Structural features in the Miocene sediments of the Pécs-Danitzpuszta sand pit (SW Hungary)

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A pécs-danitzpusztai homokbánya miocén üledékeinek szerkezeti elemei

Összefoglalás

A pécs-danitzpusztai homokbánya a Mecsek hegységperemi vetőzónája mentén fekszik, középső és felső miocén (badeni–pannóniai) üledékeket tár fel. Az erősen tektonizált rétegsor kora pannóniai és annál fiatalabb deformációk nyomait őrzi, amelyeket más feltárásban nem tanulmányozhatunk. Jelen cikkben több mint húsz év megfigyeléseit foglaljuk össze, a deformációs események korát puhatestű-rétegtan segítségével határoljuk be, és ezek alapján következtetünk a terület szerkezetalakulására. A 10,2–10,0 millió évvel ezelőtti időszak elején ÉÉNy–DDK-i irányú extenzió (transztenzió) hatására normálvetők, árokszerkezetek, negatív virágszerkezetek képződtek. Arra mutatnak, hogy a litoszféra-megnyúláshoz kapcsolódó vetőműködés még a késő miocénben is zajlott, bár kérdéses, hogy ez a deformációs esemény a Pannon-medence geodinamikai fejlődéstörténetében a szin- vagy a poszt-rift fázishoz tartozik-e. Nem sokkal később, még mindig a 10,2–10,0 millió évvel ezelőtti időszak első felében a terület É–D-i vagy ÉÉNy–DDK-i összenyomás alá került. E feszültségmező hatására feltolódások alakultak ki a pannóniai mészmárgában és homokban, és a teljes középső – felső miocén üledéksor meggyűrődött, a réteglapok mentén csúszás és a ridegebb kőzetek blokkos elforgása történt. Az éppen leülepedő homok rétegei dél felé vastagodtak, dőlésük folyamatosan változott. A homokon belül szögdiszkordancia alakult ki, képződésében a Pannon-tó vízszintjének változása is közrejátszhatott. A kompressziós eseményt Afrika és Európa közeledésével magyarázhatjuk, de regionálisan nem tudjuk korrelálni, idősebb a medenceinverzióhoz köthető eddig publikált szerkezeti eseményeknél.

Kulcsszavak: Pannon-medence, Mecsek, tektonika, poszt-rift, medenceinverzió

Abstract

The Pécs-Danitzpuszta sand pit in southern Hungary exposes middle and upper Miocene (Badenian to Pannonian/Langhian to Tortonian) sediments along the mountain front fault zone of the Mecsek Mts and preserves an essential record of tectonic events during and after the early late Miocene, which are not exposed elsewhere in the region. In this paper we present structural observations recorded over 20 years of work, date the deformation events with mollusk biostratigraphy and make inferences on the structural evolution of the area. At the beginning of the time interval between 10.2–10.0 Ma, NNW–SSE (to NW–SE) extension created normal faults and negative flower structures. These show that extension-related fault activity lasted here up to the late Miocene. Shortly thereafter, still in the early part of the time interval between 10.2–10.0 Ma, N–S to NNW–SSE compression ensued and dominated the area ever since. Deformations under this stress field included reverse faulting in the Pannonian marls and sands, folding of the whole succession, with bedding-plane slip and shearing-related block rotation in the already deposited middle and upper Miocene marl layers and continuously changing bedding dips and southward thickening layers in the Pannonian sands. Lake level changes of Lake Pannon must have played a role in the formation of an angular unconformity within the sands besides compression. The compressional event can be explained by the Africa (Adria) – Europe convergence, but cannot be correlated regionally; it pre-dates basin inversion-related events reported from the region so far.

Keywords: Pannonian Basin, Mecsek Mts, tectonics, post-rift, basin inversion

Introduction

The Pécs-Danitzpuszta sand pit in southern Hungary exposes sediments from the early history of the late Miocene – Pliocene brackish-water Lake Pannon, a descendant of the Central Paratethys. It is located along the SE margin of the Mecsek Mountains and is the most important and best-known outcrop of the lower part of Pannonian (upper Miocene) deposits in the region, both calcareous marls and limonitic sands. It has long been known for the deformations visible in the sands (Vadász 1960), and is a type locality of Lake Pannon sediments in the Mecsek area (Kleb 1973). Because of its large extent, its location along the mountain-front fault zone, and because the exposed rock units represent an age interval hardly accessible elsewhere, it preserves an essential record of tectonic events during and after the early late Miocene.

