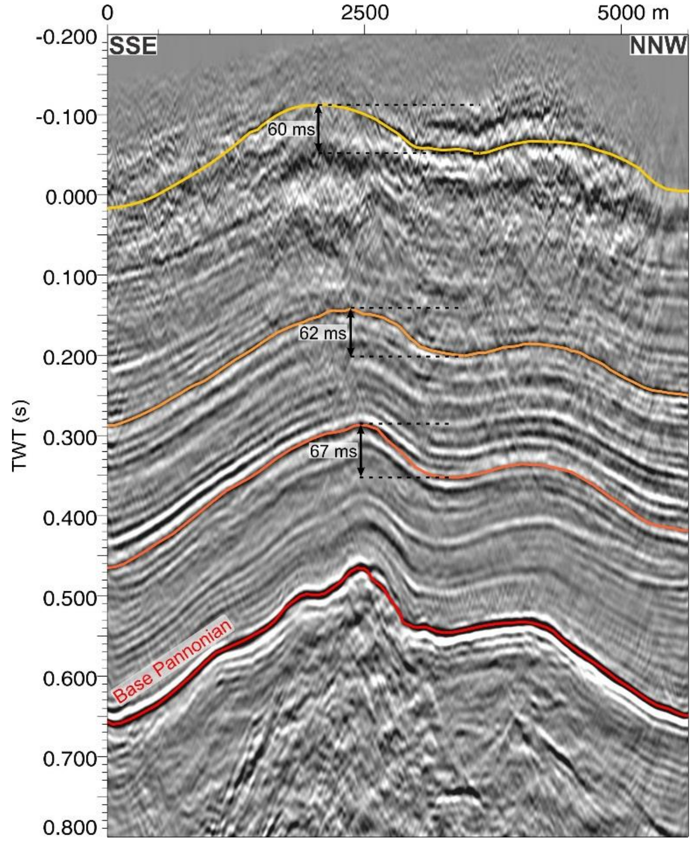


Fig. 6. Example of a tectonic fold developed above the Igal high. Note the upward nearly constant amplitude of folding of the post-rift strata. Orange and yellow lines indicate Pannonian marker horizons. For location see Figure 17a

Three groups of neotectonic folds were distinguished considering their origin and geometrical properties (*Fig. 4*):

- Compression related folds
- Differential vertical motion- and fault-related folds
- Monoclinal folds

<u>Compression-related folds</u>

Compression-related folds are those large-scale "classical" folds of structural geology, which were formed by far-field compressional lithospheric stresses. As a result, the orientation of these (sets of) folds are parallel to each other and perpendicular to the maximum horizontal stress direction. Such folds occur in western and southwestern Hungary (see Sections 6.2. and 6.3.; http://dx.doi.org/10.17632/dnjt9cmj87.1).

Differential vertical motion- and fault-related folds

These folds do not reflect directly the effect of the regional, far-field tectonic stresses, but rather their formation was constrained by nearby neotectonic faulting (i.e. rollover anticlines) or the orientation of the underlying tectonic fabric, such as basement blocks and pre-existing faults. Two types of folds were distinguished within this group.

Differential vertical motion-related folds are associated with large scale regional flexures or connected to the differential vertical movements of crustal segments, and generally show a close correlation with basement topography (*Fig. 4*). This relationship can be quite different in case of some compression-related folds as illustrated by the Lovászi anticline, which was formed above an inverted graben structure in the Zala basin. Forced folds developed above the footwall of major reactivated normal faults characterized by abrupt upward transition from faulting to folding represent typical examples.

It should also be noted that the characteristics of differential vertical motion-related folds of tectonic origin and significantly eroded compaction-related drape-over folds are very similar, since erosion removes the upper part of the anticline or syncline, which could be best used to identify the upward decreasing amplitude used for the differentiation. Similarly, low-amplitude tectonic-related folds and compaction folds are rather difficult to differentiate without detailed tectono-sedimentological investigations. In the present study folds without any significant upward decrease in the amplitude of folding were classified as differential vertical motion-related structures.

Fault-related folds are represented by drag folds, roll-over anticlines, en-echelon folds, and folds related to flower structures (*Fig. 4*). The fault(s) constraining their formation and geometrical properties were always identifiable. Such folds are widespread in the whole country, and they are typically oriented parallel to sub-parallel, or with en-echelon geometry to faults, along which the major deformation occurred. Both the wavelength and amplitude of such folding is generally (significantly) smaller than those of compression- or differential vertical motion-related folds, although they might form remarkable local structures (e.g., Fodor et al., 2005a-b; Ruszkiczay-Rüdiger et al., 2007).

Monoclinal folds

Monoclinal folds usually develop above reactivating reverse faults, however, as numerical and seismic examples show (Hardy, 2011; Nollet et al., 2012) they can also be formed by subtle, normal sense reactivation of steep normal faults. The neotectonic displacement above the controlling faults were small (*Figs. 4, 7*), therefore the faults did not cut up the post-rift sequence high enough to be classified as “classical” neotectonic faults defined earlier. This group of folds comprising only a few typical structures in SW Transdanubia (*Fig. 7*, http://dx.doi.org/10.17632/dnjt9cmj87.1), which were identified based on their characteristic geometric appearance on the seismic profiles.

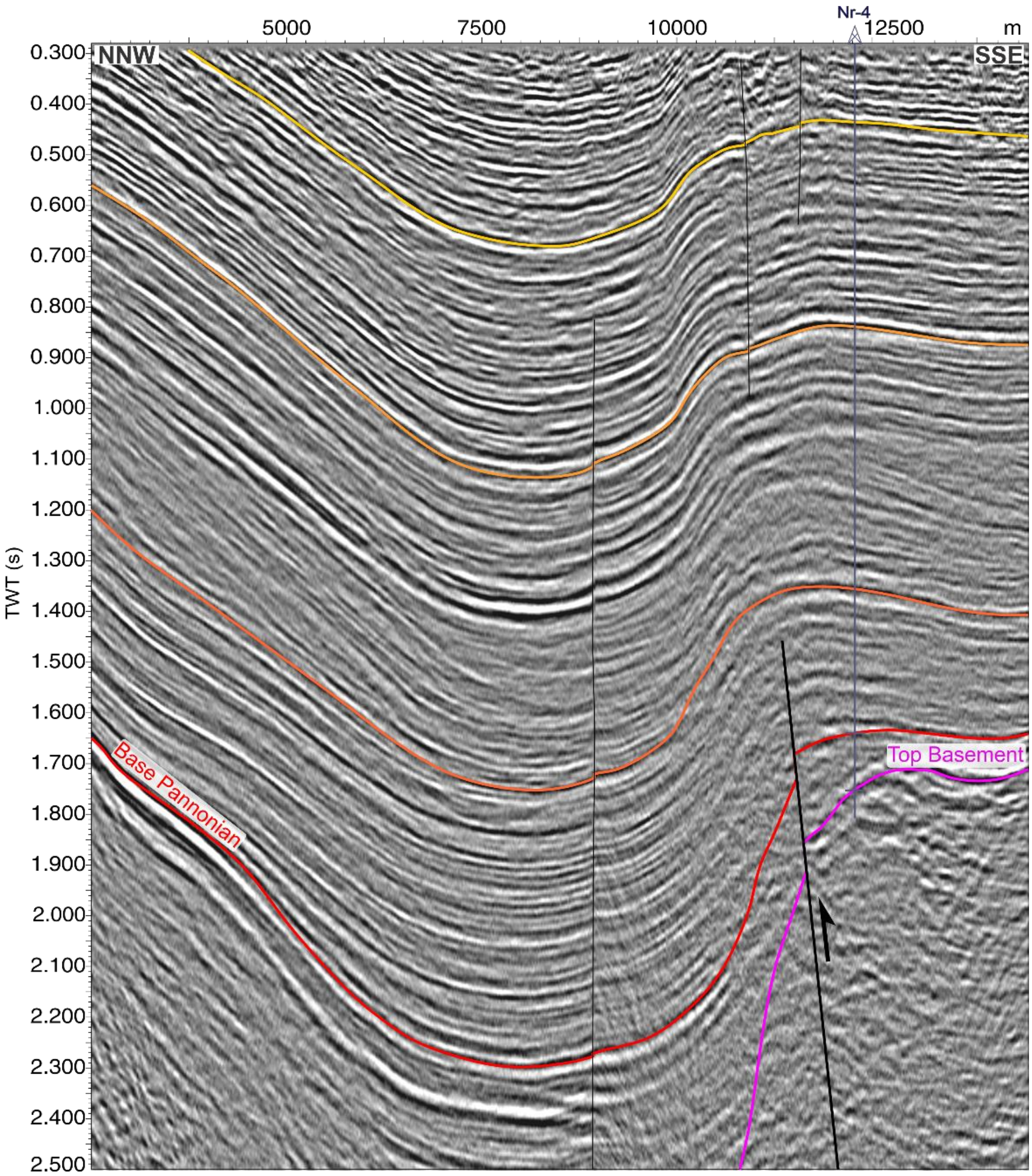


Fig. 7. Example of a monoclinal fold (right) related to a reactivated blind reverse fault. The asymmetric fold joins to a major syncline of compressional origin (left) towards the North (Zala basin, western Hungary). For location see Fig. 13.

4.3. Pre-Pannonian root zones

An essential novelty of the new map is that not only the near surface manifestations of neotectonic faults but also their roots in the underlying pre-Pannonian substratum were mapped and displayed. The roots display the localities of the faults formed mostly during the preceding Early–Middle Miocene basin evolution (Fodor et al., 2005a,b; Bada et al., 2007), which either were (partly) reactivated during the neotectonic phase or had any (even atectonic) role in the deformation of the youngest sedimentary cover. In other words, not all mapped pre-Pannonian faults zones were reactivated tectonically during the neotectonic phase producing a near surface deformation, still, their complete representation on the new map was essential in order to provide a coherent, regional structural background.

During interpretation of the roots hosted in the often poorly imaged Miocene or pre-Cenozoic basement literature data and Bouguer anomaly maps were also essential sources of information beside seismic data. The primary formation age of the mapped pre-Pannonian faults is varying, however most of them are connected to the Early/Middle Miocene tectonics of the basin. It also needs to be emphasized that the location of the root zones could not be referenced to a common stratigraphic horizon (e.g., base Pannonian) because the roots where the individual fault planes of a complex fault zone connect into a common "line" are located at different depth and within different stratigraphic units even along the same fault zone (Paleozoic–Mesozoic basement or within the overlying Paleogene–Middle Miocene basin fill).

5. Mapping principles

In the followings the principles and the most important aspects of the structural interpretation and subsequent map construction are summarized.

5.1. Structural interpretation

The primary source of information about the mapped faults and folds displayed on the map were the seismic datasets. Mapping of these structures using a countrywide uniform reference horizon was hampered by (i) the varying quality of the available seismic datasets (i.e., no or poor quality imaging in the uppermost, 0–0.4s TWT range), and (ii) by the changing basement topography. The mapped fault traces typically refer to ~400-600ms TWT in basin areas, and to 200-300ms near the basin margins, respectively, which represent roughly the highest mapable occurrence of faults in the given areas. Considering the varying reference depth of the mapping and the dip of the fault planes, several hundred meters general fault trace uncertainty can be considered when projected to the surface. Fold axis positions were determined using the shallowest, still well-imaged and laterally traceable post-rift reflection-package.

Modern 3D seismic data volumes served as starting points for the regional mapping. Coherency volumes were calculated for all 3D seismic data volumes, and coherency time slices were subsequently used as the primary tool for identification and correlation of faults (see also *Fig. 19*). The primary fault segment interpretation was subsequently cross-checked in the seismic profiles in order to verify the actual position and extension of the identified fault segments and to filter out artificial linear features. The recognized dominant structural pattern and style were considered and consequently applied during the interpretation of adjacent 2D datasets resulting in a coherent structural interpretation covering larger areas. For the correlation of structural elements between 2D seismic lines, trends seen on geophysical maps as well as on regional geological maps were fully taken into account. Published neotectonic maps were also considered, revised if needed, and integrated during interpretation, especially in areas with poor seismic coverage.

During mapping two quality classes were defined both for the faults and for the root zones:

- Constrained (i.e., proven) faults are sufficiently defined by available subsurface and surface data. Faults of this qualification, regardless of their origin, are clearly identifiable in the seismic record and deform the highermost post-rift strata, or they have been well documented by surface geological observations and/or well data.
- Poorly constrained (/suspected) classification was generally applied when the fault identification itself and/or its correlation was hampered by poor seismic quality and/or insufficient coverage. This class was also used for faults with ambiguous timing of faulting occurring mostly in uplifted areas covered by older (>6–8 Ma), eroded basin margin strata (i.e., mountain ranges and their surroundings). The neotectonic activity of

several important fault zones was suspected based only on scarce surface geological data published in the literature (Darnó zone in northeastern Hungary for example; see Fodor et al., 2005c). If neotectonic activity could not be not confirmed by our data at other localities along the fault, the "suspected" category was applied considering the entire fault.

Identification and classification of neotectonic faults were also aided by the map of historical and recent (from 1995 on) earthquakes (Tóth et al., 2020). These data were especially useful in mountainous areas characterized by a reduced or completely missing post-rift cover or poor seismic imaging.

5.2. Map construction

During final map construction the completed primary structural interpretations carried out on the integrated 2D and 3D seismic datasets has been generalized to the applied, 1:500 000 map scale. During this process, only short, irrelevant fault segments were removed, the overall structural pattern was preserved and not simplified into single tectonic lines.

Mountain ranges and their close surroundings are often characterized by the complete lack of Late Miocene–Pliocene strata, as well as very poor or no seismic coverage. In these areas neotectonic structures shown on the map essentially derive from published data (for details see Section 3). This also holds true for the Lake Balaton where published fault and structural maps were found to form a coherent and adequate neotectonic model in this area, making reinterpretation unnecessary. The published models (often using different methods and datasets) were always cross-checked with each other and with available (often sparse) seismic data, and critical re-evaluation was performed, if needed. Utilization of neotectonic results lacking any surface or subsurface geological/geophysical verification (e.g., models relying exclusively on remote sensing data; Czakó and Zelenka, 1981; Brezsnyánszky and Síkhegyi, 1987) was generally avoided during map construction.

6. Results and Discussion

Considering the important differences in the prevailing orientation and/or style of identified neotectonic deformations several major neotectonic domains — Danube-, Zala- and Dráva basins, Central Hungary, Southeast Hungary, Zagyva trough (*Fig. 8*) — could be distinguished in the country, even if their boundaries are somewhat arbitrary. The relationship between the defined domains and major tectonic units of the pre-Cenozoic basement (*Fig. 8*) provides a regional structural context for the following sections.

