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Strike-slip reactivation of a Paleogene to Miocene fold and thrust belt along the central part of the Mid-Hungarian Shear Zone

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Abstract: Recently shot 3D seismic data allowed for a detailed interpretation, aimed at the tectonic evolution of the central part of the Mid-Hungarian Shear Zone (MHZ). The MHZ acted as a NW vergent fold and thrust belt in the Late Oligocene. The intensity of shortening increased westwards, causing clockwise rotation of the western regions, relatively to the mildly deformed eastern areas. Blind thrusting and related folding in the MHZ continued in the Early Miocene. Thrusting and gentle folding in the MHZ partly continued in the earliest Pannonian, and was followed by sinistral movements in the whole MHZ, with maximal displacement along the Tóalmás zone. Late Pannonian inversion activated thrusts and generated transpressional movements along the Tóalmás zone.

Key words: tectonics, fold and thrust belt, strike-slip faulting, Mid-Hungarian Shear Zone.

Introduction

The WSW-ENE striking Mid-Hungarian Shear Zone (MHZ) separates the ALCAPA and Tisza-Dacia mega-units (Csontos & Vörös 2004). Its importance has been known for decades, but the deformation history of this zone, lying between the enigmatic Mid-Hungarian Line (MHL) to the south and the well resolved Balaton–Tóalmás lines to the north, is still debated.

Reviewing and extending tectonic studies based on 2D industrial seismic data (Csontos & Nagymarosy 1998), the current study aims at the tectonic interpretation of three recently shot overlapping 3D seismic cubes of MOL PLC. (1500 km^2) in the central part of the MHZ, southeast of Budapest (Fig. 1). The Paleogene and Neogene tectonic evolution is addressed, but this study does not focus on the Mesozoic evolution or on neotectonic events.

Geological setting

The idea that the MHL could be a mega-unit boundary was suggested already decades ago (Géczy 1973). Based on paleogeographic evidence, Kázmér & Kovács (1985) suggested 450–500 km dextral strike-slip during the Eocene–Oligocene that accompanied the extrusion of the Transdanubian Range from the Alpine units. Following an initial model by Mészáros (1984) and paleomagnetic data of Márton (1985), Balla (1984) and Balla et al. (1987) introduced the basic and generally accepted concept: the Early-Middle Miocene counterclockwise rotation of ALCAPA, in contrast to the clockwise rotation of the Tisza-Dacia unit (for a summary see Csontos & Vörös 2004), accompanied by shearing of the Dinaric units between the two major blocks. Dextral extrusion was accompanied by east-oriented extension of both mega-units into the Carpathian embayment (Balla 1984; Tari 1994; Sperner et al. 2002) and is largely responsible for the bulk offset between the two blocks.

Extrusion and rotations started already in the Eocene (Fodor et al. 1992), but the bulk of the deformation took place in the Oligocene–Early Miocene (Kázmér & Kovács 1985; Csontos et al. 1992; Fodor et al. 1992, 1998). The lack of crustal thickening and formation of mountains in this deformed zone can be attributed to orogen-parallel extension, perhaps facilitated by increased heat flux caused by large amounts of Miocene syn-tectonic volcanics (Csontos & Nagymarosy 1998; Kovács et al. 2007).

Between the ALCAPA Mega-unit (Csontos & Vörös 2004; Schmid et al. 2008), consisting of the Eastern Alps, Western Carpathians and Transdanubian Range, and the Tisza Mega-unit, made up of the Mecsek, Villány-Bihar and Codru units, an elongated zone with Dinaric-type rocks is found. In the following, the MHZ is defined as the tectonic zone with Dinaric basement between the ALCAPA and Tisza mega-units, bounded by the MHL to the south and the Balaton–Tóalmás lines to the north.

The MHL is regarded as the boundary fault between the Tisza and the MHZ. The approximate location of the line has been known from borehole data (summarized by Fülöp & Dank 1987; Dank & Fülöp 1990; Haas et al. 2010) and geophysical anomaly maps (e.g. Haáz & Komáromy 1966; Szabó & Sárhidai 1989), but only a few studies have tried to actually locate the boundary fault on seismic sections (Csontos & Nagymarosy 1998 around the current study area; Csontos et al. 2005 south of lake Balaton in the west). Technical difficulties arise from the optimalization of industrial seismic processing for the uppermost sedimentary infill, not for basement structures below, as well as from imaging problems under