Although multiple papers mentioned structural features from the sand pit in the past decades (Benkovics 1997, Csontos et al. 2002, Konrád & Sebe 2010), they contain a limited amount of observations, and the dating of events carries uncertainties as well. Since then, we have collected numerous structural measurements and observations across the large sand pit. In order to expose structural features in the Pannonian calcareous marls, a 50 m long trench was excavated in 2018 in the northern part of the sand pit. This created a marvelous exposure, revealing the downward continuation of the sedimentary succession and deformations in the mountain-front fault zone, which cannot be observed with other methods. Moreover, with the advance of mollusk biostratigraphy, it became possible to link numerical ages to Lake Pannon deposits (Magyar 2021), and this can be used for a relatively accurate dating of tectonic events as well. This dating is much needed in the fine-tuning of our knowledge about the structural evolution of the Pannonian Basin (Fodor 2019), especially in the eventful Neogene (Csontos et al. 1991; Fodor et al. 1999, 2005; Bada et al. 2007). Here we present structural observations collected in the sand pit in the past >20 years and the structural evolution of the area that can be deduced from the observations, with the highest temporal resolution achieved so far.

Geological setting

The Pécs-Danitzpuszta sand pit lies on the southern boundary fault zone of the Mecsek Mts, the Mecsekalja Fault Zone (*Figure 1*). It exposes two main lithological units of late Miocene (Pannonian/Tortonian) age: light grey, white or yellowish grey calcareous marls and silts (Endrőd Formation) in the northern wall, and the overlying yellowish brown, coarse limonitic sands (Kálla Member of the Békés Fm.) in the rest of the area (*Figure 2*). The trench starting from the northern wall of the sand pit exposed Sarmatian and Badenian (Langhian and Serravallian) mixed carbonate and clastic deposits stratigraphically below the Pannonian sediments. The whole succession is strongly tilted, thus younging is dominantly to-
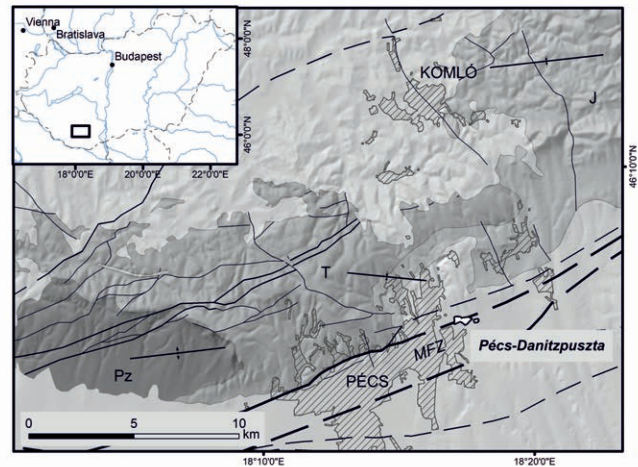

Figure 1. Tectonic setting of the Pécs-Danitzpuszta sand pit. Base map: Konrád et al. (2010)
Legend: Pz: Paleozoic; T: Triassic; J: Jurassic rocks; MFZ: Mecsekalja Fault Zone
1. ábra. A pécs-danitzpusztai homokbánya szerkezeti helyzete. Alaptérkép: Konrád et al. (2010)
Jelmagyarázat: Pz: paleozoos, T: triász, J: jura kőzetek. MFZ: Mecsekalja-öv

wards the south and not upwards. In the western wall, the limonitic sands are divided by an angular unconformity, observed previously in more eastern outcrops, e.g., by Vadász (1960) or Kleb (1973). For a detailed description of the sand pit, see Sebe et al. (2021).

Two deformation events were identified in the sand pit: syn-sedimentary transtension during the deposition of the lowermost part of the sands and syn- to post-sedimentary N–S compression (Konrád & Sebe 2010, Csontos et al. 2002). The tilting of the succession and the different dips were explained with compression-related folding above a blind, south-vergent thrust fault during the late Pannonian (Benkovics 1997, Csontos et al. 2002).

Methods

Structural measurements were carried out in various parts of the sand pit. Kinematic indicators like slickenlines were measured in the marls. They were absent in the limonitic sands; thus, in these cases the stress orientations are inferred with some uncertainty from Mohr pairs (Anderson 1951, Fodor 2010). Because of the low dip angle and the diffuse bedding planes, bedding dip measurements have uncertainties especially in case of the sand layers above the unconformity and in the uppermost, gently dipping beds below it. Stereoplots are lower hemisphere Schmidt projections.