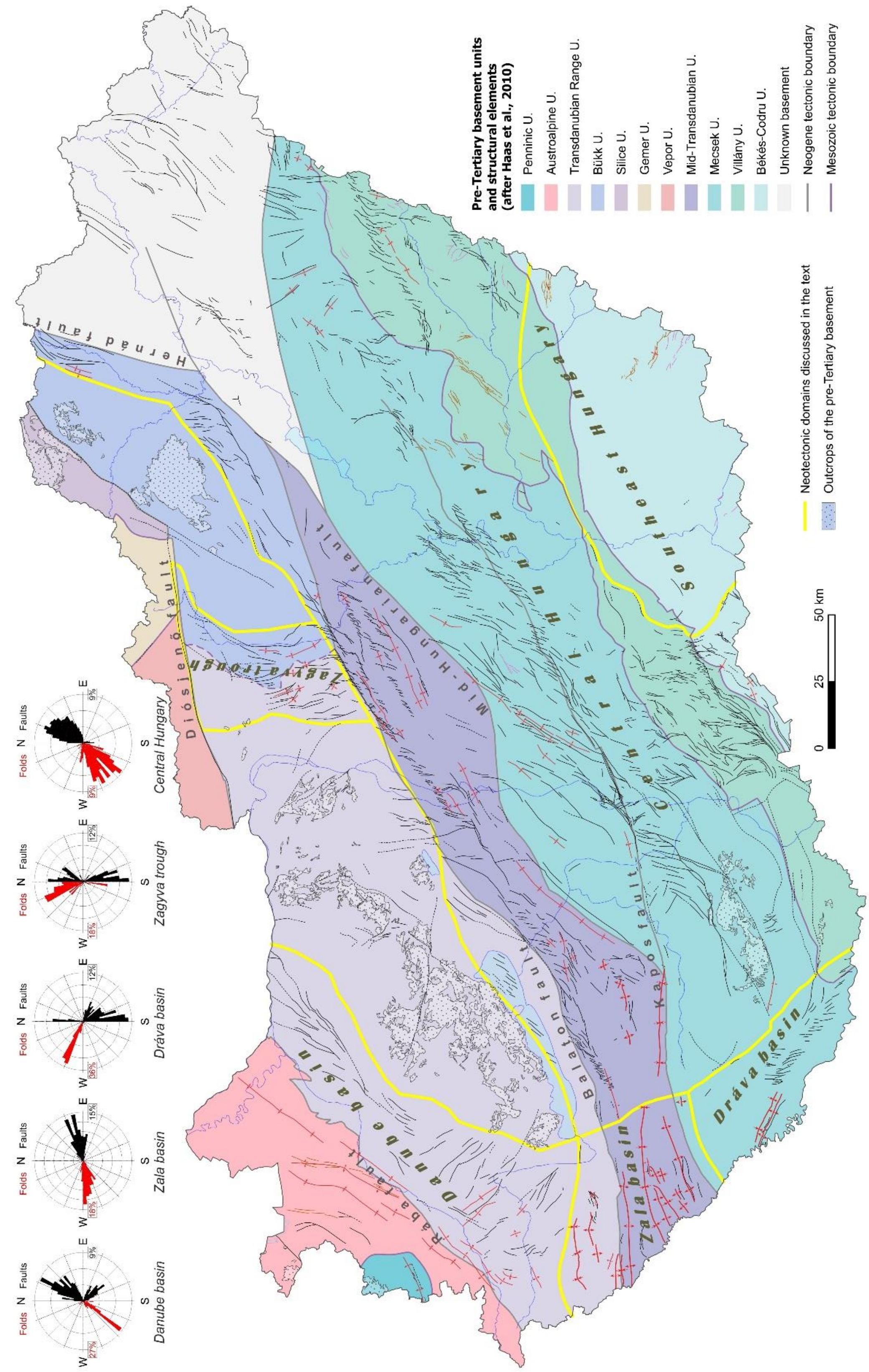


Fig. 8. Definition of neotectonic domains (yellow lines) based on the observed deformation pattern (for the legend of the mapped structures see Fig. 9). Rose charts (upper left) show the

orientation distributions of various neotectonic structures within the domains. Background image shows the major tectonic units of the pre-Cenozoic basement (after Haas et al., 2010)

6.1. Danube basin

The Danube basin is located in the northwestern part of the country (*Figs. 1, 8*) having sufficient 2D and a few 3D seismic coverage (*Fig. 3*). In general moderate neotectonic activity is observed in this domain manifested mostly in the appearance of (N)NE–(S)SW and (W)NW–(E)SE striking faults and similarly oriented folds. Using the methodology shown on *Fig 4*. the identified folds were all classified as differential vertical motion-, or fault-related (http://dx.doi.org/10.17632/dnjt9cmj87.1). This neotectonic deformation pattern shows a close relationship with the overall (N)NE–(S)SW structural trends of the pre-Tertiary basement consisting of various Austroalpine nappes formed during the Cretaceous (Eoalpine) tectogenesis and overprinted by Miocene extension (Tari, unpubl., 1996; Tari and Horváth, 2010).

The main (N)NE–(S)SW structural trend of the basement formed during multiple pre- and synrift deformations is cut by numerous (W)NW–(E)SE striking faults of Neogene age (Haas et al., 2010). Neotectonic structures of this orientation occur mostly in the southeastern part of the domain, and belong to the Transdanubian Range unit representing the highest tectonic element of the Eoalpine nappe stack. This set of neotectonic faults is practically missing in the western part of the domain underlain by deeper Austroalpine and the structurally lowest Penninic units (Haas et al., 2010) below the main Miocene extensional detachment fault (i.e., the Rába fault: Tari, unpubl., 1996; see also *Figs. 8, 9*). This indicates reactivations of deeper faults and a strong control of basement tectonics on the neotectonic orientations.

There are three subjects, where our work brought new insights and progress into the neotectonic understanding of the region (see also *Fig. 9*):

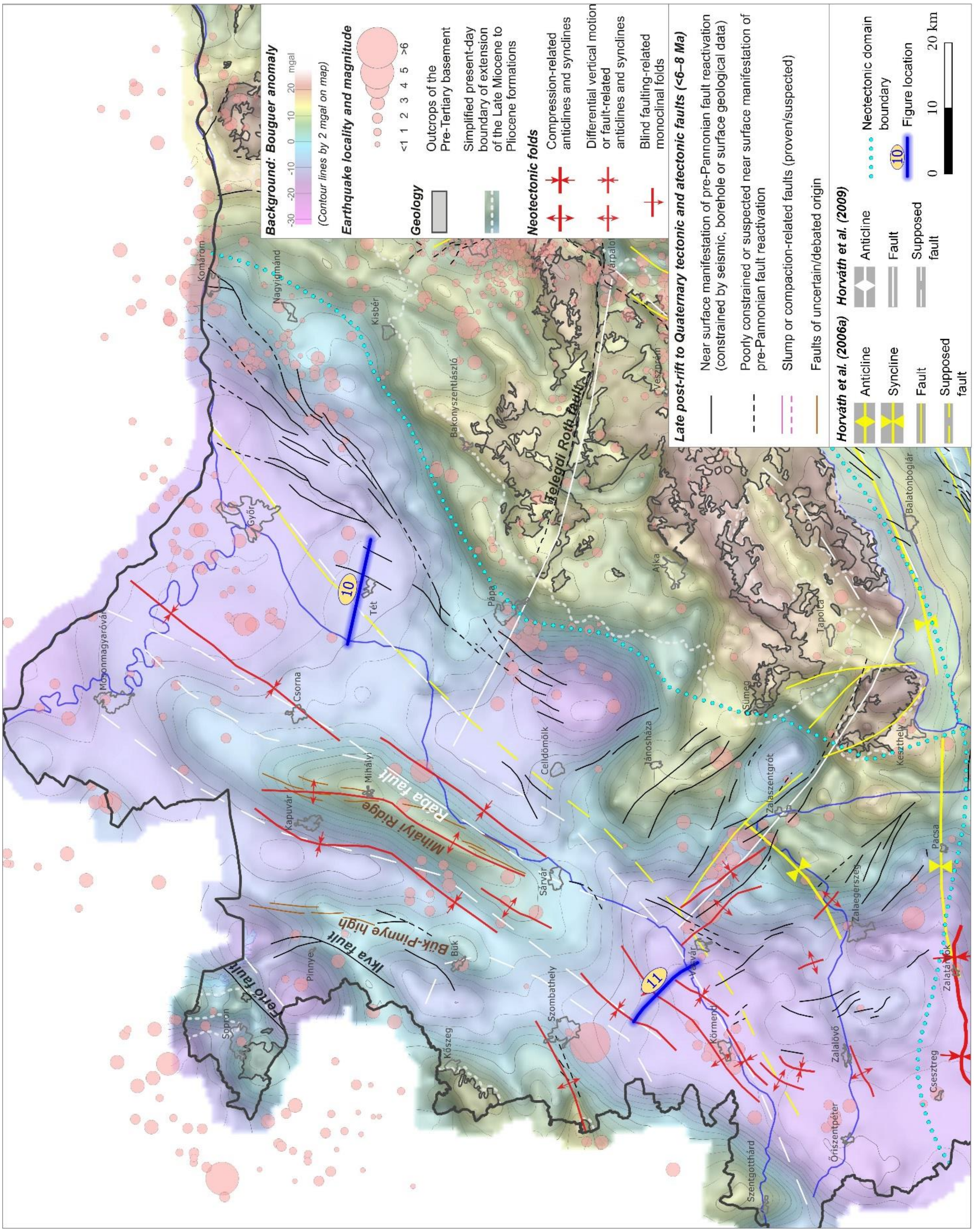


Fig. 9. *Detailed view of the mapped structures in the Danube basin compared to earlier regional studies (Horváth et al., 2006a; Horváth et al., 2009). Seismicity is shown after Tóth et al. (2020).*

(i) correlation of a wide, NE–SW striking neotectonic fault zone in the southeastern flank of the Danube basin (between the towns of Komárom and Pápa), (ii) identification of a set of NW–SE striking neotectonic faults in the southeastern part of the domain, (iii) identification of differential vertical motion-related folds occurring mostly in the western and southern part of the domain. In addition, several other, less prominent structures were correlated in the western part of the domain based on seismic interpretation and integration of published surface geological and geomorphological data (Székely et al., 2009; Zámolyi et al., 2010, Kovács et al., 2015), which show remarkable correlation with known Miocene extensional faults (Fertő-, Ikva-, Rohonc faults; see *Fig. 9* and Tari and Horváth, 2010).

The wide fault zone between the towns of Komárom and Pápa comprises several anastomosing, NNE–SSW and NE–SW oriented fault branches forming an acute angle with each other. A shorter fault branch between Pápa and Celldömölk with similar overall orientation forms probably its southwestern continuation. The arrangement of the individual NNE–SSW striking faults/fault branches and the mapped root zones largely resembles that of synthetic Riedel shears suggesting sinistral shearing along the fault zone. Although poorly constrained we believe that this fault zone continues up to the town of Komárom towards the northeast. This correlation is also supported by historical (i.e., the Komárom earthquake in 1763 with an estimated magnitude of 6.2) and recent seismicity (Tóth et al., 2020; *Fig. 9*).

The discussed fault zone transects the western flank of the Transdanubian Range unit comprising here non-metamorphic Permo-Mesozoic and underlying Lower Paleozoic low-grade metamorphic rocks (c.f., Haas et al., 2010). Integrated analysis of seismic sections and available well data suggests that neotectonic activity is related to the reactivation of a westnorthwest-dipping Miocene synrift normal fault cutting and displacing also an Eoalpine (Cretaceous) thrust in the pre-Tertiary basement *(Fig. 10)*.

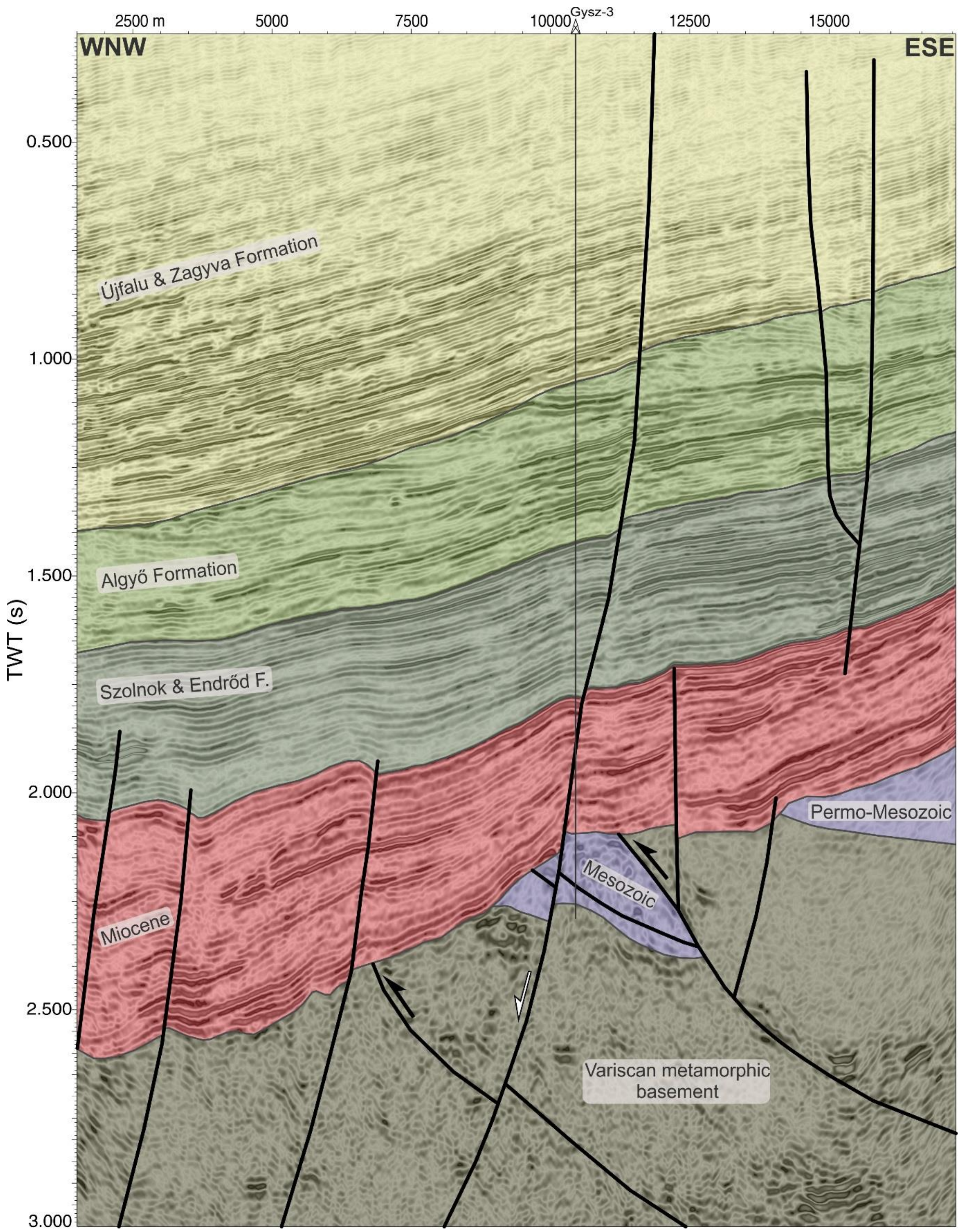


Fig. 10. WNW–ESE directed seismic profile indicating neotectonic faulting coupled with the reactivation of pre-existing, westnorthwest-dipping synrift fault within the pre-Tertiary basement of the Transdanubian Range unit. For location see Figure 9

Further to the southwest neotectonic faulting was also interpreted to be related to the reactivation of a synrift normal fault that joins directly to a low-angle Cretaceous thrust surface (Tari and Horváth, 2010), postulating an intimate structural relationship between extensional synrift and contractional pre-rift structures.