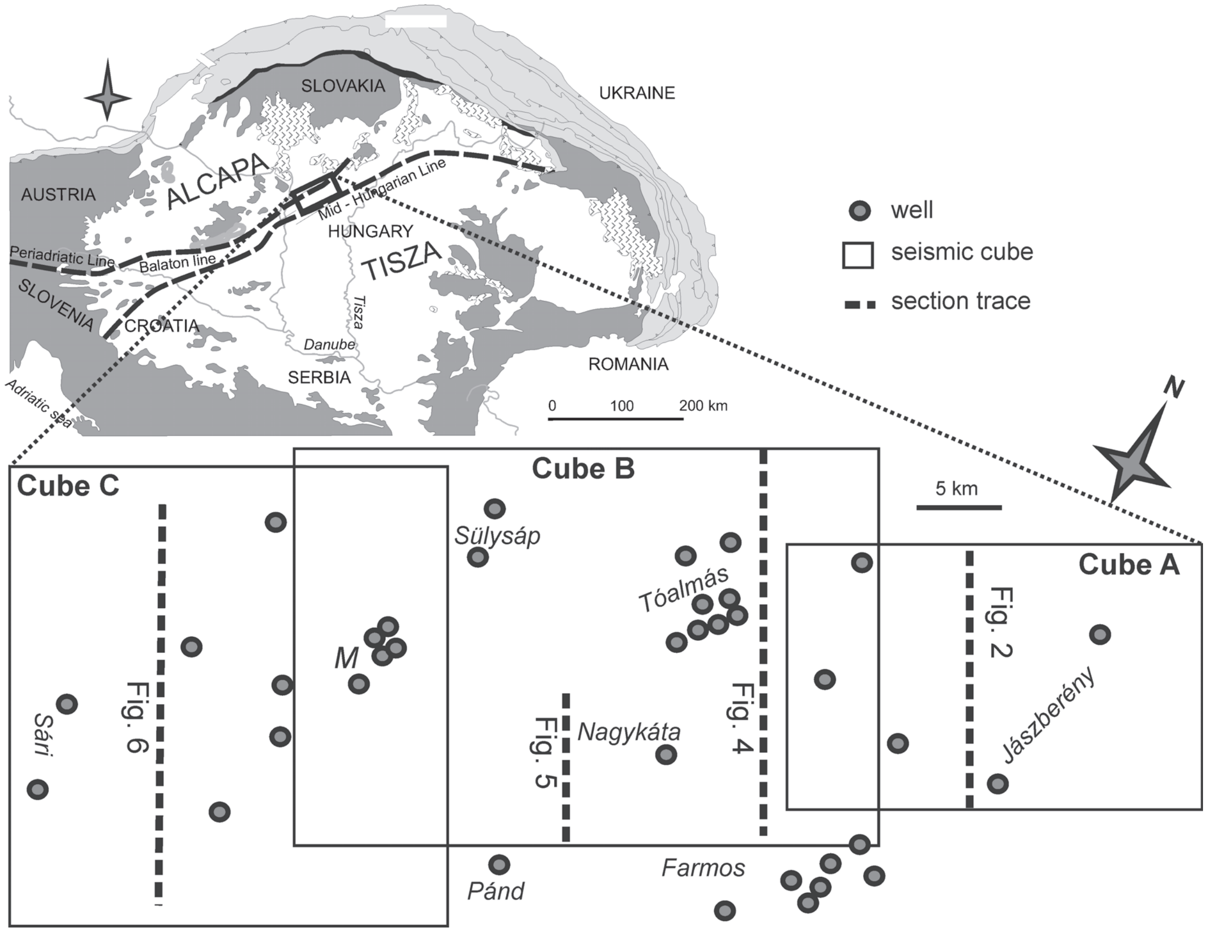

Fig. 1. Location map of the investigated area.

thick volcanic sequences. Due to the lack of exposures in the majority of the Pannonian Basin, the exact surface position and structural style of the MHL still raises questions. Only at the Poiana Botizii area, the assumed eastern termination of the MHL (Balla 1984; Csontos et al. 1992; Győrfi et al 1999; Tischler et al. 2007) can the contact be directly observed: here ALCAPA is thrust over Tisza-Dacia. The affiliation of the zone near its assumed western end, close to Zagreb, is also debated (Tari & Pamić 1998; Tomljenović & Csontos 2002).

The boundary of ALCAPA and the MHZ is much better delineated: a steep fault or fault zone called the Balaton line was recognized long ago. Considering paleomagnetic rotations (Márton & Fodor 1995, 2003), paleogeographic (Kázmér & Kovács 1985; Csontos & Vörös 2004) and geodynamic implications (Kovács et al. 2007; Schmid et al. 2008; Kovács & Szabó 2008; Ustaszewski et al. 2008), the Balaton line is the continuation of the Periadriatic Line, separating the Eastern and Southern Alps. Because the name comes from lake Balaton (Fig. 1), this is a valid name in the western part of the country. In a neotectonic study of the region (Fodor et al. 2005a), partly overlapping with the current study area, the eastern continuation of the Balaton line has been called the Tóalmás line (or zone). As we deny the direct continuity of the strike-slip system to the west (a separate study focusing on this issue is in preparation), this latter name will be used in the following.

Stratigraphy

This study focuses on the MHZ. To overview the evolution of the area, however, a short description of the general stratigraphic buildup in, and to both sides of the zone is given below.

The basement of the MHZ is greatly different from the one found north and south of it. On ALCAPA, Paleozoic to Mesozoic sequences with Alpine affinities are found (Vörös et al. 1990; Haas et al. 1995). Bükk-type and so Dinaric basement rocks characterize the MHZ between the Mid-Hungarian and Balaton-Tóalmás lines (Wein 1969; Balla 1984; Csontos et al. 1992) with a weak Cretaceous regional metamorphism (Árkai et al. 1995). As for crystalline rocks, only some Variscan granites and Paleogene tonalites are found along the Balaton line (Fülöp & Dank 1987). In contrast, on the Tisza-Dacia block, high-grade metamorphic rocks (Cserepes-Meszéna 1986) and late Variscan granites (Buda 1992) represent the basement of the non-metamorphosed, Mesozoic sedimentary formations in Germanic facies (Géczy 1973; Kovács 1982; Vörös 1993).

Upper Cretaceous rocks are almost absent in the MHZ. To the south on Tisza-Dacia, however, Upper Cretaceous deep marine red marls, conglomerates and other clastics occur in several major synforms (Szentgyörgyi 1989) in great thickness.

The Paleogene sequences also strongly differ on both sides of the MHL. The variable sequences north of the line, in the North Hungarian Paleogene Basin (Báldi & Báldi-Beke 1985; Fodor et al. 1992; Tari et al. 1993) comprise Upper Eocene clastics, limestones, and deep marine marls, followed by anoxic deposits and deep marine clays in the Oligocene. This sedimentation terminated with an erosional event ca. 25 Ma. Tuff horizons in the Paleogene deposits of the Mid-Hungarian Zone indicate continuous volcanic activity.

South of the MHL, Paleogene rocks are restricted to the Szolnok trough (Nagymarosy & Báldi-Beke 1993), where marine clastics are topped by Oligocene shales. No such deposits are found in the immediate surroundings of the MHL.

While north of the MHL a shallow marine Lower Miocene sandstone unit covers the Oligocene (Sztanó & Tari 1993), in the south, rocks of similar age are missing. Isochronous turbidites are only found in the Transylvanian prolongation of the Szolnok trough (Nagymarosy & Báldi-Beke 1993).

Despite significant thickness changes close to the MHL, Middle and Upper Miocene deposits cannot be differentiated any more on both sides. Ample Middle Miocene volcanics mark the vicinity of the MHL. After an episode of shallow marine limestone formation, the clastic infill of lake Pannon characterizes the Late Miocene and Pliocene sedimentation of the area.

Seismic stratigraphy and interpretation

The following 3D seismic horizons (supplemented by some 2D lines) were mapped using GeoProbe and SeisWorks (Fig. 2):

1. Base Pannonian: a regional unconformity at 11.6 Ma (Piller et al. 2007), characterized by high amplitude positive reflections. The Pannonian of the Central Paratethys includes Upper Miocene as well as Pliocene standard stages, although no well data have been examined to prove Pliocene ages in the area. In the following, we will use the terms 'Pannonian' for the units above, and 'Early to Middle' or 'pre-Pannonian' Miocene for the units below this unconformity.

2. Base Miocene: negative reflections, mainly above Oligocene clayey formations, often, but not always with an erosional contact. Lower and Middle Miocene units were not further differentiated.

3. Top Eocene: positive reflections above carbonates. As at some locations Oligocene formations are extremely thin, or even missing, Eocene rocks may directly underlie the Miocene.

A model of the area was built with the Move Software of Midland Valley Ltd. Because no significant difference between time and depth surface patterns was expected, no depth conversion has been undertaken.

Interpreted structures

Deformation patterns were mainly obtained from two-way travel (TWT) time maps of interpreted horizons (Figs. 3, 7 and 8). Please note that the maps are not northward oriented. Individual maps show the superposition of (1) the paleotopography at, and (2) the total deformation after the time of formation. In the following, structures are discussed from 'top to bottom', that is beginning from the youngest, and proceeding to older ones.