Deformation events were dated by biostratigraphy, mostly by mollusks, based on the endemic species of Lake Pannon (Magyar & Geary 2012; Sebe & Magyar submitted). This provides a resolution on the order of magnitude of ~1 Ma. For this, systematic collection of mollusks was carried out in the Pannonian calcareous marls. In the limonitic sands, most mollusks came from the industrial sieving of the sands, they were found in the coarse fraction remaining after sieving. Thus their exact stratigraphic position was usually
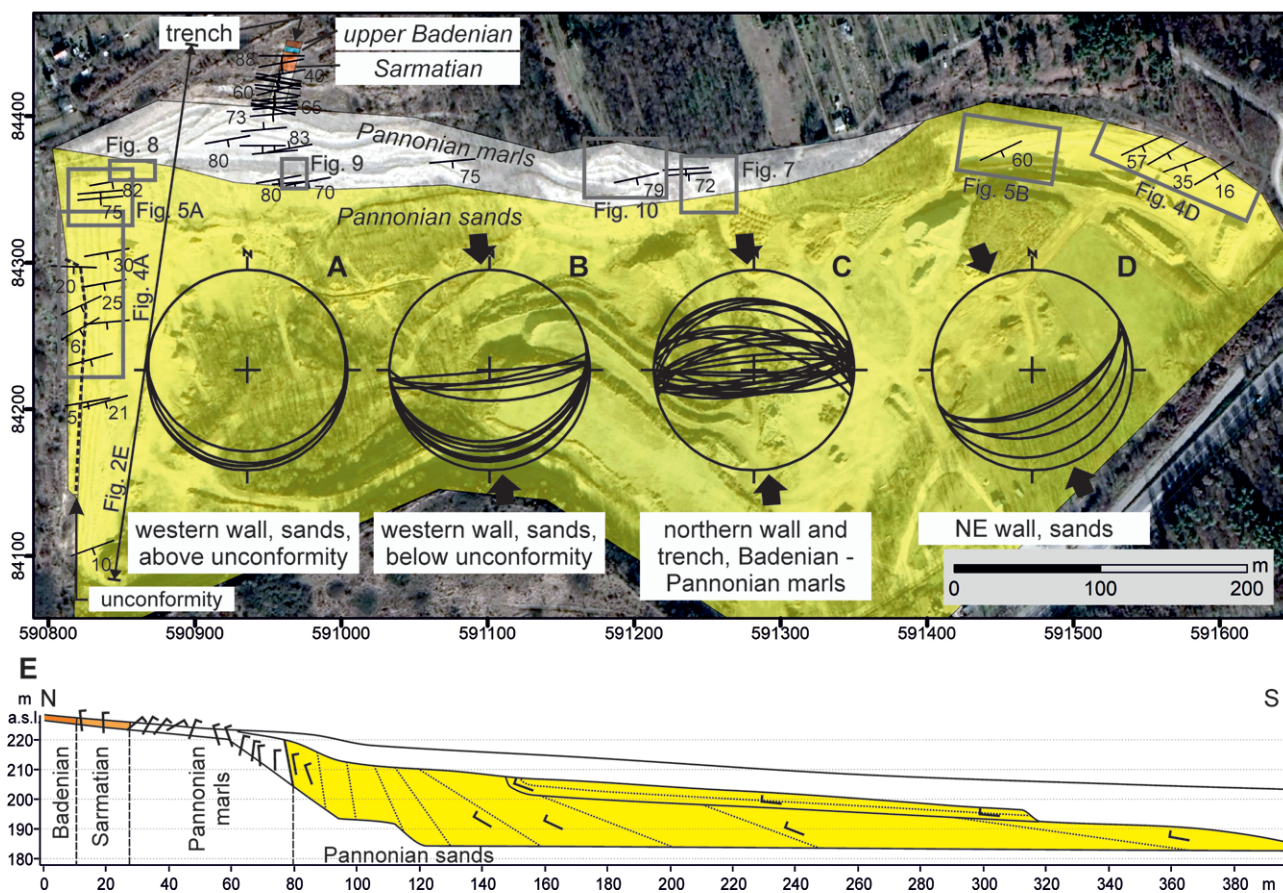
Figure 2. Stratigraphic units and bedding dips in the sand pit. All northerly dips belong to overturned beds. Marks in the cross-section indicate true dip angles

2. ábra. A bányában észlelt rétegtani egységek és rétegdőlések. Az északias dőlések átbuktatott rétegek dőlései. A szelvény jelei a valódi dőlésszögeket mutatják

unknown, it could only be confined to a relatively large portion of the wall being extracted at the given time. We therefore executed collecting campaigns targeted for tectonically interesting parts of the sand pit, e.g., above the unconformity or at the very base of the sands.