A novel outcome of the new mapping is the correlation of several NW–SE striking neotectonic faults and fault-related folds in the southeastern part of the domain above the buried Mesozoic formations of the Transdanubian Range unit. Similar neotectonic faults previously were only indicated at the margins of the Keszthely Mts. and along the Telegdi-Roth fault (e.g Horváth et al., 2006a; Horváth et al., 2009; *Fig. 9*). Regarding their origin, large part of these reactivating NW–SE striking faults was considered to be related either to Cretaceous compression (e.g., Tari and Horváth, 2010), or preceding pre-orogenic (Late Triassic to Jurassic) tension (Héja et al., 2018), that were in part reactivated as normal or dextral faults during Miocene basin evolution. Neotectonic activity probably also occurred along these faults in the uplifted part of the Transdanubian Range unit, however, this cannot be verified due to the limited presence/thickness of young sediments and to the lack of appropriate seismic coverage.

Widespread occurence of tectonic (differential vertical motion-related) folding in this domain were not shown previously (c.f., *Fig. 9)*. These folds generally follow the main (N)NE–(S)SW structural trend of the domain and show a close correlation with basement morphology (http://dx.doi.org/10.17632/dnjt9cmj87.1) resembling the characteristics of drape-over anticlines of compaction origin at a first sight. Detailed analysis reveals however, that they are characterized by a practically constant amplitude of folding vertically within the entire imaged post-rift sequence being incompatible with a purely compactional origin (c.f., *Figs. 4, 11*). The striking spatial correlation between fold locations of this study and the very gentle surface morphological trends observed in the youngest fluvial sediments of the Rába river (*Fig. 12*) suggest that folding affects even the youngest sediments of the present day surface. This is also an indication against their compaction origin. Taking into account the young uplift of the neighboring mountain ranges (e.g., Tari, unpubl.; Horváth, 1995; Sacchi et al., 1999) we consider these folds to be related to the tectonically driven differential vertical movements of adjacent basement segments.

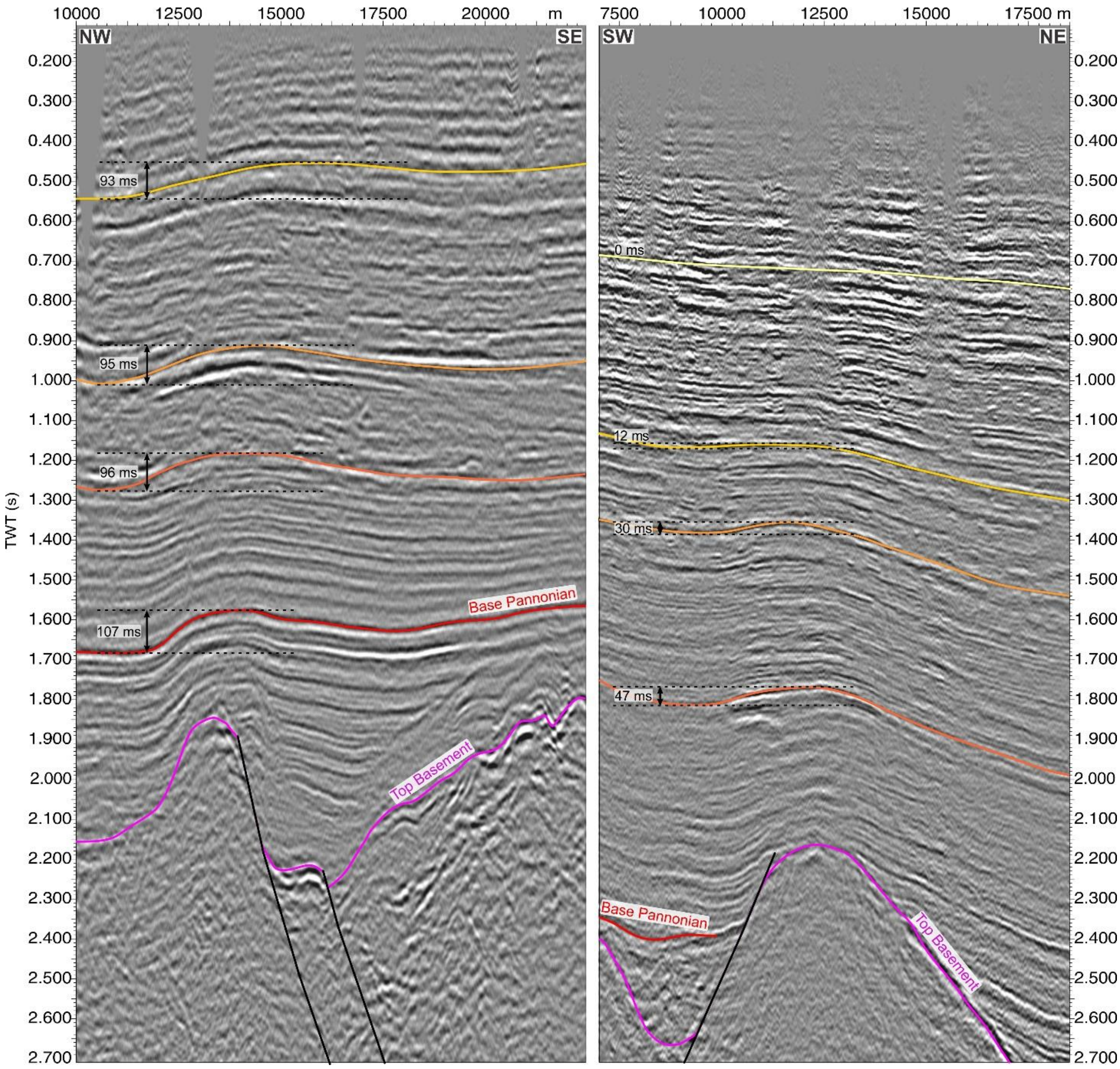


Fig. 11. Fold characteristics from SW Danube basin (left) compared to the drape-over anticline above the Algyő high (SE Great Hungarian Plain; right). Note the strikingly different vertical pattern of fold amplitudes (constant vs. upward diminishing) supporting the

presence of tectonic folding in the Danube Basin. Orange and yellow lines indicate arbitrary, uncorrelated Pannonian marker horizons. For location see Figs. 9 and 17a.

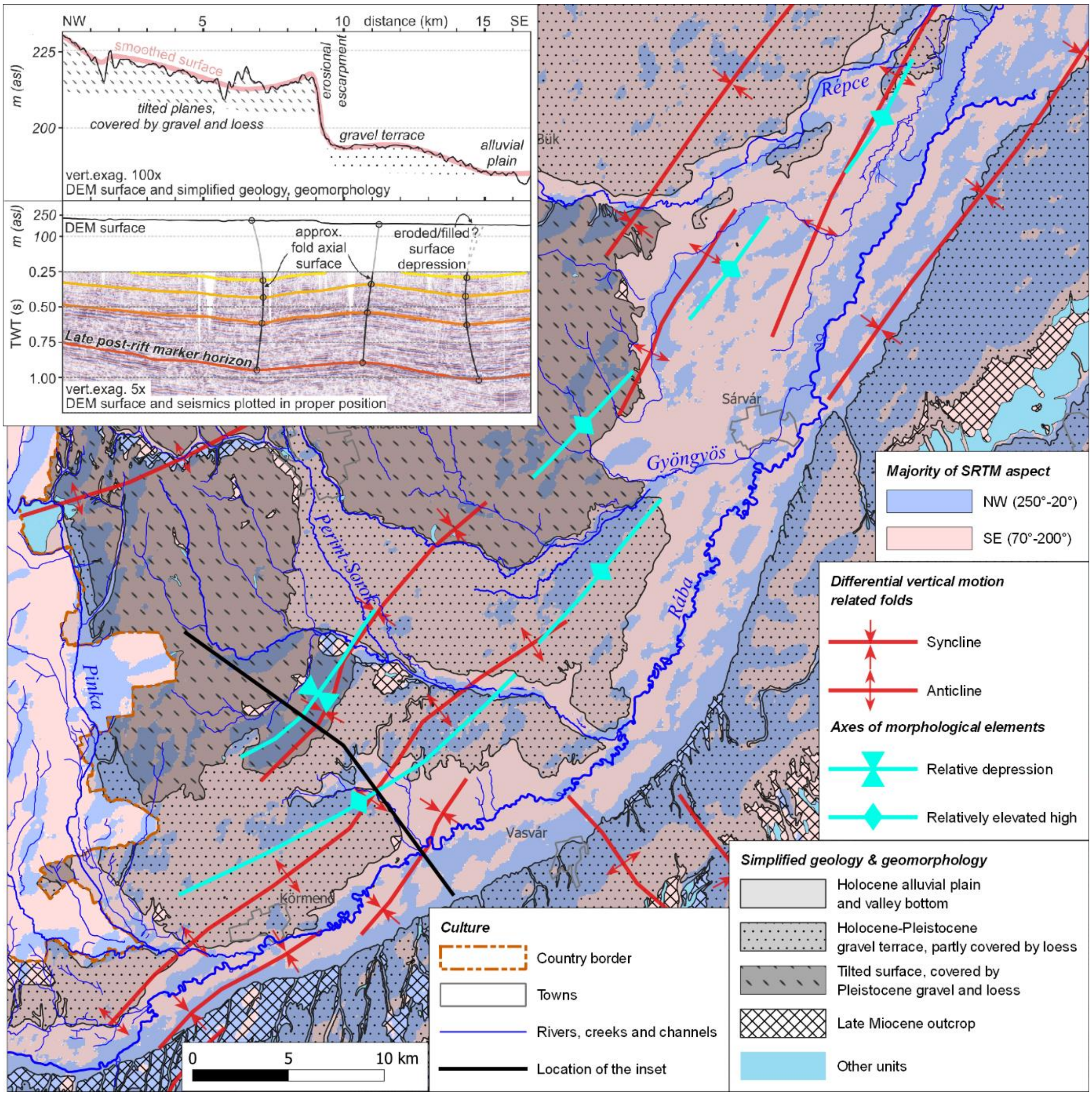


Fig. 12. Spatial correlation between fold locations of this study and surface morphological elements revealed by independent analysis of digital elevation models (SRTM and DDM-10; Kovács et al., 2014). The very gentle morphological trends within the fluvial sediments of the Rába river shown by the terrain aspect attribute of the DEM correlate well with underlying folds interpreted on the seismic dataset.

6.2. Zala basin

The Zala basin (*Figs. 1, 8*) represents the classic area of Hungarian structural geology, where E–W trending, compression-related folds were described from the early twentieth century on (Pávai Vajna, 1925; Dank, 1962; Horváth and Rumpler, 1984). These folds clearly dominate the overall neotectonic deformation style of the domain (c.f., also Fodor et al., 2005a-b; Bada et al., 2006, 2007, 2010; http://dx.doi.org/10.17632/dnjt9cmj87.1). The E–W and ENE–WSW oriented structural trends generally characterize the domain despite the fact, that the area comprises several large tectonic units separated by first order tectonic fault zones (i.e., Balaton and Kapos fault zones; *Figs. 8, 13)*.

Compression-related neotectonic folding was essentially coupled with north-vergent blind reverse faulting along pre-existing synrift normal faults in the Zala basin (Horváth and Rumpler, 1984; Horváth, 1995; Fodor et al., 2005a-b, 2013; Bada et al., 2006). The folding therefore was directly related to the regional neotectonic stress field characterized by a ca. N–S oriented horizontal maximum stress axis (σ_1). The most prominent example is the long-known, E–W trending Budafa anticline (*Fig. 14*), but several smaller folds of this type (e.g., the Belezna and Semjénháza anticlines and an associated syncline between them) were also correlated. These smaller folds were not or often inaccurately shown in former neotectonic syntheses (e.g., Fodor et al., 2005a-b, 2013; Horváth et al., 2006a, 2009; Bada et al., 2007; 2010; see *Fig. 13*). The location of the blind reverse faults coupled with prominent contractional anticlines (Fodor et al., 2013) are in good agreement with the identified monoclinal structures developed above these faults.

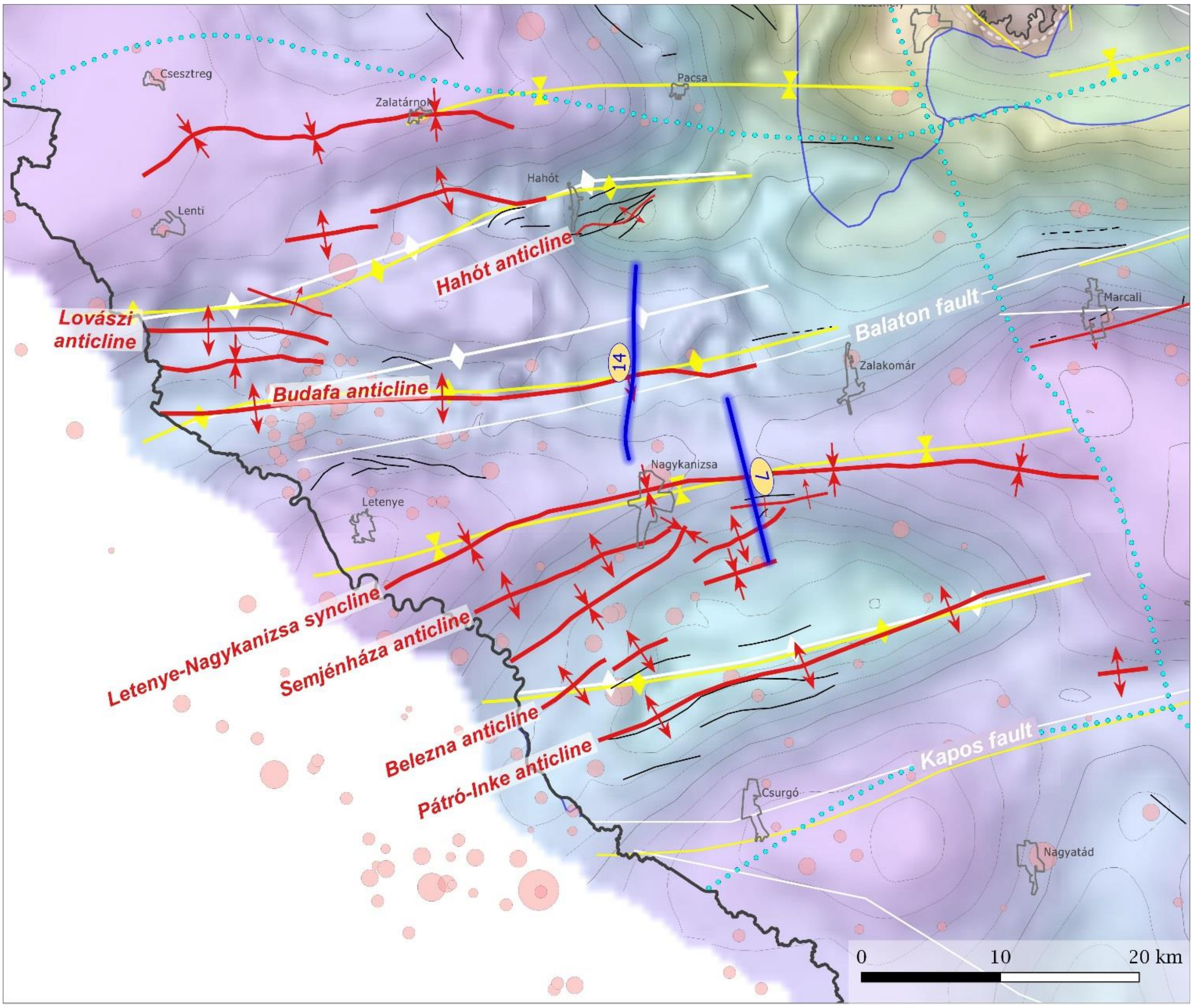


Fig. 13. Detailed view of the Zala basin folds compared to earlier regional studies (yellow: Horváth et al., 2006a; white: Horváth et al., 2009; for detailed legend see Fig. 9). Location of Figs. 7 and 14 is shown by blue line. Seismicity is shown after Tóth et al. (2020).