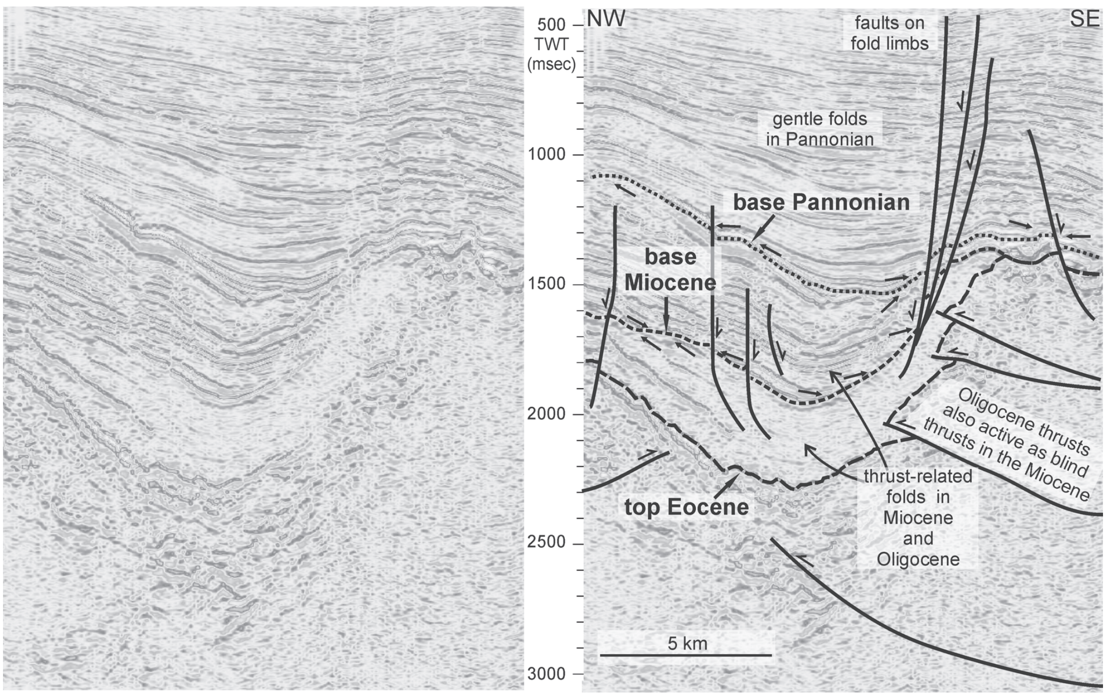

Fig. 2. Uninterpreted and interpreted seismic section with identified horizons and characteristic structures. Note small arrows for horizon terminations. Horizon styles apply for all seismic lines shown later. For location see Fig. 1. The foredeep of NW-vergent thrusts in the central part is a Pannonian structure, as Lower and Middle Miocene formations thicken only in the north-western part, indicating a shift of depocenters.

Pannonian

The Pannonian and post-Pannonian deformation pattern is dominated by (1) the Tóalmás zone and (2) NW vergent thrust propagation folds (Fig. 3).

The *Tóalmás zone* is a slightly bent, NE-SW trending strike-slip system, perhaps terminating just at the eastern margin of cube B. Here, at Tóalmás, an asymmetric strike-slip pop-up complex (Fig. 4) creates a pronounced ridge. Pannonian sedimentation starts on the north-western side of the ridge: the earliest Pannonian reflectors onlap against the elevated high, and are even normally offset. This indicates the transtensional activity of the zone in earliest Pannonian times. The Late Pannonian reflectors form a broad, asymmetrically SE-wards tilted antiform above the larger strike-slip zone, suggesting young, perhaps Pliocene or even Quaternary doming (see also Ruszkiczay-Rüdiger et al. 2007, 2009).

Two steep strike-slip fault segments form a right-stepping stepover north of Tóalmás (Fig. 3). A small east-vergent reverse fault between them offsets top Eocene and base Miocene horizons, and drags base Pannonian, thus creating a restraining stepover. The geometry of this structure clearly shows a sinistral character.

The above mentioned pop-up structure marks the eastern end of the continuous Tóalmás zone. When trying to map the fault zone on 2D seismic lines NE of 3D cube B, no clear evidence for further prolongation of similar structures was found. Even in 3D, fault splays around Tóalmás suggest the ending of the strike-slip zone. However, the Darnó Zone, a prominent strike slip and thrust zone with a Mesozoic-Paleo-

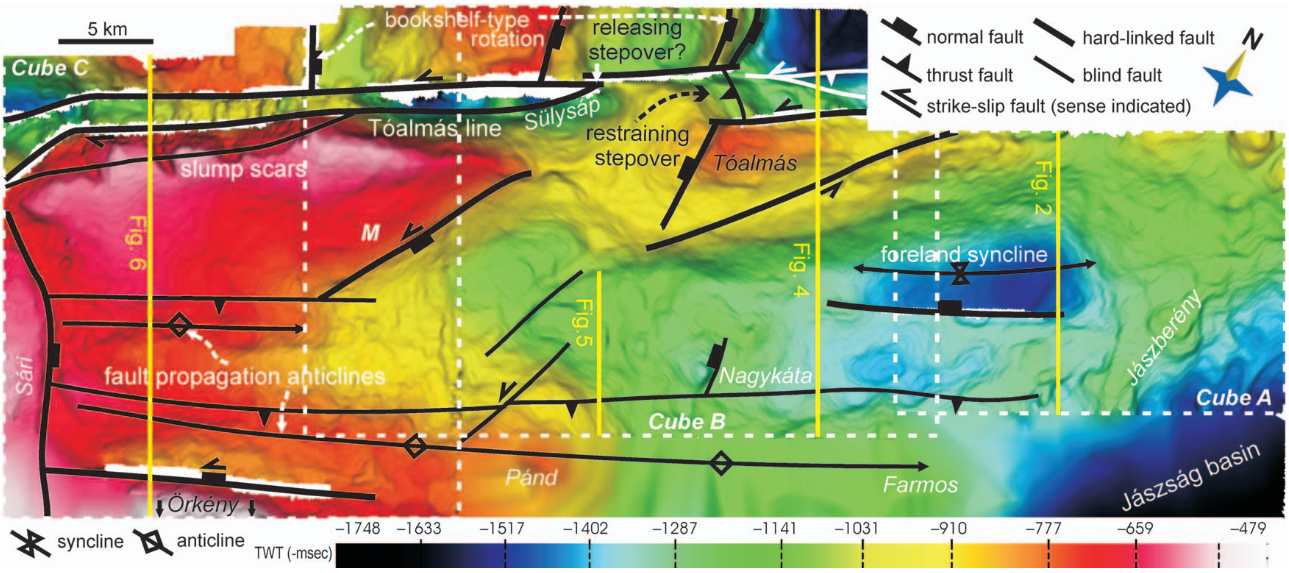

Fig. 3. Base Pannonian TWT time map. See text for details.