Results

Bedding dips

The older, northern part of the succession – the Sarmatian deposits and most of the upper Miocene calcareous marls – is dominantly overturned, with varying dip angles (*Figure 2E*). Bedding dip then decreases within the upper part of the Pannonian marls, i.e., it approaches the vertical in the southern end of the trench (*Figure 3*). The marl/sand boundary within the Pannonian succession is vertical or subvertical, though both its dip angle and dip direction vary along strike. Bedding dip returns to normal in the Pannonian sands and decreases continuously towards the south, i.e., upsection, to ~15°, observable both in the western and northeastern wall of the sand pit. This succession with the continuously changing dip angles is truncated by a sharp angular unconformity, visible in the western wall, and is overlain by nearly horizontal sand layers of the same lithology

(*Figure 3*, *Figure 4A*). Dip directions scatter around SSE for layers with normal dip and N–NNW for overturned beds (*Figure 2*).

Figure 3. Northward-dipping, overturned Pannonian calcareous marls in the trench (foreground), and south-dipping sands in the western wall of the sand pit (background). Photo taken along the trench, looking southwest. Western wall pictured in the top of the photo (cf., map of *Figure 2*)

3. ábra. Észak felé dőlő, átbuktatott pannóniai mészmárgaösszlet a kutatóárokban (előtérben) és délre dőlő homokrétegek a bánya nyugati falában (háttérben). A kép az árok mentén készült, DNy felé nézve. A bánya nyugati fala a kép felső részén látható (a feltárások elhelyezkedését l. a 2. ábrán)
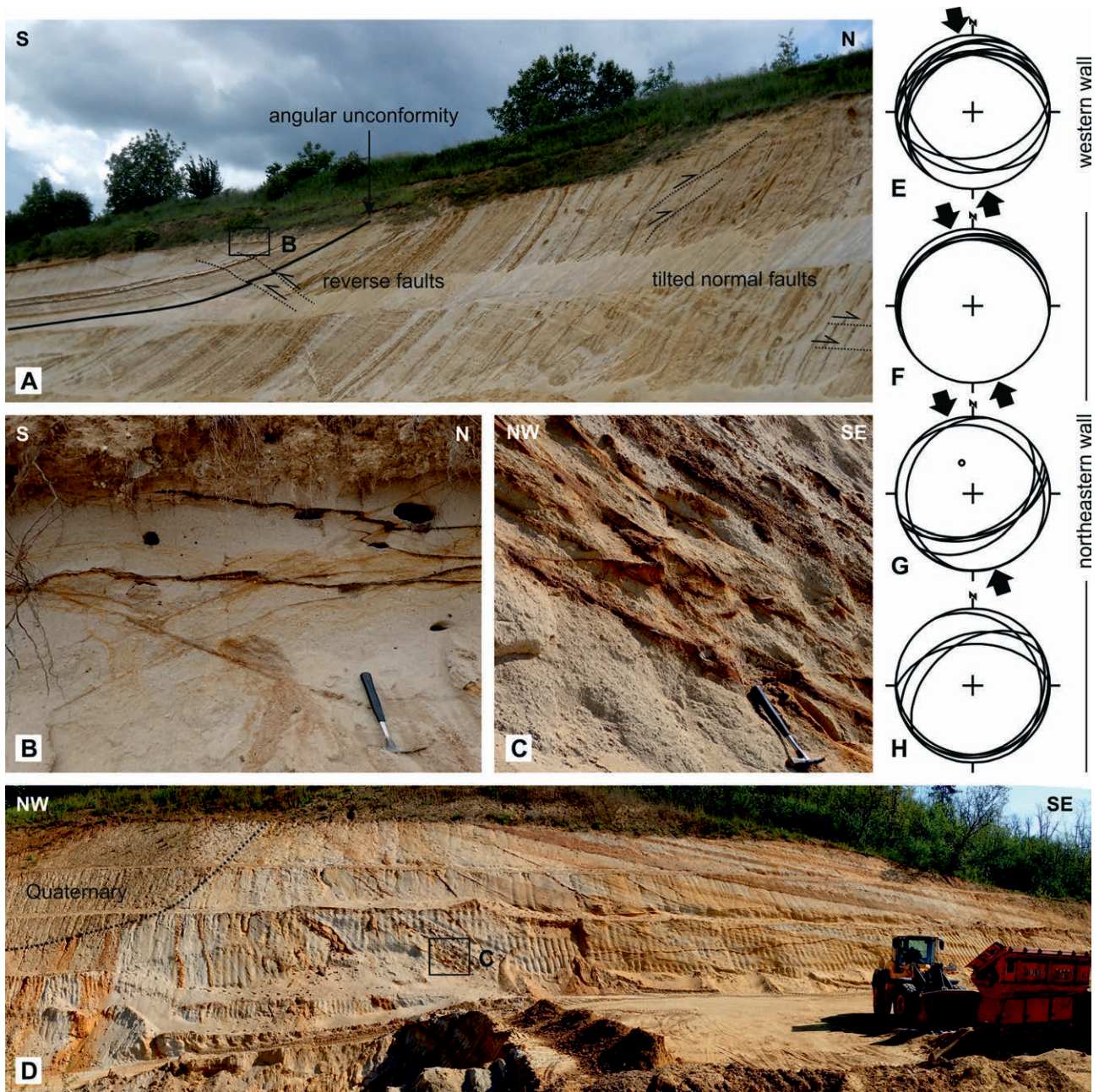
Figure 4. Structural features in the sands. A) Changing dip angle and angular unconformity in the western wall in 2016; B) reverse faults in the western wall displacing dark limonitic bands (2021); C) tilted reverse faults in the NE wall highlighted by the displaced limonite banding (2020); D) changing dip angle in the NE wall (2020); E–H) stereoplots of reverse faults: western wall (E), post-tilt faults of NE wall (F), syn-tilt faults of the NE wall in Fig. C, with pole of local bedding dip (G), the latter backtilted with bedding (H)