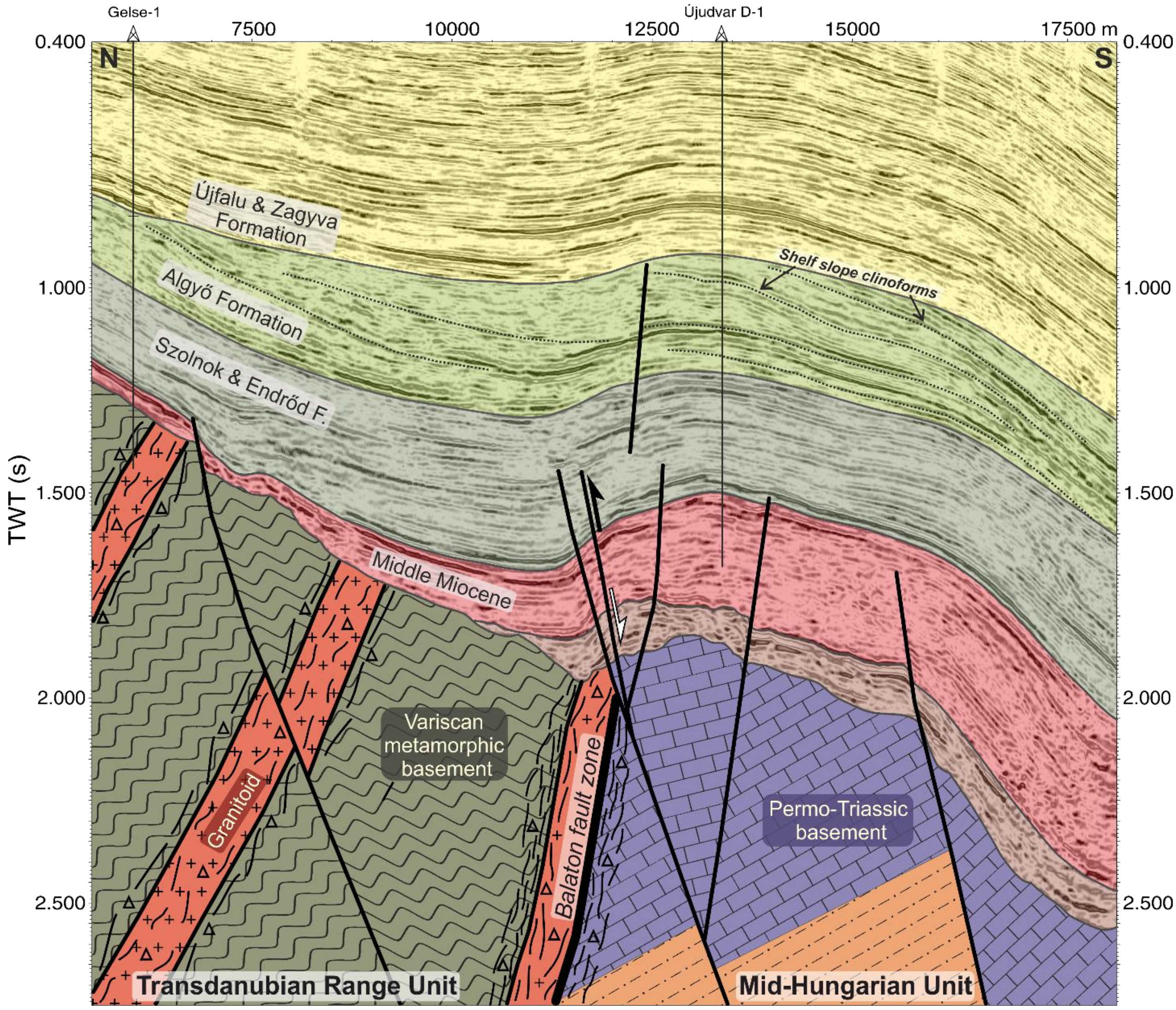


Fig. 14. Compressional folding related to graben inversion: the Budafa anticline. For location see Figure 13

Beside its fold-dominated nature another striking feature of this domain is the subordinate role of neotectonic faults. They are typically oriented (sub)parallel to fold hinges and the underlying pre-Pannonian faults (http://dx.doi.org/10.17632/dnjt9cmj87.1), and often represent the continuation of blind reverse faults to shallow stratigraphic levels. Their symmetrical arrangement on both sides of the Budafa anticline (*Fig. 13*) indicates the formation (or contemporaneous reactivation) of an antithetic, north-dipping fault producing a pop-up like structure during inversion in the middle sector of the anticline. In other cases faults either form flower structures (Hahót anticline; c.f., also Bada et al., 2006: Fig. 4) or are organized into a set of steep, (sub)parallel faults (Pátró-Inke anticline) in seismic sections. These observations altogether indicate a compressional stress regime being perpendicular to the pre-existing structural fabric during the neotectonic deformation phase in this area.

It is important to emphasize, that practically no near surface manifestation of neotectonic faulting occurs along the western segments of the Balaton and Kapos faults being in contrast with their eastern continuations characterized by peculiar neotectonic flower structures in the shallow post-rift strata (see also Section 6.4.). This feature indicates the lack of detectable strike-slip reactivation of these faults within the domain (questioned also by e.g., Bada et al., 2010) being in contrast with former regional neotectonic models (c.f., *Fig. 13*). However, based on recent and historical seismicity (Tóth et al., 2020) the western segments of these major fault zones can be considered as seismoactive (*Fig. 13*).

6.3. Dráva basin

The Dráva basin is located in the southwestern part of the country extending in a NW–SE direction parallel to the river Dráva (*Figs. 1, 15*). Good seismic coverage with numerous modern 3D seismic volumes is available (*Fig. 3*) except for the area of the Mecsek and Villány Mts.

The Dráva basin represents a unique domain in the sense that the prominent (W)NW–(E)SE neotectonic structural trend is not characteristic elsewhere in the country. This structural trend has been long recognized in the basement structure (Csalagovits et al., 1967; Fülöp and Dank, 1987; Haas et al., 2010). Altogether a moderate neotectonic activity occurs in this domain manifested in the formation of pronounced, NW–SE striking right lateral shear zones as well as compression-related folds. The new mapping has complemented the existing tectonic knowledge of the area and provided a detailed model of the Szulok-Sellye-Cún dextral strike-slip fault zone. The map also proposes an alternative structural model compared to other (neo)tectonic maps regarding the boundary of the Dráva and Mecsek-Villány tectonic units (http://dx.doi.org/10.17632/dnjt9cmj87.1; *Fig. 15*).

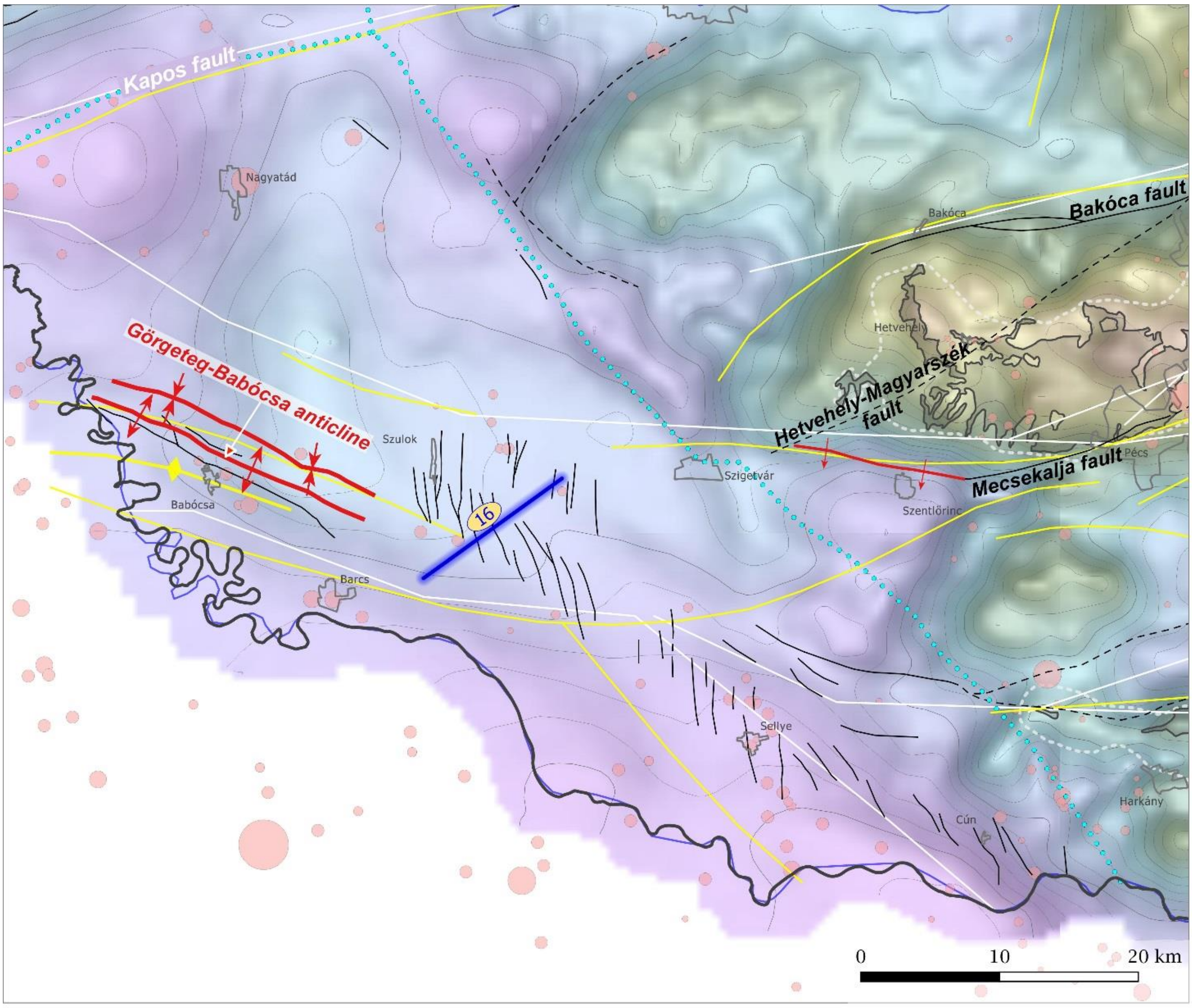


Fig. 15. Detailed view of the mapped structures in the Dráva basin compared to earlier regional studies (yellow: Horváth et al., 2006a; white: Horváth et al., 2009; for detailed legend see Fig. 9). Location of Figure 16 is shown by blue line. Seismicity is shown after Tóth et al. (2020).

The dominant neotectonic feature of the domain is a nearly 60 kilometer long, WNW–ESE striking fault zone running between the localities of Szulok and Cún. The fault zone is built up by a large number of individual fault segments up to a length of ca. 6 kilometers oriented between NW–SE and N–S. Both their map view arrangement (i.e., typical en-echelon geometry) and their seismic image (i.e., characteristic flower structure) clearly suggest a strike-slip fault zone of dextral shear. This fault zone provides an excellent example for the neotectonic reactivation of ancient basement structures (*Fig. 16*): it was partly developed along the southwestern border fault of a Carboniferous (see Haas et al., 2010) molasse graben, but neotectonic fault reactivation also occurs at the northern graben margin to a limited extent (http://dx.doi.org/10.17632/dnjt9cmj87.1).

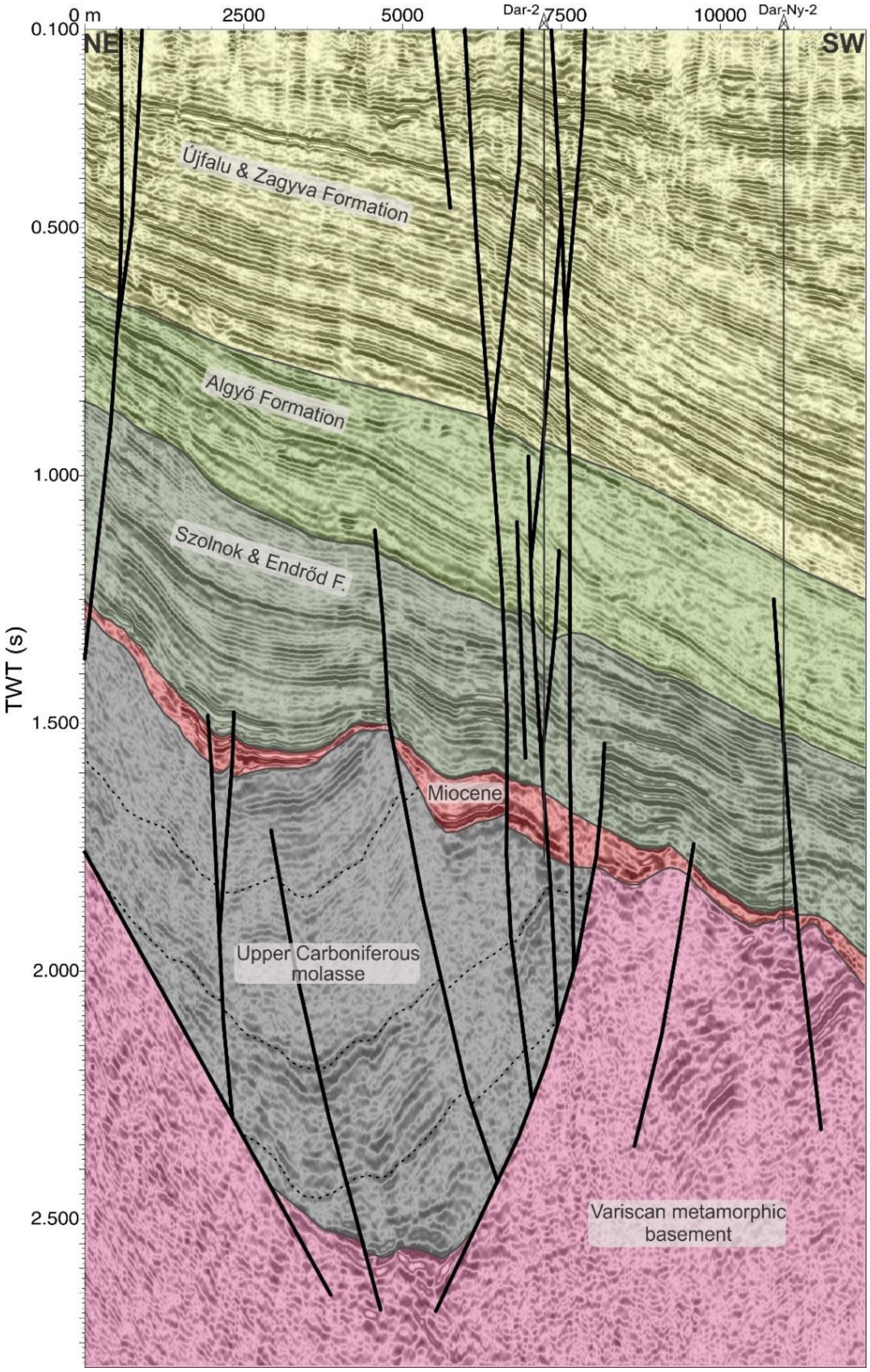


Fig. 16. NE–SW oriented seismic profile showing neotectonic reactivation of the border faults of a Late Carboniferous molasse graben. Note also the folding of the graben fill (marker horizons by dotted lines) due to Late Variscan and/or Eoalpine (Cretaceous) compressional event(s). For location see Figure 15

The graben gradually becomes narrower towards the southeast and finally disappears (near Sellye), however, a southwestward facing basement fault with associated neotectonic reactivation can be traced further in the seismic dataset up to the locality Cún. Recent seismicity documented along the entire length of the fault zone, and especially near the locality Sellye (Tóth et al., 2020; *Fig. 15*) is in good accordance with the observed neotectonic activity.