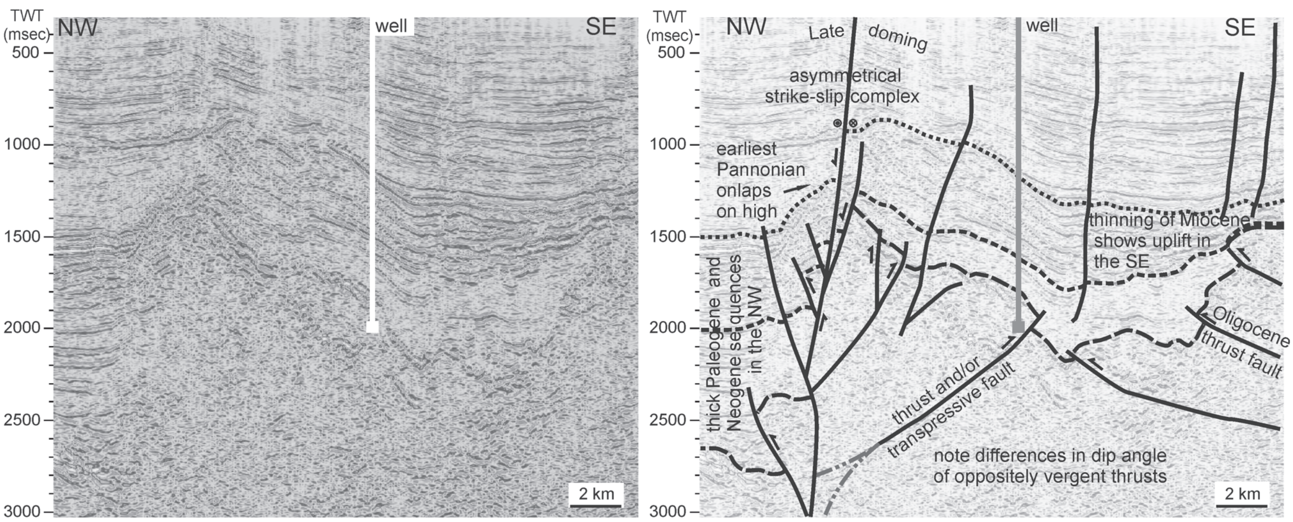

Fig. 4. Uninterpreted and interpreted seismic section in cube B. For horizon style see Fig. 2, for location Fig. 1. Note the asymmetrical character of the strike-slip zone, forming a wide dome in the Late Pannonian (probably even younger). Lower and Middle Miocene formations are thickest in the vicinity of this zone, indicating post-Early to Middle Miocene uplift.

gene core is found on the trend and in the apparent continuation of the Tóalmás zone (Fig. 9).

At Sülysáp the strike-slip fault splits into two parallel segments, creating a narrow trench in-between that runs westwards for ca. 25 km to the SW, with minor undulations in the base Pannonian surface. Near the western end of cube C, the southeastern fault segment turns SSW and then diminishes: it cannot be traced on 2D lines nearby.

A third, blind segment can be traced in cube C. Above this, on the southern flank of the Tóalmás zone, one large (in the immediate north-eastern vicinity of Fig. 6) and two smaller, almost perpendicular incisions can be observed at the base of Pannonian formations. We interpret these features as slump scars on the faulted margin above the blind fault segment.

A steep SE dipping fault at *M* with relatively large normal separation, and similar structures at the north-western boundary of the Pánd High, between Pánd and *M* as well as east of Tóalmás can be interpreted as Riedel shears to the main sinistral strike-slip zone. These faults detach/diminish in the Lower to Middle Miocene strata (Fig. 7B), and suggest that strike-slip movements in the Pannonian were not restricted to the Tóalmás zone s.str., but occurred in a broader zone within the MHZ. Strike-slip motions along the northwestern boundary fault of the Örkény High cannot be excluded either, due to its steep dip (Fig. 6).

South-westwards increasing intensity of compressional structures characterizes the MHZ. The N-S trending ridge at Jászberény (Fig. 3) might be caused by the activity of a W-vergent blind thrust below, although the Pannonian activity of this structure is unclear.

A larger footwall syncline with syntectonic Lower Pannonian sedimentary infill is found in cube A (Fig. 3). Here, and near the north-eastern margin of the Örkény High (Fig. 6), normal faults accommodate space problems on syncline limbs. The possible strike-slip component of the main normal fault might be related to the movements of the Tóalmás zone (see above).

The elevated ridge of the base Pannonian surface between Sári and Farmos is a thrust propagation anticline that gently plunges NE-wards with decreasing offset along faults. This means that the southwestern areas are much more elevated than those in the NE. A major step in the base Pannonian surface is seen at Pánd. Another, shorter thrust (and related anticline) to the NW of the mentioned one diminishes within cube C.

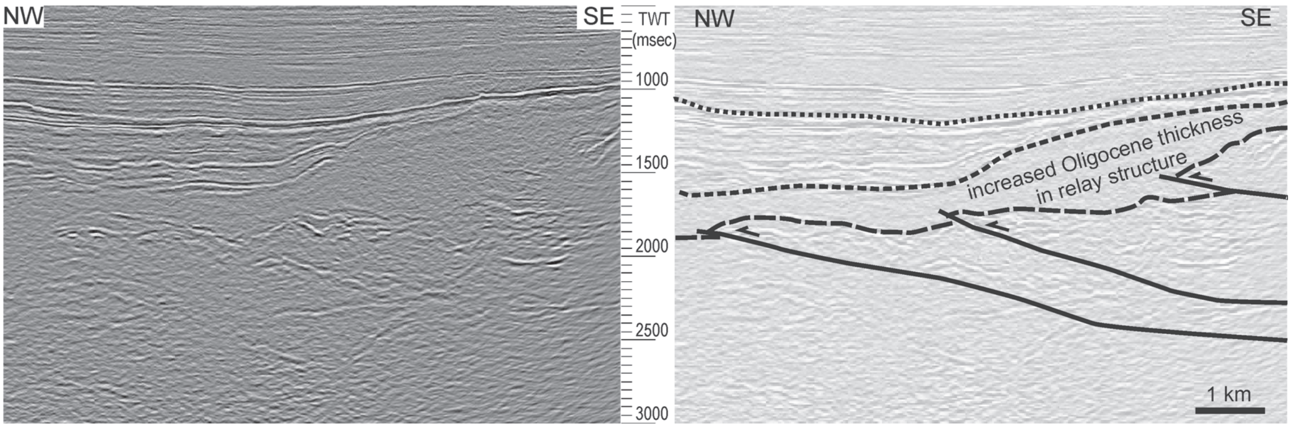

Fig. 5. Uninterpreted and interpreted seismic section in cube B. For horizon style see Fig. 2, for location Fig. 1. Note the increased Oligocene thickness in the SE, perhaps related to relay structures — see Fig. 8.