4. ábra. Szerkezeti elemek a pannóniai homokösszletben. A) Változó rétegdőlés és szögdiszkordancia a nyugati falban 2016-ban; B) vastag limonitsávokat elvető feltolódások a nyugati falban (2021); C) limonitosodás miatt kipreparálódott kibillent feltolódások az ÉK-i falban (2020); D) változó dőlésszögű rétegek az ÉK-i falban (2020); E–H) a feltolódások sztereogramjai: nyugati fal (E), az ÉK-i fal billenés utáni vetői (F), a C kép billenés alatti vetői az ÉK-i falban, a helyi rétegdőlés pólusponttal jelölve (G), valamint ez utóbbiak a rétegdőléssel visszabillentve (H)

The trench has revealed that the uppermost 1–2 m of the steeply dipping layers are dragged downslope by surface processes. In some cases this includes a change in dip direction: e.g., in the Sarmatian and Badenian beds, the dip of the same bed is southerly near the bottom of the trench, while northerly (overturned) in the dragged upper part of the layers (see *Figure 5.* in Sebe et al., 2021). This resolves the problem that KONRÁD & SEBE (2010) called attention to, namely that significantly different bedding dips were observed within a dis-

tance of just a few metres (20–30° northerly and 70° southerly dip within 10 m). The trench revealed that there is no fault between the differently dipping layers; it is surface drag (slope creep) that caused the difference in the dips. This also means that dip angles recorded in small surface outcrops should be handled with caution, even in seemingly in situ, well-layered sediments. Because of the near-surface deformation, bedding dips in the trench were measured at the deepest possible location along a given bed.
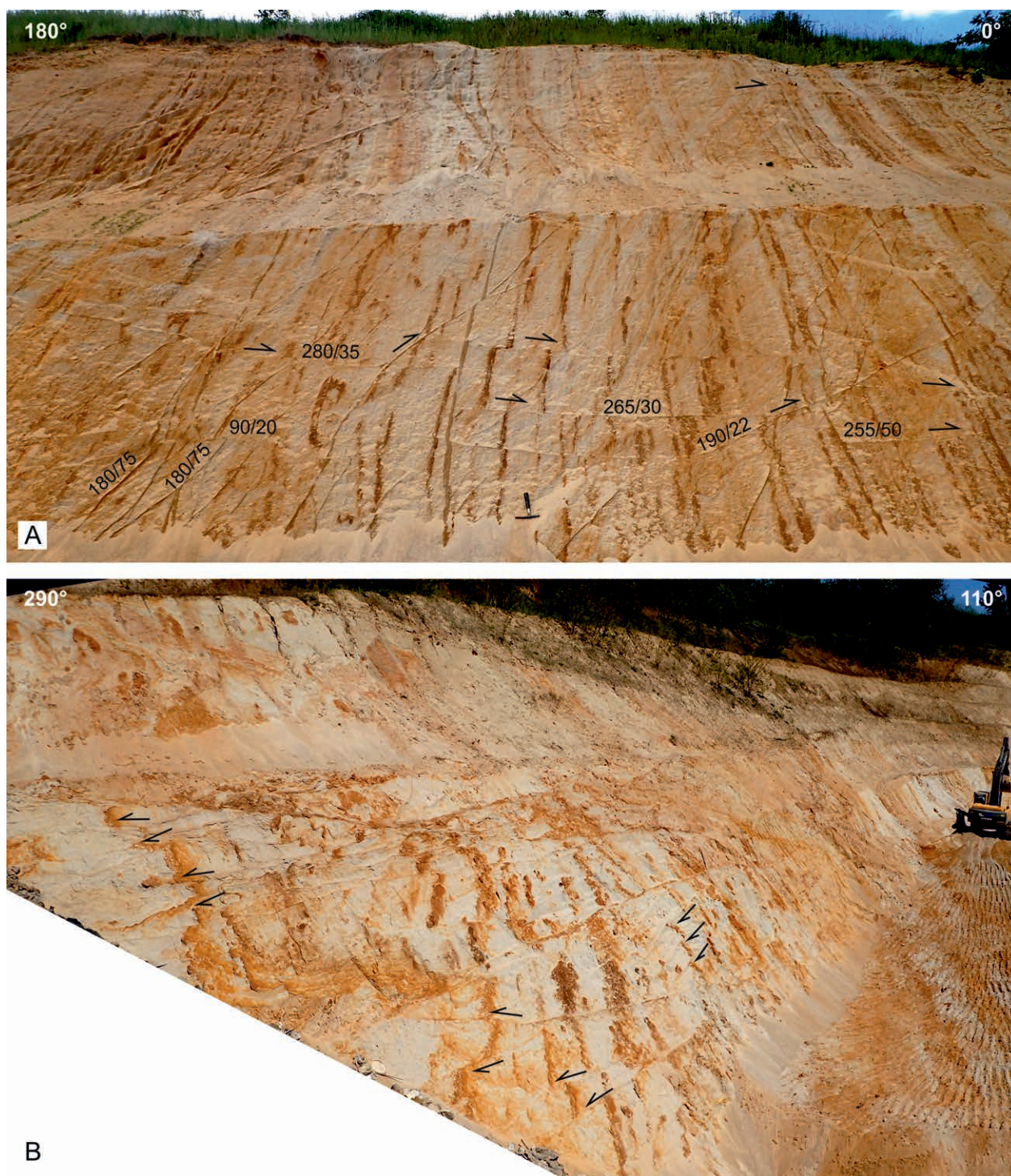
Figure 5. Syn-sedimentary normal fault arrays in sands. A) Northern end of the western wall, 2016. Bedding dips are all 80–70° to the south (*Figure 2B*), the beds in the right side of the image appear overturned only because of the wide viewing angle. Stereoplots in *Figure 6A. B*) Eastern end of the northern wall, 2020. Note that the photo was taken oblique to the wall, approximately in strike direction of the layers. Stereoplots in *Figure 6E*

5. ábra. Üledékképződéssel egyidejű normálvető-rajok a homokban. A) A Ny-i fal északi vége 2016-ban. A rétegdőlés végig délies, 70–80° körüli, a kép jobb oldalán a rétegek csak a széles látószög miatt tűnnek átbuktatottnak. A vetők sztereogramja a 6A ábrán látható. B) Az északi fal K-i vége 2020-ban. A fénykép nem a falra merőlegesen, hanem ferde szögben, a rétegek csapásirányában készült. Sztereogram a 6E ábrán