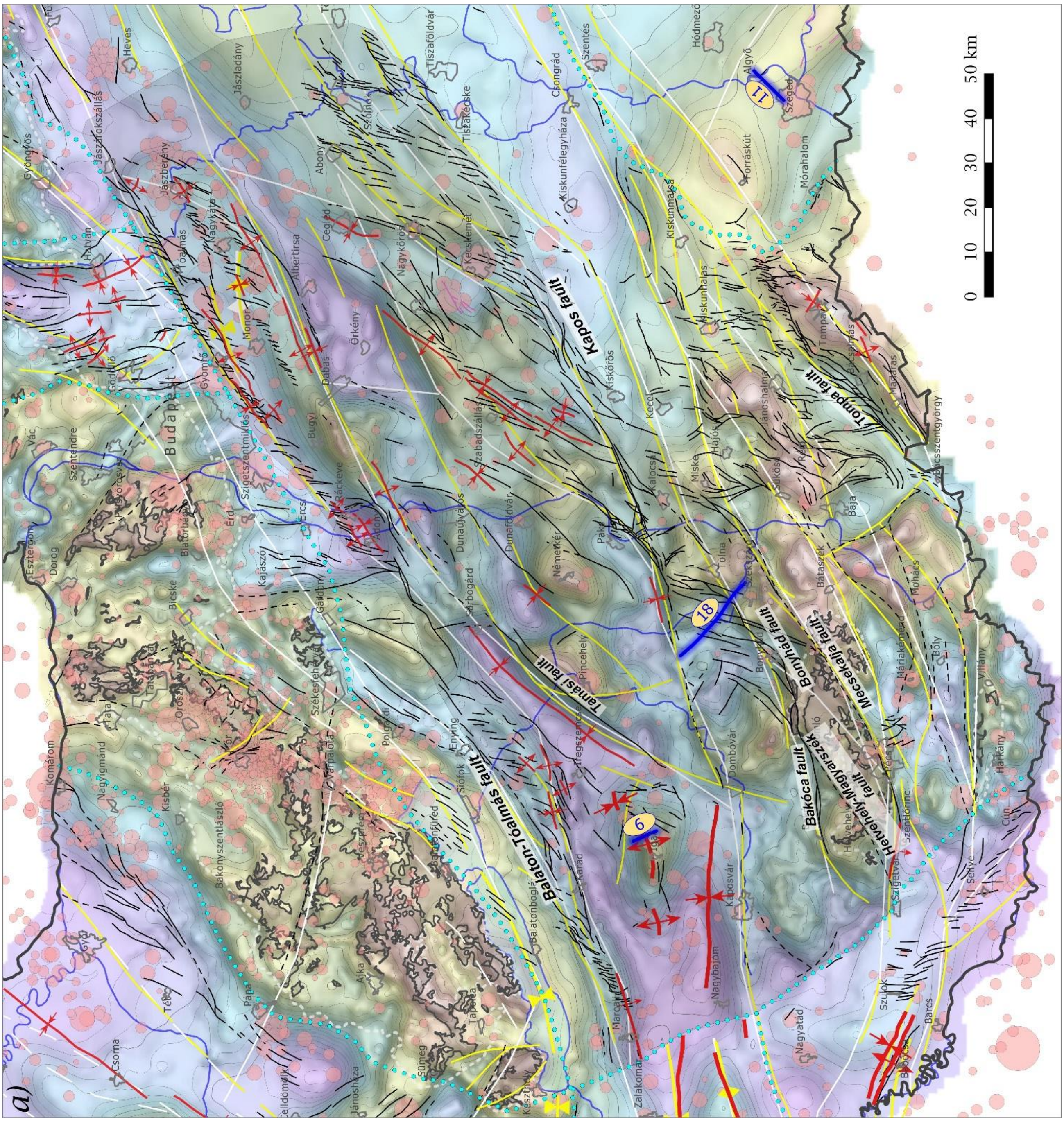
The Görgeteg-Babócsa anticline is probably the best-known neotectonic structure of the domain, which (together with the associated, parallel syncline to the north) was mapped, in great details (c.f., *Fig. 15*). A prominent, mostly northeast-dipping neotectonic fault is situated south of the anticline axis, whereas a shorter parallel fault segment north of the anticline axis represents a minor southwest-dipping antithetic fault. The formation of this anticline was generally connected to the reverse reactivation of a former, southwest-dipping fault appearing at the northwestern part of the anticline by compressional forces (Saftić et al., 2003; Wórum and Hámori, unpubl.; Horváth et al., 2015) using the structural analogy of the Zala basin (see Section 6.2.).

For the eastern boundary of the Dráva domain an alternative structural model is proposed (reflected by the pre-Pannonian fault pattern, http://dx.doi.org/10.17632/dnjt9cmj87.1), where we favor a prominent, NW–SE striking fault separating the Dráva and the Central Hungary domains between the Kapos fault zone and Hungarian-Croatian border. This interpretation is based on Bouguer anomaly patterns and only on limited number of seismic surveys. However, it was necessitated, because available data do not support the direct structural continuation of the Mecsekalja and other parallel fault zones of the Central Hungary domain (see also Section 6.4.) into the Dráva domain as it was indicated in former models (c.f., *Fig. 15*). In our view this fault represents the northern limit of the "Dinaric" type structural orientations being also dominant in Croatia, although this area is considered as part of the Tisza megaunit (Schmid et al., 2008; Haas et al., 2010).

6.4. Central Hungary

This domain comprises the central portion of the country including southeastern Transdanubia and large part of the Great Hungarian Plain (*Figs. 1, 8*). Apart from the area of the Mecsek and Villány Mts. and their surroundings good seismic coverage (including many 3D seismic volumes in the east) exists in this area (*Fig. 3*).

The overall neotectonic deformation pattern is dominated by ENE–WSW and NE–SW trending faults/fault zones and associated fault-related, rarely en-echelon folds, whereas structures of other orientations occur less frequently. Despite the generally dominant ENE–WSW and NE–SW structural trends notable differences exist in the neotectonic deformation pattern within this large domain allowing the separation of several distinct subareas. These include (i) the re-defined Mid-Hungarian mobile belt south of the Balaton-Tóalmás fault zone (ii) the southern Danube-Tisza interfluve and (iii) the Eastern Great Hungarian Plain. The whole Central Hungary domain displays a significantly more complex neotectonic deformation pattern than shown by former neotectonic syntheses (*Fig. 17a-b*).


a)
0 10 20 30 40 50 km
Kapos fault
Tamási fault
Balaton-Tolnai fault
Bonyhád fault
Mecsekalja fault
Bakóca fault
Hetvehely-Magyarszék fault
Tompa fault
Budapest

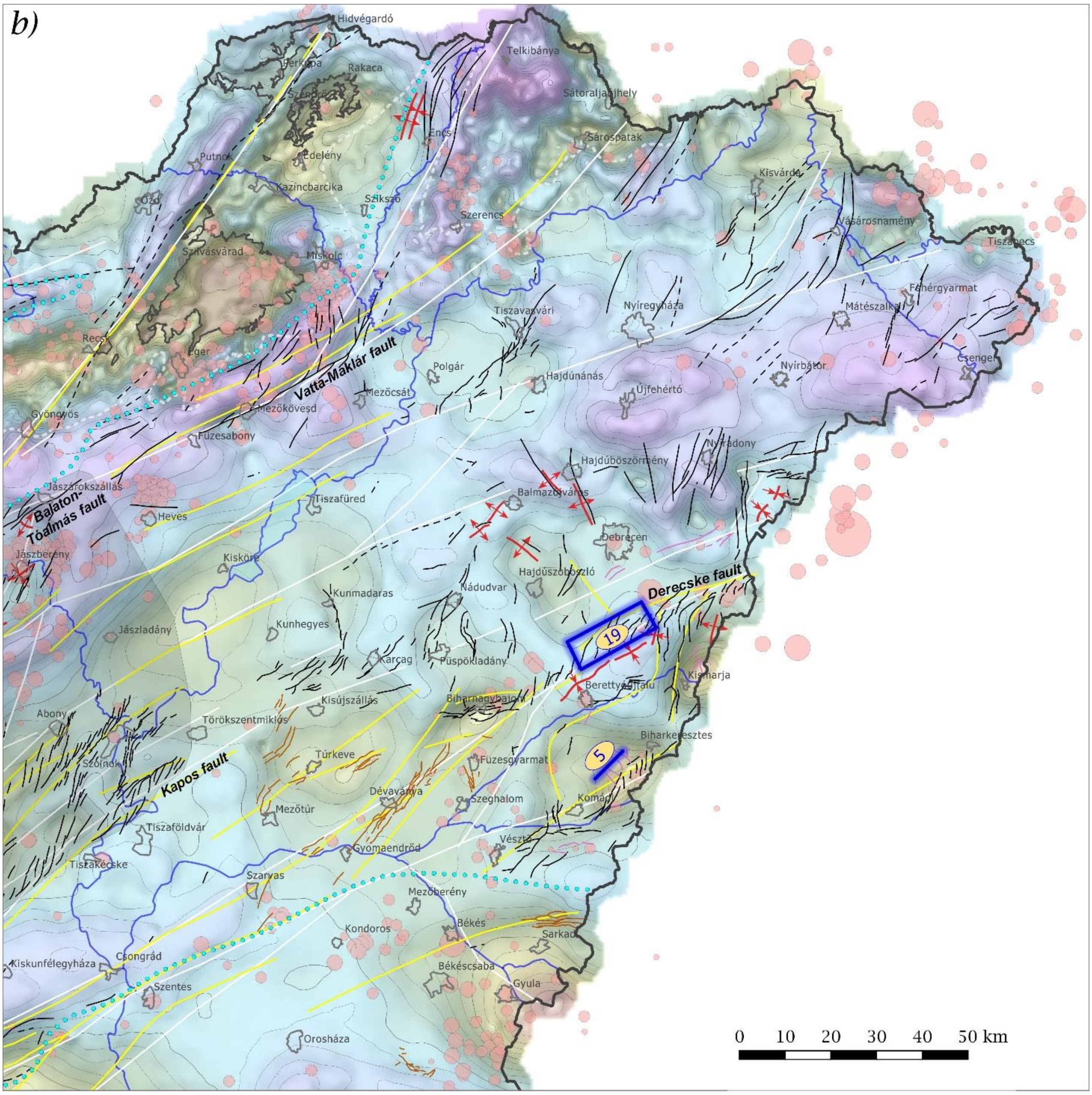


Fig. 17. Detailed view of the mapped structures in the western (a) and eastern (b) Central Hungary domain, and their comparison to earlier regional studies (yellow: Horváth et al., 2006a; white: Horváth et al., 2009; for detailed legend see Fig. 9). Shaded gray polygon indicates the area of the Mid-Hungarian mobile belt redefined in this study. Locations of Figs. 5, 6, 11, 18 and 19 are shown by blue lines. Seismicity is shown after Tóth et al. (2020).

Mid-Hungarian mobile belt (redefined after Detzky Lőrincz et al., 2002)

The northern part of the Central Hungary domain consists of an approx. 60-80 km wide belt of distributed strike-slip deformation that can be followed more than 200 kilometers along strike (*Fig. 17a*). The eastern part of this wide zone located between the ENE–WSW striking Balaton-Tóalmás fault in the north and the eastern Kapos fault in the south was previously recognized and called as *Mid-Hungarian mobile belt* (Detzky Lőrincz et al., 2002; Juhász et al., 2013). In the pre-Tertiary basement it incorporates the entire Mid-Transdanubian unit (i.e., the classical area of the Mid-Hungarian Fault Zone; Csontos and Nagymarosy, 1998) and the northern portion (i.e., the Mecsek unit) of the Tisza-Dacia megaunit (see *Fig. 8*). Considering the new mapping as well as most recent neotectonic models (Horváth et al., 2019) we extend this deformation belt towards the southwest up to the town of Szigetvár. The southwestern extension contains the Bonyhád fault zone joining to the Northern Imbricate Zone of the Mecsek Mts., the Bakóca and Hetvehely-Magyarszék faults, and the Mecsekalja fault zone (*Fig. 17a*). These tectonic elements seem to accommodate most of the young deformations (e.g., Tari, 1992; Horváth et al., unpubl., 2019; Csontos et al., 2002; Wórum and Hámori, unpubl.; Konrád and Sebe, 2010; Kovács et al., 2018) southwest of the river Danube, whereas only minor, westward diminishing neotectonic faulting appears along the western Kapos fault (Horváth et al., 2019). The same holds true for the Balaton-Tóalmás fault zone west of the town Marcali, where folding dominates the neotectonic deformation instead of near surface faulting (see Section 6.2.).

Towards the East intensive near surface neotectonic faulting along the Mid-Hungarian mobile belt seems to diminish near the towns Jászberény and Szolnok (http://dx.doi.org/10.17632/dnjt9cmj87.1). Hence, our study does not verify the presence of regional-scale neotectonic strike-slip shear zones crosscutting the entire territory of Hungary (c.f., Horváth et al., 2009). Although near-surface neotectonic faulting is not continuous, our detailed mapping suggests that the northernmost root zone of the Balaton-Tóalmás fault zone (i.e., the Tápió-Tóalmás fault; Ruszkiczay-Rüdiger et al., 2007) towards the east is connected to the ENE–WSW striking boundary fault system of the Vatta-Maklár trough showing prominent neotectonic reactivation. East of the Vatta-Maklár trough the continuation is uncertain due to lack of seismic data, its correlation with the neotectonically active Hernád fault towards the northeast is highly model-driven and was primarily based on gravity data.