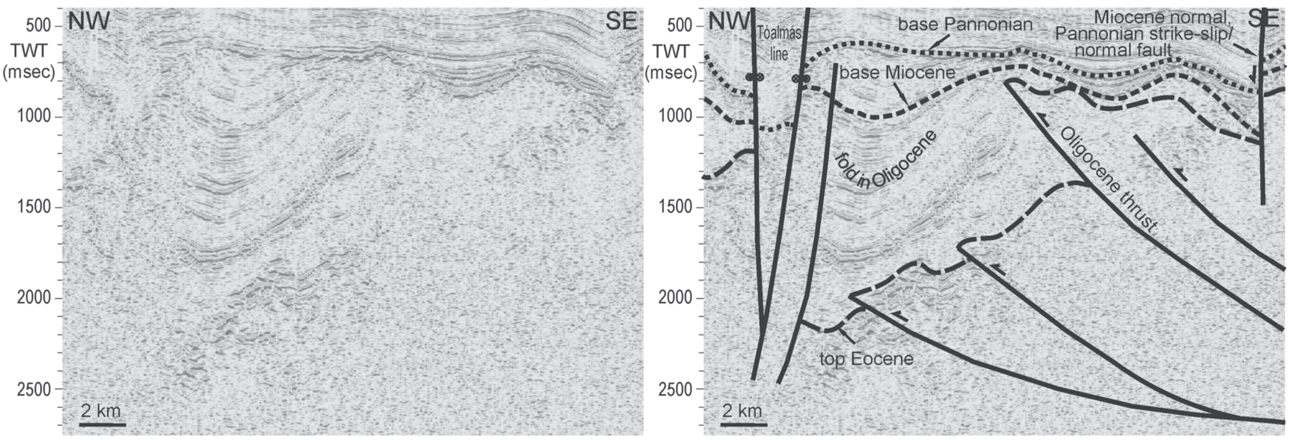

Fig. 6. Uninterpreted and interpreted seismic section in cube C. For horizon style see Fig. 2, for location Fig. 1.

At the south-eastern margin of cube C, a slightly bent, NNW-SSE oriented, rather diffusely imaged half-graben separates the Bugyi–Sári high in the SW from all the MHZ structures mentioned above.

NW of the Tóalmás zone (in cubes B & C) ENE dipping planar normal faults offset Lower Pannonian formations, creating a bookshelf structure (Tari 1992; Németh 1999; Fodor et al. 2005; Ruszkiczay-Rüdiger et al. 2007). These faults all terminate against the main strike-slip zone.

In the easternmost parts (Fig. 1), the margin of the Jászság Basin was mapped: Early Pannonian delta systems prograde into the SE-ward deepening basin.

Early and Middle Miocene

Lower and Middle Miocene formations were not distinguished during seismic mapping, thus any distinction between tectonic events of different pre-Pannonian Miocene age is hypothetical. The Early and Middle Miocene deformation pattern is illustrated on a TWT time map (Fig. 7A) as well as on a TWT thickness map (Fig. 7B). The Early and Middle Miocene deformation is — to some extent — similar to the Pannonian pattern, but also shows characteristic differences.

Pre-Pannonian Miocene structures are much more offset on either side of the Tóalmás zone to be sufficiently correlated, although thickness variations at the restraining stepover north of Tóalmás confirm that at least at some time within the Early to Middle Miocene, sinistral transpression prevailed in the zone.

NW of the Tóalmás zone NE dipping bookshelf-type faults, similar to the bulk of Pannonian deformation, characterize the deformation pattern; thickness variations indicate ongoing faulting throughout the Miocene.

In the MHZ, structures in the SW are more elevated than those in the NE: shortening seems to increase westwards. The transition zone between the relatively high and low regions, lies between Pánd and Sülysáp. The most prominent feature is a thrust propagation syncline with a thick Early/Middle Miocene syntectonic infill (Fig. 7B) in the foreland of the Sári–Farmos–Jászberény thrust and fault propagation anticlines. These anticlines, with their Early/Middle Miocene activity best seen on the thickness map (Fig. 7B), are composed of three segments. In the SW, two parallel anticlines are found that largely correlate with Pannonian-age structures, indicating ongoing, NW vergent shortening. The southern fault propagation anticline continues from Sári to the NE through Pánd to Farmos, where it turns NNE to form the WNW vergent Jászberény segment, and gradually diminishes nortwards. East of the Jászberény ridge no compressional structures are observed.

The location of the thickest pre-Pannonian Miocene formations (Fig. 7B) lies SE of the topographic depression in the base Miocene surface (Fig. 7A). This means that the Tóalmás ridge experienced great uplift in the Pannonian, inverting the depocentre of the pre-Pannonian Miocene basin. This asymmetrical uplift is shown on Fig. 4, whereas Fig. 7 demonstrates thickness variations and depression geometry in this zone.

In the footwall syncline in cube A (Fig. 3), normal faults accomodate space problems on fold limbs. A similar situation might exist in the southern part of cube C, where a narrow trench was formed in front of normal faults (Fig. 6) at the very margin of the 3D cube: the thrust behind can only be assumed.

All observed structures: thrusts, related folds and faults terminate against a NNW-SSE oriented, ENE dipping half-graben in the south-western part of cube C (Fig. 7), coincident with the Pannonian-age structure above it that bounds the Bugyi-Sári high to the SE. A closer look shows that the master fault is segmented into two parts with slightly different dip directions. The north-western segment is cut by the Tóalmás zone in the north. The architecture of the relay structure between the two segments is below mapping resolution. On the western side of this fault, no mappable Early to Middle Miocene-age features were found in the marginal zone of the 3D cube.

Paleogene

Paleogene deformation is shown on a top Eocene TWT time map (Fig. 8A) and a seismic thickness map for the Oligocene (Fig. 8B). To investigate Eocene tectonics, the mapping of the pre-Tertiary (typically Triassic carbonate) basement would be necessary. A preliminary study, however, showed no major difference in the topography of top Eocene and the top of the Mesozoic basement — the interpretation of the latter one is thus omitted here.

Again, the structural style of both sides of the Tóalmás zone greatly differs, indicating significant Neogene movements and inhibiting direct correlation of the two compartments.

In the MHZ a large number of flat, mainly NW vergent thrusts are found that clearly offset top Eocene, showing that they were active in the Oligocene. Towards the SW, thrust offset greatly increases on individual faults (compare Figs. 2, 4 and 5 with Fig. 6), also increasing uplift in these regions. In the NE two, in the SW three major thrust sheets were mapped, with a number of smaller transfer faults. Filling synsedimentary synclines, Oligocene formations reach their greatest thickness in the foreland of the south-westernmost thrusts.

Oligocene sequences are very thin, or (in the Jászberény-south area) even missing on the thrusted Sári–Pánd–Jászberény high, suggesting its Paleogene activity.