Normal faults

Arrays of originally normal faults, both antithetic and synthetic, were recorded in the uppermost few metres of the calcareous marls (in the transitional interval towards the sands, composed of marls and calcareous silts) and in the lowermost 15-20 m of the sands. An example just above the marl/sand boundary was shown by KONRÁD & SEBE (2010) (*Figure 6C*). The deeper parts of the succession have not been exposed in large surfaces, so faults, even if existent,
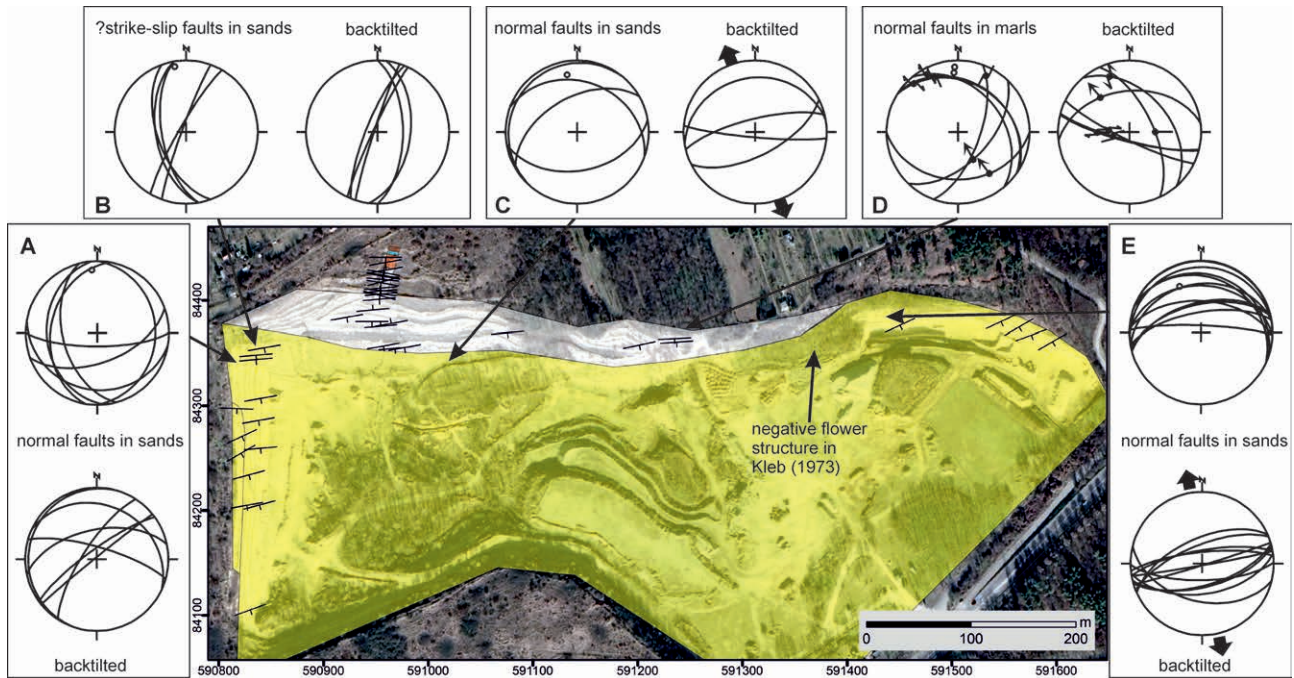
Figure 6. Spatial orientation of normal and strike-slip faults
6. ábra. A normálvetők és eltolódások térbeli helyzete

could go unnoticed. The fault arrays occur in subvertical layers and thus appear mostly as reverse faults today, but their geometries and their orientation relative to bedding suggest that they formed as faults with normal component before the tilting of the succession. Therefore, their present dip data were backtilted with the local bedding dips to investigate their original orientation.

Faults in the sands are distributed at a few tens of cm from each other and have displacements of a few tens of cm (*Figure 5*). Strictly speaking, all types of faults in the sands are deformation bands; however, for the sake of simplicity, we refer to them as faults. As bed boundaries in the sand are uneven and rather diffuse, it is hard to say if beds systematically thicken along one side of a certain fault. Nevertheless, the faults, which have relatively low dip angles today, die out and are sealed upwards, suggesting syn-sedimentary movement. The sense of movement was mostly normal in these cases, but also some reverse slips occur.

If backtilted with the local bedding dip, the faults have ENE–WSW or NE–SW strikes and their dips reach relatively steep angles, close to vertical (*Figure 6A, C, E*). In the NE wall, the faults now appear as north-dipping reverse faults, but their dip angles show too large scatter (*Figure 5B, Figure 6E*). If backtilted with the local bedding, their orientations give a symmetrical pattern typical of fault arrays with normal component (*Figure 6E*). The backtilted pattern is similar for the centre of the northern wall (*Figure 6C*). Slickenlines are not preserved in the coarse sands, but the relatively steep dip angles and occasionally opposite (inverse instead of normal) movement directions of some faults refer to oblique – normal plus strike-slip – movement of the fault arrays. So do flower structures like the one shown by KLEB

(1973, figure 19). In the western wall, gently west- and east-dipping faults show dominantly strike-slip displacement today (*Figure 5A*); if backtilted, most of them become normal faults as well, with strikes similar to the previous two locations (*Figure 6A*). Differently oriented further faults in this wall may point to multiple deformation events. Less steep south-dipping faults might have formed as reverse faults as well during the tilting (folding) of the succession.