Although poorly constrained below the thick Miocene volcanites we share the view of Fülöp and Dank (1987) that the prominent, well-expressed fault zone between Dabas and Albertirsa continues towards the northeast into the Nyírség area (through the localities of Polgár and Tiszavasvári; see also http://dx.doi.org/10.17632/dnjt9cmj87.1). This interpretation is in line with tectonic restorations connecting the Bogdan-Voda Dragos-Voda fault system of the Eastern Carpathians (*Fig. 1*) to the Mid-Hungarian Fault Zone (Györfi et al., 1999; Tischler et al., 2007). The Nyírség area (underlain mostly by Miocene volcanics) was a former neotectonic "white patch" of the country. Our new mapping revealed here a predominate ENE–WSW and (N)NE–(S)SW oriented neotectonic fault pattern, similarly to the western parts of the Central Hungary domain.

Our study has managed to reveal not only the internal fine structure, but also the regional structural relationships of the Mid-Hungarian mobile belt in such details that were not seen before. As well-reflected also on the background Bouguer anomaly image of the new map the Mid-Hungarian mobile belt is made up of a system of NE–SW and ENE–WSW oriented, elongated morphological elements (e.g., small basins at Adony, Örkény and Bonyhád for example, and a set of en-echelon oriented narrow highs between the municipality of Pincehely and Lajosmizse, http://dx.doi.org/10.17632/dnjt9cmj87.1). These morphological units are bounded by faults (e.g., the Paks-Szabadszállás, Kalocsa-Szabadszállás-Lajosmizse, Kecskemét-Nagykőrös-Abony and the fault system in the Tiszakécske-Szolnok area), which all connect to the Kapos fault (and less clearly to the Mid-Hungarian fault zone in the north). These elements are all characterized by pronounced neotectonic activity represented by a complex system of individual en-echelon faults in the young sedimentary section. The internal structure of these fault zones generally show typical flower structures on the seismic profiles recording strike-slip tectonics along them (*Fig. 18*) being in agreement with previous results obtained for the various elements of the Mid-Hungarian mobile belt (Pogácsás et al., 1989; Detzky Lőrincz 1997; Tóth and Horváth, 1997; Csontos and Nagymarosy, 1998; Detzky Lőrincz et al., 2002; Tóth, unpubl.; Csontos et al., 2005; Fodor et al., 2005a-b; Ruszkiczay-Rüdiger et al., 2007; Bada et al., 2010; Palotai and Csontos, 2010; Várkonyi, unpubl.; Várkonyi et al., 2013; Juhász et al., 2013; Visnovitz et al., 2015; Horváth et al., 2019).

The fine internal structure of these fault zones, together with the overall alignment and geometry of the morphological elements mentioned above suggests a general left-lateral shear between the Kapos and Balaton-Tóalmás faults both during the Middle Miocene and the neotectonic deformation phase. This large scale shearing and deformation is manifested both on a local (individual (N)NE–(S)SW oriented, en-echelon Riedel or oblique-slip faults) and on the meso-scale (en-echelon/shear duplex geometry of the larger morphological elements — pull apart basins and horsts — within this mega-shear). Based purely on neotectonic fault pattern analysis, the largest fault offsets are occurring along the boundary of this shear zone (NE of the municipality of Gyömrő along the Tóalmás fault and north of Kalocsa along the Kapos fault), where the individual neotectonic Riedel faults were crosscut/replaced by subsequently developed Y-faults creating 20–25km long continuous fault segments above the PDZs.

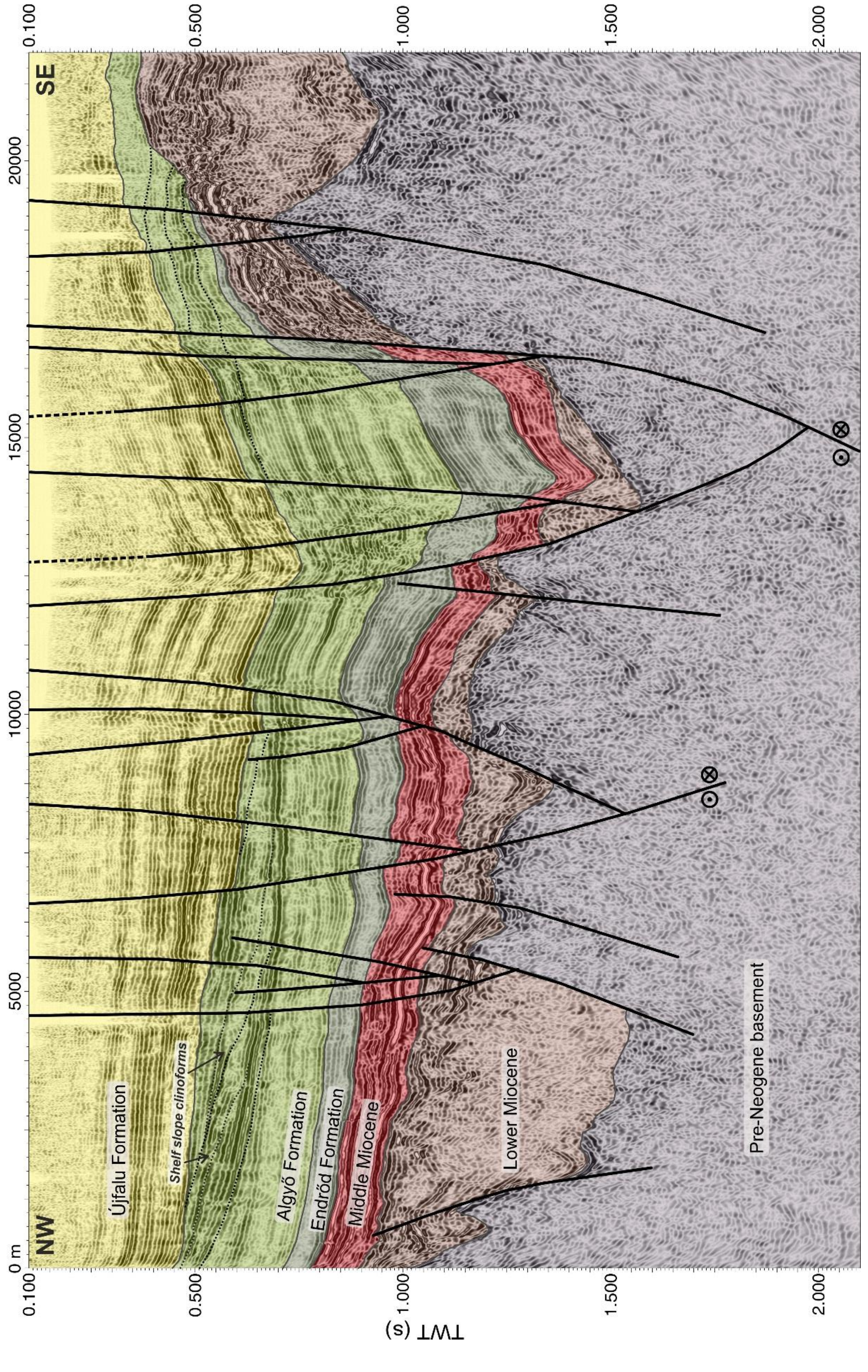


Fig. 18. Neotectonic strike-slip faulting in the Bonyhád basin associated with typical flower structures. For location see Figure 17a

Neotectonic fault reactivation occurring along the complex, interconnected network of ENE–WSW and NE–SW striking faults are bounding transtensional/transpressional fault domains and strike-slip duplexes (see also Fodor, unpubl.). Neotectonic transtensional/transpressional fault reactivation seems to be basically the function of structural orientation indicating a consistent, ~NNE–SSW oriented maximum horizontal stress direction during the neotectonic phase: transtension is namely connected to ~NE–SW striking fault segments (see e.g., Horváth et al., 2019), whereas transpression appears along ~E–W (Mecsekalja fault zone near Szentlőrinc, Northern Imbricate Zone of the Mecsek Mts (Tari, 1992)), or WNW–ESE (Palotai and Csontos, 2010) oriented fault segments. As suggested by the identified overall neotectonic fault pattern (http://dx.doi.org/10.17632/dnjt9cmj87.1), transpressional reactivation rather occurred only at certain segments of the ENE–WSW striking Tóalmás fault zone than along the entire fault (Ruszkiczay-Rüdiger et al., 2007; Palotai and Csontos, 2010).

The predominant ENE–WSW and NE–SW structural trends of the belt are explicitly reflected both in gravity data (http://dx.doi.org/10.17632/dnjt9cmj87.1) and the basement structure (Fülöp and Dank, 1987; Haas et al., 2010). Their origin was related essentially to the Early Miocene juxtaposition of the Alcapa and Tisza-Dacia megaunits (see also Section 2. and *Fig. 1*) by large-scale horizontal movements along the Mid-Hungarian Fault Zone. However, the observed neotectonic fault pattern indicates that the easily reactivating weakness zones of the crust only partly coincide with the presently known tectonic boundaries of major pre-Tertiary units (*Fig. 8*), and even if this relationship exists in certain segments it can rapidly change along strike.

Southern Danube-Tisza interfluve

Neotectonic deformation in this area has resulted in a more complex fault pattern than in the adjacent Mid-Hungarian mobile belt, since previously not considered NNW–SSE and N–S oriented fault systems also appear (http://dx.doi.org/10.17632/dnjt9cmj87.1) beside the prevailing ENE–WSW and (N)NE–(S)SW structural trends. NNW–SSE and N–S striking neotectonic faults occur mostly at the margins of shallow seated basement blocks (Miske, Sükösd-Rém and Jánoshalma basement highs) in the northern part of the area that form the direct eastern continuation of the outcropping Mecsek and shallow subsurface Villány (i.e., the Máriakéménd zone) nappes of the Tisza-Dacia megaunit. The underlying faults were probably formed during Miocene extension similarly to the major, NW–SE striking synrift faults in the adjacent Southeast Hungary domain (see Section 6.5.). The small, elongated basin bounded by such NNW–SSE to N–S striking faults at the town of Baja (http://dx.doi.org/10.17632/dnjt9cmj87.1) gives a typical example. Identified NNW–SSE striking roots display a significantly more complex geometry in the pre-Cenozoic basement than shown previously (Haas et al., 2010).

The most prominent neotectonic element of this area is the ENE–WSW striking Bácsszentgyörgy-Tompa fault zone (Pogácsás et al., 1989; referred as Tompa fault on *Fig. 17a*) separating the elongated Tompa-Madaras basement high and the Bácsalmás basin. Characteristic Riedel fault pattern indicates sinistral kinematics along this major fault (http://dx.doi.org/10.17632/dnjt9cmj87.1). Its root zone is represented by a steeply, NNW-dipping Miocene border fault running roughly parallel to the inferred nearby Cretaceous nappe contact of the Villány and Békés-Codru units (Haas et al., 2010; *Fig. 8*) suggesting a possible, but in details not studied connection between the two.

The sigmoid shape of the Bácsalmás depression, as well as the geometry of the bounding ENE–WSW and (N)NE–(S)SW striking fault system argues for its pull-apart origin during Miocene tension/transtension in a left-lateral strike-slip shear zone. Moreover, this basin is divided into two smaller, elongated subbasins by a NNE–SSW oriented narrow ridge as shown both by the Bouguer residual anomaly map and the seismic sections. Most of the bounding faults, including the fault underlying the mentioned narrow ridge, were — at least partly — reactivated during the neotectonic phase. The map view arrangement of the individual (N)NE–(S)SW striking fault branches joining to the major ENE–WSW striking fault zone suggest sinistral kinematics, similarly to the observed Riedel fault pattern further to the east. Although at a much smaller scale, but the overall alignment of the deformation pattern in this area is similar to the shearing within the Mid-Hungarian mobile belt discussed above, where the sinistral deformation occurs along a wide zone and is reflected both in the local and in the meso-scale tectonic features.

Eastern Great Hungarian Plain

The neotectonic deformation pattern in the eastern part of the Great Hungarian Plain is similar, yet very different from that of the other parts of the Central Hungary domain. In general ENE–WSW and NE–SW striking faults dominate here as well, but NNW–SSE, N–S and locally E–W oriented fault systems and associated fault-related folds also occur (http://dx.doi.org/10.17632/dnjt9cmj87.1). These structural trends seem to appear in smaller, spatially separated areas creating for a first glance a "diffuse", patchy network of variably oriented faults/fault systems without any well-defined regional trend. Although deep-seated structural connection seems to exist (see pre-Pannonian fault pattern), the neotectonic near-surface deformation in this area cannot be considered as the eastern continuation of the deformation zone in the Mid-Hungarian mobile belt, which appears to diminish near Törökszentmiklós.

NNW–SSE, N–S and subordinate E–W striking neotectonic faults occur mainly in the northern part of the area. The roots of these faults north of the city Debrecen bound small (half)grabens and horsts in the pre-Pannonian basement that were most probably formed during E(SE)–W(NW) directed Middle Miocene tension (e.g. Fodor et al., 1999). Such structures were also identified further to the southwest (near the towns of Hajdúszoboszló, Püspökladány and Kunhegyes).

South of this area the ENE–WSW oriented, well-documented Derecske fault zone forms the most prominent neotectonic element (*Fig. 19*) between the Hungarian/Romanian national border and the Biharnagybajom basement high (http://dx.doi.org/10.17632/dnjt9cmj87.1).