A step within the uplifted ridge of Oligocene formations is seen just north of the Pánd area. However, this is much sharper than the similar structure in the Miocene above it. This implies an increase in Oligocene thickness in the zone between the steps in base Miocene and top Eocene (Figs. 5 and 8B), perhaps caused by fault transfer geometries.

N and NW dipping normal faults also occur within the main thrust-related basin in cube A. These faults were hard to map, and seem to be cut by thrusts, thus pre-dating the compressional phase. An alternative solution would be that, because they are basically perpendicular to thrusts, they are related to them.

In the central and eastern parts, namely in cubes A & B, two larger antithetic (SW vergent) thrusts were mapped at, and east of Tóalmás. These might have initiated as a single thrust that was offset later, or, alternatively, a relay structure might connect them. The Tóalmás and Nagykáta Highs were interpreted as pop-ups.

Folding intensity generally increases SW-wards. Whereas in the NE only gentle synclines are characteristic (Figs. 4, 5),

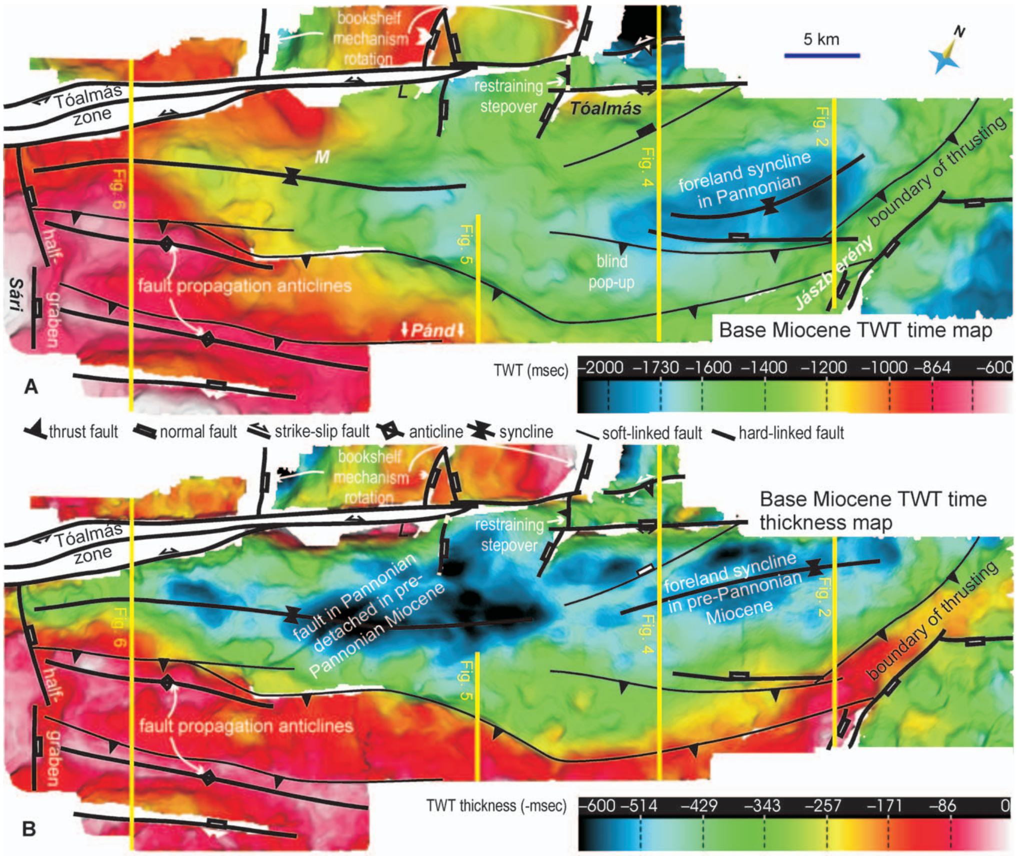

Fig. 7. Base Miocene TWT time map (**A**) and TWT time thickness map (**B**). Note pattern differences to conclude for pre-Pannonian Miocene (B) or Pannonian (A) age deformation. Structures present on both maps were active throughout both stages.

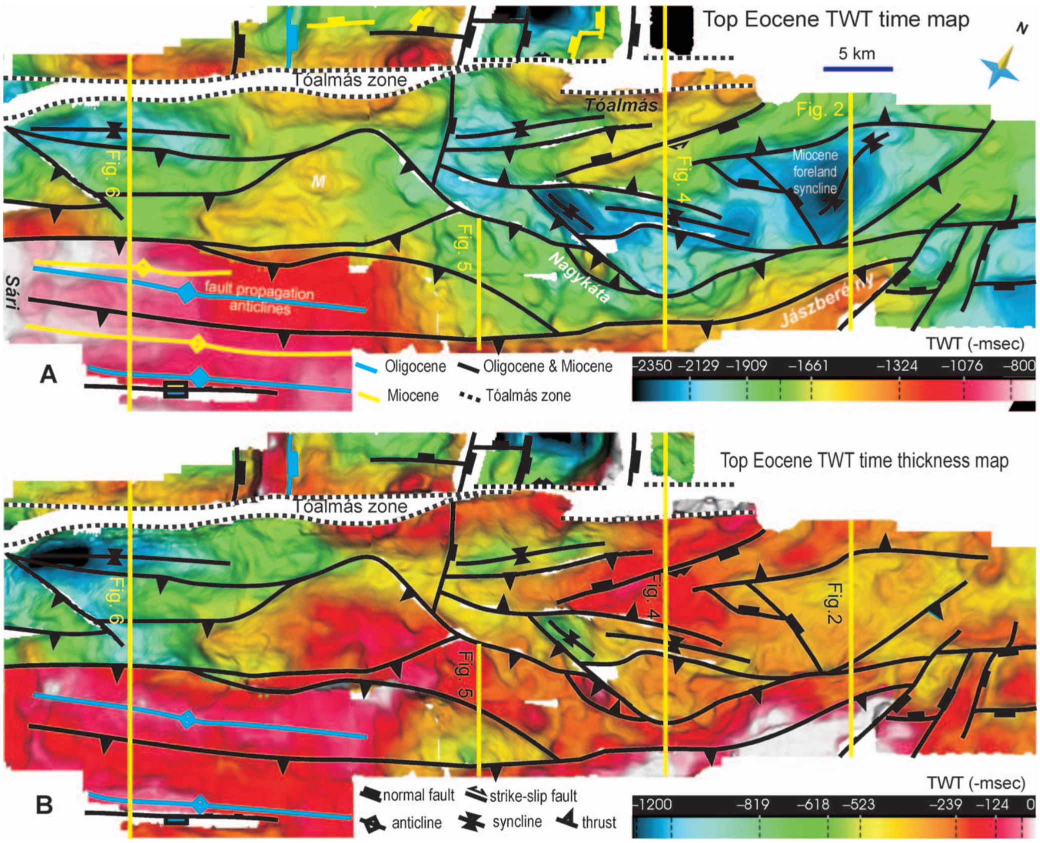

Fig. 8. Top Eocene TWT time map (**A**) and TWT time thickness map (**B**). Note pattern differences to conclude for Oligocene (B) or Early to Middle Miocene (A) age deformation. Structures present on both maps were active throughout both stages. Note that no correlation across the Tóalmás zone was possible.

fold amplitude and tightness is much higher in the SW, culminating in the north-western foreland of Sári (Fig. 6).

NW of the Balaton zone NW and NE dipping normal faults were assumed, but the vicinity of 3D cube margins inhibited a detailed observation of these structures.

Discussion

Structural evolution: evidence and novelties for kinematics and timing

The **Oligocene** of the MHZ is characterized by mainly NW vergent thrusts and related folds, generated in a stress field with NW-SE compression. The amount of shortening increases westwards, with a major intensity change in the Pánd area. The thrust system starts to build up in cube A, a feature first described here. The main strike of structures is NE-SW in the west, and turns gradually to N-S eastwards. This change in apparent strike might be due to many factors, but we suggest that it is mainly on the account of different amounts of thrusting. Since the folds and thrusts seem to fade away towards the east, it is proposed here that the original shortening direction was WNW–ESE (still preserved in the orientation of the easternmost structures), but due to rotations induced by increasing shortening towards the west it changed apparently to NW-SE there (Fig. 9).

Although the Paleogene shortening directions in the region suggested by Csontos & Nagymarosy (1998) are similar to our ideas, the interpretation of recently shot high quality 3D seismic surveys showed thrust vergencies opposite to the south-eastern ones proposed by those authors.

The large-scale model of Fodor et al. (1999) supposes NW-SE to WNW-ESE oriented compression, NW to WNW vergent thrusting and related folding in the MHZ of the current study area between the Middle Eocene and the late Early Oligocene. This is roughly in accordance with our results.

In the Buda Mts, Fodor et al. (1994) demonstrated WNW-ESE compression in the Late Paleogene and Early Miocene, with ESE vergent blind thrusting and E-W oriented dextral transpressional strike-slip zones at the range margins. The main shortening directions are identical to our supposed original (i.e. eastern) ones, therefore it is probable that no large scale structures separated the MHZ from the Buda Mts in these times. In other words the Tóalmás zone, as a strike-slip belt, was not yet active, an idea also supported by shortening directions in the western parts of the study area being perpendicular to the zone (Fig. 9). However, the different orientations of structures in the west suggest compartmentalization along the strike of the belt.

The zone north of the MHZ shows signs of NW-SE as well as NE/ENE-SW/WSW oriented tension. The assumed NW-SE oriented extensional regime does not correlate with known stress fields — but this is not fully constrained because it is at the margin of the study area.

The **pre-Pannonian Miocene** in the MHZ generally follows Paleogene patterns, with some important differences. Compression is apparently E-W/NNW-SSE oriented in the east, but NW-SE in the western parts; this could be explained by the rotation model, similarily to the Paleogene situation (see above). The model for the MHZ Early Miocene (Eggenburgian–Ottnangian) of Fodor et al. (1999) nicely fits these observations.

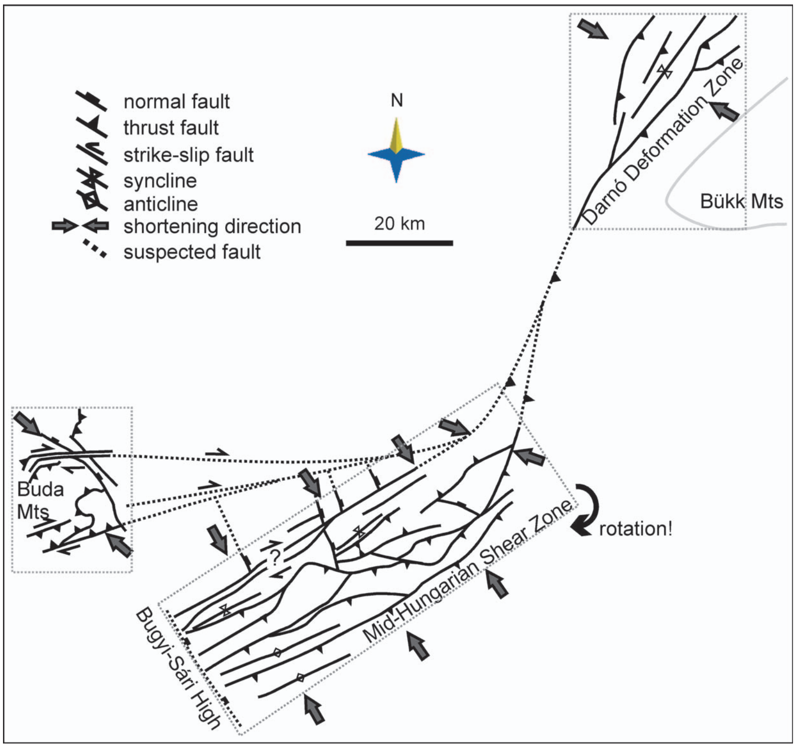

Fig. 9. Work hypothesis for the Late Paleogene of the region showing possible connections of tectonic units. Dashed boxes show source of maps: Buda Mts — Fodor et al. 1994; Darnó Zone — Fodor et al. 2005b; MHZ — this study. For details see text.

Syntectonic depocentres in thrust foredeeps, shown in detail for the first time in our work (Figs. 7–8B), indicate increased shortening in the central-western zones; the cube C region underwent the largest shortening. The lack of thick foreland deposits can be attributed to the (present day) vicinity of the Tóalmás zone. Normal faults on syncline limbs have a geometrical/gravity reason and possibly do not relate to any regional stress field.

ENE-WSW oriented tension of unclear Miocene age can be derived from the half-graben bounding the Bugyi-Sári high. Miocene structures terminate against this structure. Based on 2D data, Csontos & Nagymarosy (1998) mapped N-S striking post-Pannonian normal faults around the Bugyi High, but their position shows slight differences from the structure seen in the high resolution 3D seismics, and also has opposite dips (W in the previous, E in the current work). The bent character (in the Pannonian), and assumed relay structure between mapped segments (pre-Pannonian

Miocene) are also considered as novelties. The evaluation of the Bugyi-Sári high will be the subject of a separate paper.

Tensional directions at the eastern margin of the Jászberény ridge comply with late Middle Miocene (Sarmatian) data of Fodor et al. (1999) in the Jászság Basin. The obtained NE-SW oriented tension north of the MHZ complies with stress field directions in the Middle Miocene (Karpatian–Badenian) of the Zagyva half-graben in the northern continuation of the study area (Benkovics 1991). Bearing in mind that this zone is at the margin of our study area, with only small fault segments to map north of the Tóalmás zone, the existence of the late Middle Miocene (Sarmatian) E-W to NW-SE tension of the Zagyva half-graben (Benkovics 1991; Fodor et al. 1999) was not proven in the study area.