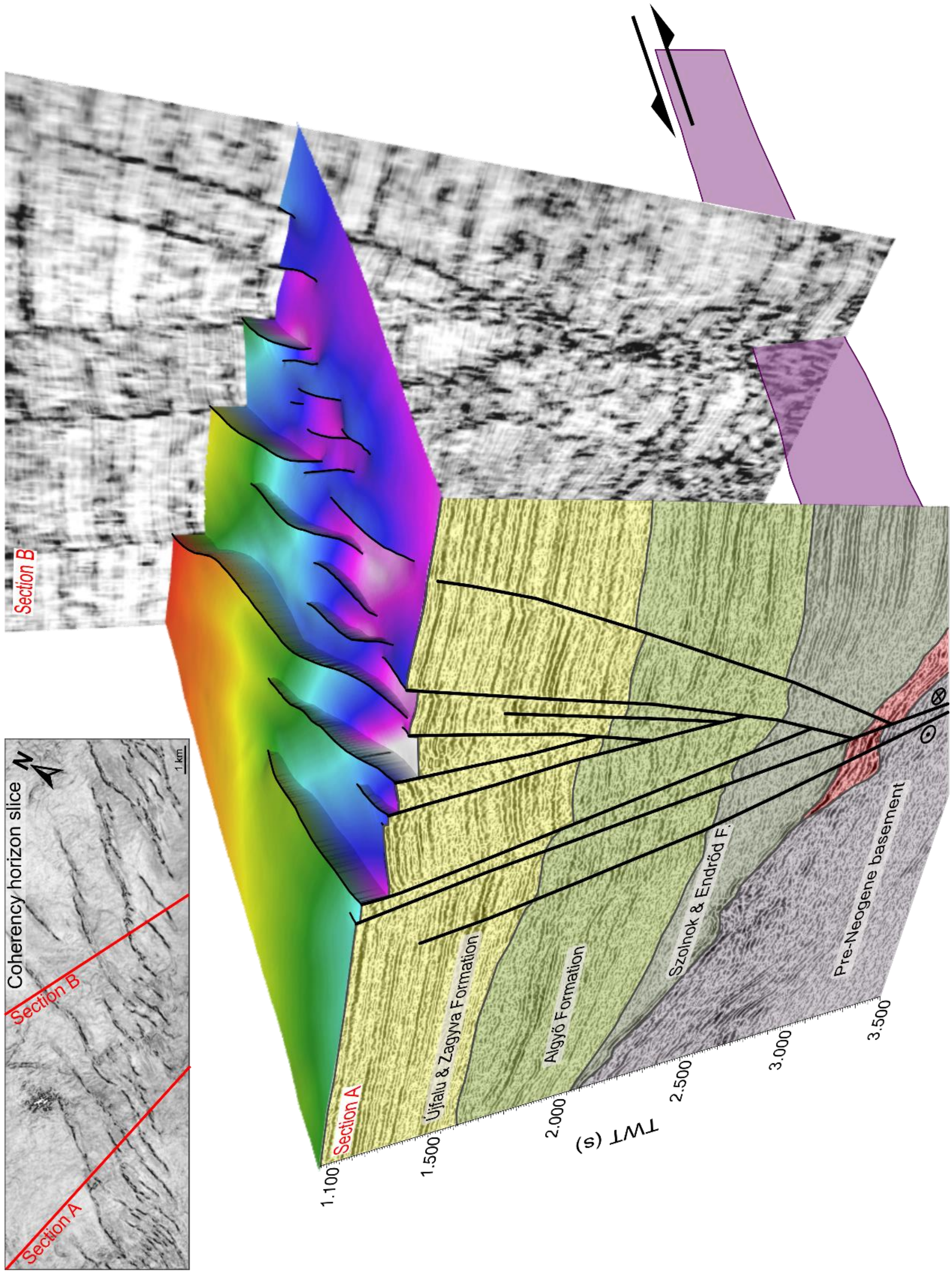


Fig. 19. Neotectonic sinistral strike-slip faulting in the Derecske through as indicated by the characteristic Riedel fault array observed on the coherency horizon slice (upper left) mapped

within the alluvial plain deposits. Cross sections A and B (locations shown by red lines on the coherency horizon slice) show typical negative flower structure. For location see Figure 17b

The Érmellék earthquake with estimated magnitude of 6.2 in 1834 was directly related to its eastern continuation in Romania associated with faults reaching even the surface. The fault zone runs along the northern margin of the Derecske trough and is characterized by a typical Riedel fault array indicating sinistral shearing (*Fig. 19*) as also indicated by several tectono-sedimentological and modelling studies (Lemberkovics et al., 2005, Windhoffer and Bada, 2005; Windhoffer et al., 2005). Interestingly, Riedel fault array changes to anastomosing, subparallel network of faults with rare Riedel elements above the Biharnagybajom high, which (as confirmed by seismic data) forms the direct western continuation of the Derecske fault zone. Correlation of its pre-Pannonian roots towards the southwest and west indicates a structural connection with the NE–SW oriented Dévaványa-Gyomaendrőd and possibly also with the Túrkeve and Mezőtúr basement highs. Near surface faulting appears all above(/near) these basement highs, showing dominantly an anastomosing fault pattern.

Balázs et al. (2016, 2018) recently proposed the compaction origin of the faults above the Dévaványa and Túrkeve highs based on various criteria. Without doubt typical Riedel fault pattern and significant lateral offset are missing above the mentioned highs, instead, a network of anastomosing, subparallel faults appear forming characteristic flower structures in a cross section (Balázs et al., 2018). Similar neotectonic fault pattern, however, exists elsewhere in the broader area (near the town of Paks (Horváth et al., 2019), Biharnagybajom, SW of Komádi), where the tectonic origin is unquestionable. Among these the Biharnagybajom high represents the direct western continuation of the Derecske fault zone without any interruption in neotectonic activity. Therefore, the change in the fault segment geometry from typical en echelon array to anastomosing, subparallel pattern above this high is rather attributed to the strongly changing basement morphology (and/or root zone geometry) than to the change in faulting mechanism (i.e., from tectonic to compaction faulting).

Seismic sections across fault systems of tectonic origin developed above basement highs generally show characteristic flower structures and direct rooting into underlying pre-Pannonian fault(s). Literature data indicate, however, that compaction faults typically form standalone (Misra, 2018; like those developed at the margins of the Algyő high, http://dx.doi.org/10.17632/dnjt9cmj87.1), graben-like (Maillard et. al., 2003), or locally, a set of uniformly dipping or conjugate, usually rootless structures (Williams, 1987, Xu et. al., 2015). Flower structures of compactional origin with roots in the basement are explicitly rare (e.g., Xu et. al., 2015).

Taking the above mentioned characteristics and different structural interpretations into account, we classified the localized young faults above these basement highs with anastomosing, subparallel fault geometry as faults with uncertain/debated origin, but with a bias toward tectonics. Observed seismicity (Tóth et al., 2020) seems to support the tectonic origin of the fault systems developed above the Biharnagybajom, Dévaványa-Gyomaendrőd, Endrőd-Szarvas, Szeghalom, Komádi and Kismarja basement highs (*Fig 17b*). If one accepts their tectonic origin the neotectonic fault pattern and the overall alignment of the deformation zones in Eastern Hungary resemble the elements of a wide, left-lateral shear zone being in agreement with the deformation style identified further to the west. The main participants of this large-scale sigmoid shape, often fragmented shear zone includes the Derecske fault, the fault system above the Dévaványa-Gyomaendrőd highs as well as the fault zones developed along the Komádi-Biharkeresztes and Kismarja highs.

6.5. Southeast Hungary

This domain (*Fig. 8*) hosts the deepest depocenters (Szeged and Békés basins, Makó trough; *Fig. 1*) in the whole Pannonian Basin. It is largely covered by modern 3D seismic volumes providing excellent opportunity for the identification of neotectonic deformations (*Fig. 3*).

Despite of this practically no neotectonic activity was identified, representing the most striking and surprising characteristic of this domain. Identified rare young faults (both with tectonic and atectonic origin) strike NW–SE at the margins of the Békés and Szeged basins (http://dx.doi.org/10.17632/dnjt9cmj87.1) underlain by major Neogene faults (Haas et al., 2010) formed during Miocene basin formation (see e.g., Tari et al., 1999). The general lack of NE–SW striking neotectonic faults is an important difference compared to the adjacent Central Hungary domain (see Section 6.4.).

The “missing” neotectonic activity is a still poorly understood feature of this domain, especially in comparison to the adjacent Central Hungary domain. On one hand, the neotectonic reactivation of the predominant NW–SE striking faults might have been hampered by the unfavorable orientation of the neotectonic stress field characterized by a ca. NE–SW directed maximum horizontal stress axis in this area (Bada, 1999; Bada et al., 1999, 2007; Horváth et al., 2006a).

On the other, recent claybox modelling study of Hatem et al. (2017) draws the attention to the importance of the depth of basal shear, and the presence of preexisting faults in strike-slip fault development, fault complexity and the kinematic efficiency of a fault zone. Considering their modelling results and scaling factors an estimated 750–1800m of lateral displacement is required along a deep-seated, localized PDZ (3–6km, similar to the Neogene thickness in SE Hungary) in the basement until distributed shear becomes focused and the first Riedel shears appear near the surface. The same amount of displacement in case of a shallow-seated PDZ (1.5–3km) is more than enough to produce interaction and propagation of Riedel shears resulting in a well-developed Riedel system above the PDZ (for more details see also Section

6.7.). In other words, it is speculated, that the thick sedimentary cover and/or the smaller displacement along the basal PDZ-s in SE Hungary compared to other parts of the country simply did not "allow" the formation of neotectonic faults within the Late Miocene–Pliocene sequence. The exact background of this phenomenon should be addressed by further detailed (modelling) studies.

6.6. Zagyva trough

The neotectonic deformation pattern in the Zagyva trough includes NNW–SSE oriented faults and fault-related folds in the southern part of the domain, but towards the North the general orientation gradually changes to NE–SW along the trough axis (http://dx.doi.org/10.17632/dnjt9cmj87.1). The overall neotectonic deformation pattern displays a pronounced contrast compared to the adjacent areas: in the south the bounding Balaton-Tóalmás fault (see also Section 6.4.) and the whole Central Hungary domain in general are characterized by prevailing ENE–WSW oriented structures. To the west a prominent Neogene NW–SE striking fault system (Haas et al., 2010) appears that developed during the synrift phase (Fodor et al., 1999; Fodor, unpubl.). Certain elements of this system might have been neotectonically reactivated (http://dx.doi.org/10.17632/dnjt9cmj87.1) considering the results of detailed single- and multi-channel seismic surveys carried out on the river Danube (Oláh et al., 2014), as well as outcomes of surface geological studies in the nearby Buda Mts. (Fodor et al., 1994; Korpás et al., 2002; Palotai et al., 2012).

In the north the Zagyva through is bounded by the ENE–WSW striking Hrubanovo-Diósjenő fault (referred as Diósjenő fault on *Fig. 8*) forming a first-order tectonic boundary that separates the Transdanubian Range and Bükk units from the Veporic and Gemeric units of the Inner Western Carpathians (Balla, 1989; Haas et al., 2010). Despite the absence of post-rift strata and poor seismic coverage (*Fig. 3*) the prominent seismicity (Tóth et al., 2020) suggests the neotectonic activity of this element being in agreement with the results from the Slovakian part of Danube basin (Kováč et al., 2002). Although Middle Miocene and youger Neogene sediments are missing, available seismic data indicate intense faulting even within the shallowest imaged late Paleogene to earliest Miocene strata along this fault zone (*Fig. 20*). The age of faulting can not be determined more precisely (at least Neogene), however, the evidences introduced above strongly support the neotectonic classification of this fault.

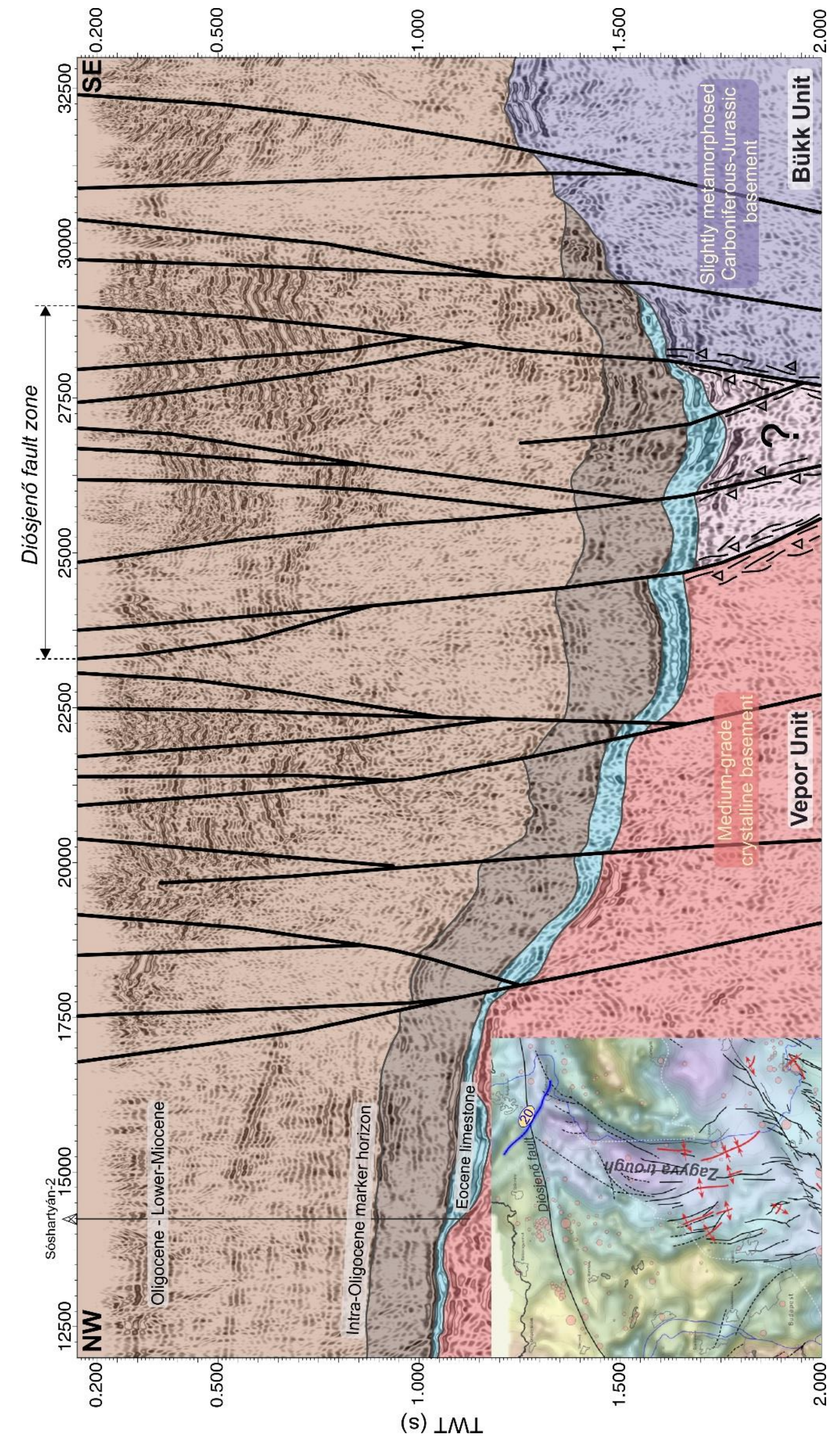


Fig. 20. Seismic profile crossing the Hrubanovo-Diósjenő fault zone displacing Paleogene–Earliest Miocene strata. For location see inset map at lower left, legend given in Fig. 9.

The "anomalous" neotectonic structural trend of the Zagyva through agrees with that of the underlying fault system formed basically during the Middle Miocene rifting phase of the Pannonian basin (e.g., Benkovics, unpubl.; Tari et al., 1992; Tari, unpubl.; Fodor et al., 1999; Fodor, unpubl.; Soós, unpubl.), and is well reflected in the Bouguer anomaly map (http://dx.doi.org/10.17632/dnjt9cmj87.1). Further to southwest the small Kajászó basin (Dudko, 1988; Horváth et al., 2004) between the river Danube and the lake Velence represents a structurally (Balla et al., 1987) largely analogous area north of the Tóalmás-Balaton fault zone characterized by similar N–S oriented neotectonic fault pattern and associated recent seismicity (Tóth et al., 2020; *Fig. 17a*).