In the **Pannonian**, bulk shortening continued, but individual thrusts were hard to recognize: gentle folds suggest the uplift or subsidence of broader areas. The — in detail previously unpublished — syncline in cube A (Fig. 3) has a thick Lower Pannonian syntectonic infill proving its activity.

Anticlines in the western area also show Early Pannonian NW-SE compression, slightly different from the idea of Fodor et al. (1999), who suggested NNW-SSE oriented compressional directions for this period.

The sinistral character of the Tóalmás zone in the Early Pannonian (compatible with the ideas of Csontos & Nagymarosy (1998), Fodor et al. (1999) and Ruszkiczay-Rüdiger et al. (2007)) is constrained by the restraining step-over at Tóalmás (Fig. 2), first imaged in great detail here. Steep NNE-SSW striking faults as synthetic Riedel shears at *M*, Pánd and in between, as well as east of Tóalmás, also suggest widespread left-lateral movements. All these features corroborate the — previously not supposed — idea that sinistral displacement was not restricted to the Tóalmás zone, but distributed in a wider deformation belt, presumably including the whole MHZ. This event clearly post-dates folding mentioned above, but is still constrained to the Early Pannonian.

Although still a problem to be solved, the splayed character of the Tóalmás zone near Tóalmás (Fig. 2), proves that the eastern termination of the zone has to be close to the present study area. So far, no clear correlation with structures further to the E/NE, such as the Darnó Zone (Fodor et al. 2005b), has been found, but similarities in the Paleogene tectonic style and shortening directions of the Darnó Zone and the eastern parts of the mapped area suggest that these regions could have been connected to each other (Fig. 9), and were separated only later, most likely during the Miocene.

NE-SW oriented normal faulting north of the MHZ is compatible with structures in the Zagyva Graben (Benkovics 1991; Fodor et al. 1999), indicating the existence of a single northern unit. The same applies to the Buda Mts, where E-W to NW-SE oriented tension prevailed from the Middle Miocene until the Pliocene (Fodor et al. 1994), indicating a single unit with only minor internal rotations.

The last documented phase affects even Upper Pannonian deposits. Thrusts as well as segments of the Tóalmás zone were reactivated during this event. This is corroborated by doming of the Upper Pannonian at Tóalmás, as already observed by Fodor et al. (2005a) and Ruszkiczay-Rüdiger et al. (2007). As no detailed sedimentological mapping for the Pannonian has been undertaken, the absolute age of this phase remaines to be solved.

Almost no evidence is seen regarding the pre-Pannonian activity of the Balaton–**Tóalmás zone**. Stress field correlations (see above) suggest that the MHZ and ALCAPA were not separated by large-scale structures, so no great offset is expected. The Budaörs right lateral shear zone (Fodor et al. 1994) has a similar trend to the Tóalmás zone, suggesting that the latter one could also have acted as a dextral strike-slip fault zone during the Paleogene, or, more likely, in the Early Miocene (Fig. 9). Its Paleogene activity is debated, as — based upon thrust dips — Paleogene shortening directions in the western parts of the study area are basically perpendicular to the Tóalmás zone. We thus assume that the activity of the Tóalmás zone started in the Early Miocene. Along this zone only a (most likely late Middle Miocene) sinistral transpressional event could be documented. In the Early Pannonian, a possibly large, but still undetermined amount of sinistral movement was determined, as discussed already by Csontos & Nagymarosy (1988) and Ruszkiczay-Rüdiger et al. (2007). Associated structures suggest that after the cessation of NW-SE compressive folding, probably the whole MHZ acted as a sinistral strike-slip zone in the Early Pannonian, with maximal displacement along the Tóalmás zone.

Geodynamic implications

As an inter-plate deformation zone during the Paleogene and Early Miocene, the MHZ shows signs of significant shortening. Balla (1984) and Csontos et al. (1992) suggested that the ALCAPA and Tisza blocks underwent opposite rotations. The idea was based on paleomagnetic data (Márton 1985; Márton & Márton 1989; Márton & Fodor 2003). Bearing the sheared character of the MHZ in mind, the above mentioned changes in Paleogene and Early Miocene tectonic directions along the study area strike can easily be regarded as internally rotating blocks within the MHZ.

Because no mountain chain is found in the zone, and even the crust is strongly thinned (Kilényi & Šefara 1989), Csontos & Nagymarosy (1998) proposed significant orogen-parallel, that is NE-SW oriented stretching. Detailed mapping in this study, however, failed to detect such large scale extensional structures in the Paleogene and Early Miocene: only small normal faults, mainly perpendicular to thrusts, were found, suggesting that the loci of Late Paleogene–Early Miocene stretching were elsewhere (see also Tomljenovic & Csontos 1999; Csontos et al. 2005). In any case, this issue needs further investigations.

As the MHL runs south of the study area proper, the geometry and deformation along the MHL itself remains to be solved. The general NW vergent character of Paleogene and Miocene thrusting, however, suggests that — at least in this part of the orogen — the MHZ, intermittent between the Tisza and ALCAPA, likely overrode ALCAPA, in contrast to the idea of Csontos & Nagymarosy (1998) and Schmid et al. (2008). As an alternative, the described thrusts in the present work may form a larger backthrust zone to the main, SE verging thrust of the MHL.

The activity of the Tóalmás zone is likely to have started only after the Paleogene, but its correlation with the Balaton and Periadriatic lines is a question to be further analysed. It is possible that the belt currently defined as the Tóalmás strike-slip zone is a reactivation of a Paleogene tectonic zone, an idea also supported by the fact that basement rocks essentially differ on both sides of the zone, while facies diversity diminishes in the younger formations.

Conclusions

On the basis of detailed maps of horizons for top Eocene, base Miocene and base Pannonian, as well as on fault geometries from 3D seismics, the structural evolution of the studied segment of the MHZ can be described as follows.

1. The MHZ acted as a generally NW vergent fold and thrust belt at least in the Late Oligocene, beginning probably already in the late Early Oligocene.

2. The intensity of shortening generally increased westwards, with a major step at Pánd. It is likely that the gradual change in thrusting directions to the west was caused by differential rotation within the shear zone between the ALCAPA and Tisza blocks, with the original shortening directions preserved in the relatively mildly deformed eastern parts.

3. Transport directions in the Early Miocene were similar to those of the Oligocene, but instead of hard-linked faults, blind thrusts and related folds prevailed.

4. The Tóalmás zone (possibly as a reactivation of a Paleogene thrust belt) initiated most probably in the Early Miocene as a dextral strike-slip zone.

5. Top NE thrusting and gentle folding in the MHZ partly continued in the earliest Pannonian, and was followed by sinistral movements in the whole zone (with maximal displacement along the Tóalmás zone). The latest observed tectonic event was the Pliocene-Quaternary inversion of the Tóalmás zone.

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