Regarding the regional structural pattern introduced above we propose that the Zagyva through was formed and acted as an important transfer zone during the Miocene and neotectonic phases accommodating extension by a complex set of normal faults (Soós, 2017) between the left-lateral (Fodor et al., 1999; Fodor, unpubl.) Tóalmás-Tápió fault in the south and the similarly oriented Hrubanovo-Diósjenő fault in the north (*Fig. 21*). Mapping results show significant neotectonic activity along this complex fault system with sinistral kinematics along the Tóalmás-Tápió fault (see Section 6.4.), whereas sinistral shear is also supposed along the Hrubanovo-Diósjenő fault based on its orientation and obtained stress field data for the neotectonic phase (Bada, 1999; Bada et al., 1999, 2007, Fodor et al., 2005a, Ruszkiczay-Rüdiger et al., 2007). This model can explain the decreasing (and diminishing) neotectonic activity along the Tóalmás-Tápió fault east of the Zagyva trough, since deformation was more accommodated by the transfer zone (i.e., the Zagyva trough itself) and the Hrubanovo-Diósjenő fault in the north. The basic kinematic characteristics in the Zagyva trough seem to be largely stable during the Late Neogene that is compatible with determined late Middle Miocene stress field evolution characterized basically by ca. E–W oriented, minimum horizontal stress axis (σ_3) (Fodor et al., 1999, 2005a; Ruszkiczay-Rüdiger et al., 2007; Fodor, unpubl.).

6.7. General kinematics

Summarizing all observations on neotectonic fault kinematics a fairly consistent pattern is seen in the whole country: sinistral and dextral shear occurs along (E)NE–(W)SW (e.g., the Balaton-Tóalmás-, Balatonfő-, Kapos-, Bácsszentgyörgy-Tompa, Derecske fault zones), and (W)NW–(E)SE oriented (e.g., Szulok-Sellye-Cún or southeast Danube basin) fault zones, respectively, while ca. N–S oriented structures usually exhibit normal faulting/pull apart nature and were often acted as transfer zones (e.g. Zagyva trough) between the various strike-slip shear zones (*Fig. 21*).

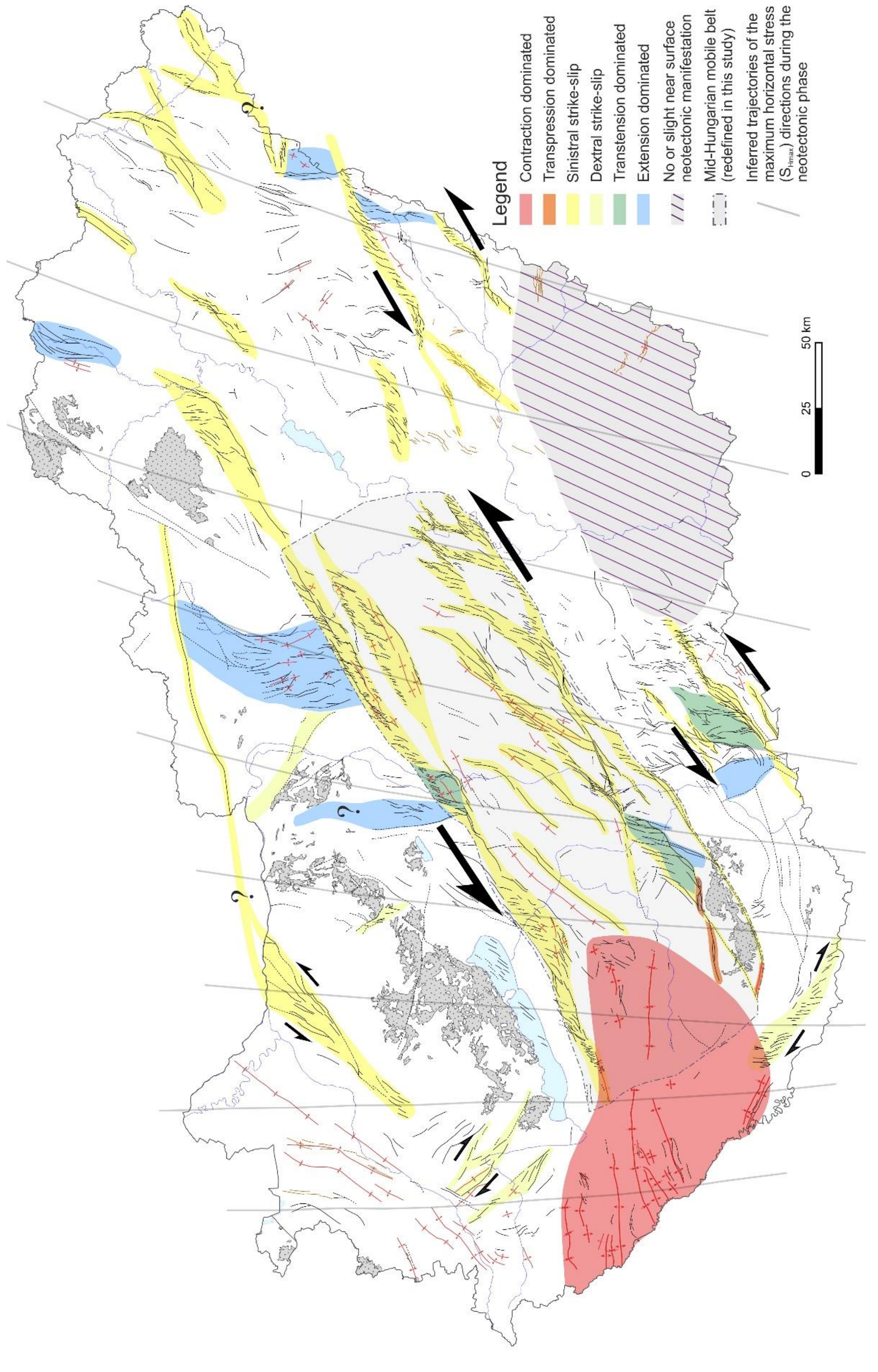


Fig. 21. Kinematic interpretation of the mapped tectonic deformations. For the legend of the mapped structures see Fig. 9.

The map scale pattern of the individual fault branches, as well as the overall alignment and geometry of the various fault zones and morphological elements within the redefined Mid-Hungarian mobile belt, the Danube-Tisza interfluve and Eastern Hungary (Section 6.4.) are all compatible with the sinistral shear sense deduced from the detailed fault patterns mapped within the individual shear zones. This is in agreement with the results of earlier studies (e.g., Pogácsás et al., 1989; Detzky Lőrincz et al., 2002; Horváth et al., 2006a, 2009; Fodor et al., 2005a-b; Bada et al., 2006, 2007; Ruszkiczay-Rüdiger et al., 2007). Considering also the E–W trending neotectonic compression-related folds in the west (i.e., the Zala domain; see Section 6.2.) and similarly oriented transpression/compression-related reverse faults/imbricated structures in the south (i.e., at the northern and southern margins of the Mecsek Mts.; see e.g., Wein, 1961; Hámor, 1966; Wéber, 1977; Némedi Varga, 1983; Tari, 1992; Csontos et al., 2002; Wórum and Hámori, unpubl.; Konrád and Sebe, 2010; Kovács et al., 2018) a N–S oriented and eastward slightly rotating maximum horizontal stress axis (σ_1) can be envisaged on a basin scale during the neotectonic phase (*Fig. 21*). The mapped deformation pattern clearly shows a dominant strike-slip stress regime associated with an E–W to ESE–WNW oriented horizontal minimum stress axis (σ_3) except for the westernmost part of the country, where a compressional stress regime associated with E–W oriented folding prevailed. This regional (paleo)stress pattern, inferred from the mapped fault pattern directly related to the stress field during neotectonic fault genesis, explains well the observed neotectonic features and, in basic tendencies, shows similarities with the recent stress field orientation (Bada 1999, Bada et al., 1999, 2007). One of the main differences is that a significantly smaller rotation of the maximum horizontal stress axis was inferred towards the northeast compared to the recent stress pattern, which (being parallel to it) cannot explain adequately the sinistral fault reactivations, for example along the Derecske fault zone. The deduced general stress field orientation fits basically well to the reported neotectonic stress field orientations varying between (N)NW–(S)SE and (N)NE–

(S)SW determined either for the entire Pannonian basin (Bada, 1999; Fodor et al., 1999; Gerner et al., 1999), or at local scale within the basin (Bergerat and Csontos, 1988; Pogácsás et al., 1989; Tari, 1992; Csontos and Bergerat, 1993; Detzky Lőrincz, 1997; Tomljenović and Csontos, 2001; Detzky Lőrincz et al., 2002; Fodor et al., 2002, 2008; Márton et al., 2002; Csontos et al., 2002, 2005; Konrád and Sebe, 2010; Skorday, unpubl.; Bodor, unpubl.; Várkonyi, unpubl.; Várkonyi et al., 2013; Visnovitz et al., 2015; Petrik, unpubl.; Kovács et al., 2018; Beke et al, 2019; Budai, 2019; Héja, unpubl.).

There are only few efforts published in the past estimating the magnitude of displacement occurred along the various neotectonic strike-slip fault zones in the country. Early estimations using 2D seismic data provided a sinistral offset of approximately 5–10 kilometers along various segments (Kiskőrös, Szolnok) of the Kapos fault zone for the Late Miocene–Quaternary interval (Pogácsás et al., 1989; Detzky Lőrincz, 1997). Along the Derecske fault zone a total sinistral offset of 4.5–6 km was estimated based on a sequence stratigraphic approach (Lemberkovics et al., 2005), whereas a typical offset range of several hundreds of meters was inferred for the individual fault segments. Horizontal displacement along the Balatonfő fault (below Lake Balaton) amounts several hundreds of meters based on the analysis of ultra-high resolution water seismic data (Visnovitz et al., 2015). Using former results deriving from 3D seismic data (Várkonyi et al., 2013) the left-lateral horizontal offset in the Late Miocene–Pliocene strata was estimated about 1.0–1.5 km along the 3–4 km wide Balaton fault zone in the Buzsák area (Visnovitz et al., 2015).

The drawback of these estimations that they are usually based on correlation of various linear elements identified within the Late Miocene–Pliocene sequence thought to be interconnected originally on the opposite sides of a fault zone. On one hand this method is highly uncertain in our opinion, and on the other it does not take into account that significant displacement needs to occur along a deep-seated PDZ until the first shear deformations (i.e., Riedel shears) appear near the surface (i.e., Hatem et al., 2017). Following the strike-slip faulting stage classification used by Hatem et al. (2017) and Crider and Peacock (2004) majority of the strike-slip deformation developed in Hungary reached Stages I and II only (development of en-echelon faults, and their subsequent interaction and propagation). The best, textbook examples of these stages of deformation are represented by the Derecske, Sellye and Balaton fault systems. Stage III deformation (slip along a through-going fault) in our view occurred only along the Tóalmás fault near the municipality of Gyömrő, along the Kapos-east fault North of Kalocsa and perhaps along the Bácsszentgyörgy-Tompa fault near Tompa, based purely on analysis of the nearsurface neotectonic fault pattern.

An effort was made to estimate possible displacement along typical neotectonic faults in Hungary using the modelling results and scaling factors of Hatem et al. (2017). Using wet kaolin claybox models calibrated and scaled to the strength and lenght of the crust (10 mm in the claybox is equivalent to 500–1200 m of continental crust) these authors investigated the relationship between the amount of displacement along PDZ-s buried at various depths and the style as well as the evolution of near surface faulting above the PDZ. It was determined how much cumulative slip along the buried PDZ was required in order to develop the characteristic fault patterns of the well-distinguished deformation stages (0-III) at the surface. Considering a typical PDZ depth of 1.5–3km in the Pannonian basin (corresponding to the ULS model of Hatem et al. 2017) a 1000–2500m and 1200–3000m of displacement is required along the PDZ in the basement to develop a Stage II Riedel system seen along the eastern Derecske fault and a Stage III deformation seen along the Tóalmás fault, respectively (20 and 25 mm of displacement in Fig. 5a of Hatem et al., 2017). It needs to be emphasized, that these estimations are referring to displacement along the PDZ in the basement and not along fault planes developed in the Late Miocene–Pliocene sequence, indicating that displacement estimation methods using Late Miocene–Pliocene features significantly overestimate the real displacement.

In summary, we think that neotectonic displacement magnitudes along the major fault zones are probably less than previously anticipated and are in the order of maximum 2–3 kilometers along their PDZ-s, even along the most prominent neotectonic shear zones during the neotectonic phase. Comparing to recent active strike-slip zones in the world the neotectonic deformation phase in Hungary can be considered as a rather weak tectonic event caused primarily by the continuous northward indentation of the Adriatic microplate (“Adria-push”; Bada et al., 2007) affecting a completely landlocked basin.

7. Conclusions

1. The new map of young geological deformations in Hungary presented in this paper provides a detailed and significantly more accurate definition (actual position, extension and geometry) of young deformations compared to previous studies. Based on nearly 2900 2D seismic profiles and 70 3D seismic volumes, as well as the results of former regional neotectonic syntheses and many local studies, the new map includes all important deformation structures (faults and folds, both tectonic and atectonic) related to the neotectonic evolutionary phase of the Pannonian basin, except for large-wavelength, drape-over folds formed due to the differential compaction of the young sedimentary pile. Beside near surface structures the new map also displays the pre-Pannonian root zones of the neotectonic faults, aiding the better understanding of the geometric and genetic relationships between the shallow and deep-seated structures.

2. The new map allowed the identification of several neotectonic domains with markedly different deformation patterns. In all domains the neotectonic fault pattern clearly reflects the control of identically oriented pre-Pannonian (mostly synrift) fault systems during the neotectonic phase. Markedly different orientations of neotectonic structures indicate important differences in the overall orientation of the underlying tectonic fabric. These observations

clearly demonstrate that neotectonic activity is predominantly due to the reactivation of pre-existing structures all over the Pannonian basin, as also indicated by previous studies.

3. Despite experiencing the largest Middle- to Late Miocene extension and the formation of the deepest depocenters in the whole Pannonian basin, SE Hungary practically lacks any observable neotectonic activity, which is a striking, but still poorly understood feature. Unfavorable fault orientations or the combination of thick sedimentary cover and insufficient displacements along the major PDZs are speculated behind this phenomena.

4. Fault segment geometries in neotectonic fault zones indicates a consistent regional displacement pattern: sinistral shear along (E)NE–(W)SW oriented, and dextral shear along (W)NW–(E)SE oriented fault zones, respectively. These observations — together with the E–W trending contractional/transpressional structures (folds, reverse faults, imbricates) occurring locally in western and southern Hungary — indicate a dominantly strike-slip stress regime with a laterally slightly rotating (from N–S to NNE–SSW) maximum horizontal stress axis (σ_1) during the neotectonic phase.

5. Regarding its magnitude, the neotectonic phase within Pannonian Basin can be considered as a weak tectonic event compared to active tectonic movements related to plate boundaries. Maximum 2–3km of lateral displacement is envisaged along the PDZ-s of major neotectonic faults zones in the basin, which is less than that estimated by other authors based mainly on the correlation of geological features on the opposite sides of the deformation zones.

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Data Availability

The ditital map constructed during this study can be found at http://dx.doi.org/10.17632/dnjt9cmj87.1 hosted at Mendeley Data (Status: Draft, Version 1) and www.geomega.hu (Wórum et al., 2020).

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