In the uppermost part of the marls, faults with originally normal component appear at varying distances from each other (*Figure 7*). At present, single faults could also be interpreted as reverse faults, but their convergence and merging downsection (towards older layers) (*Figure 7B*) indicates that they belong to normal fault sets. They often crosscut only a few layers (*Figure 7A*), sometimes they form antithetic pairs. Although in cross-section they appear as normal faults, slickenlines indicate oblique, dominantly strike-slip displacement (*Figure 6D*).

Faults with normal component are restricted to a relatively small interval of the sedimentary succession, and this evokes the conclusion that they formed during the same deformation event, in the same stress field. The features pointing to normal displacement indicate that they were created before the tilting of the succession. Besides being syn-sedimentary, relatively short normal faults – crosscutting only a limited number of layers – can also form along fold hinges due to local stretching (fold-accommodation faults), in a buried position. It cannot be excluded that normal faults around the marl/sand boundary were created this way during the folding of the succession. The asymmetry of some fault groups in backtilted position (e.g., in the marls, *Figure 6D* and *Figure 7B*) may refer to compression-related (syn-tilt)
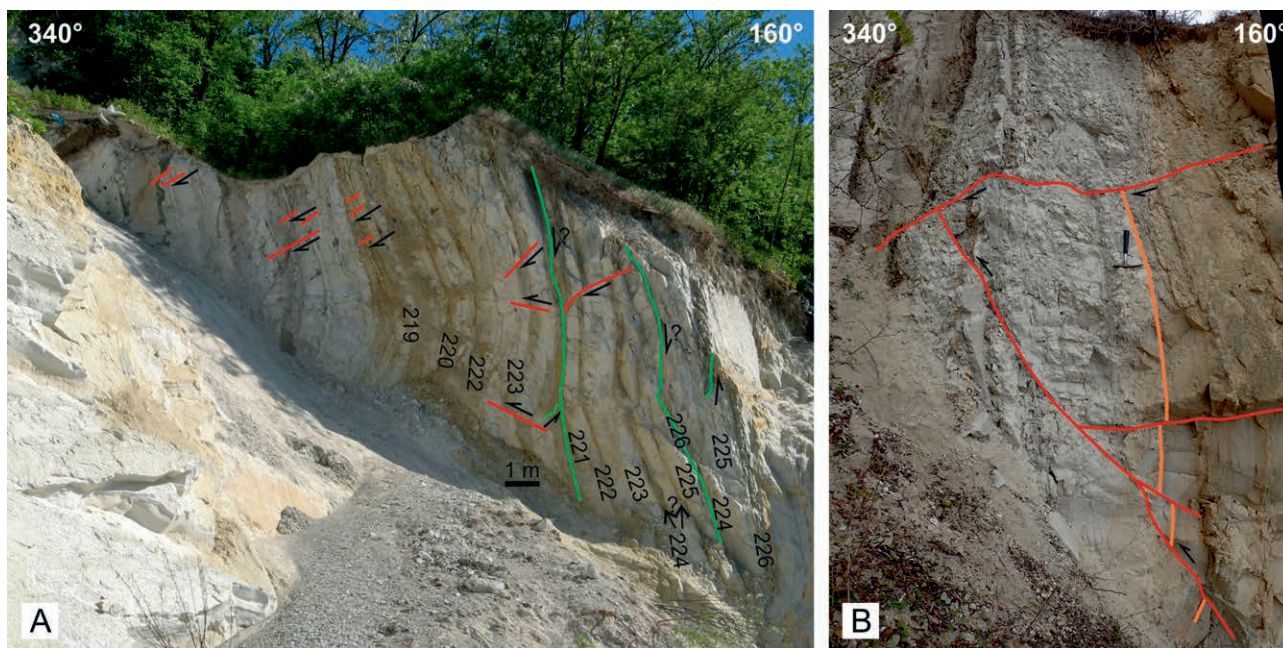
Figure 7. Tilted normal faults (light red) and post-sedimentary thrusts between repeated layer packages (green, partly along bedding planes) in marls and silts. A) Central part of northern wall, 2015. B) Detail of a parallel outcrop ~ 40 m to the west, 2020; hammer for scale. The sense of thrusts (whether originally north- or south-vergent) could not be identified

7. ábra. Kibillent normálvetők (pirossal jelölve) és ismétlődő rétegcsoportok közti későbbi feltolódások (zöld, részben réteglapok mentén) a pannóniai mészmárgasorozat felső részében. A) Feltárás az északi fal középső részén 2015-ben. B) Az előzőtől nyugatra kb. 40 m-re húzódó párhuzamos feltárás részlete, 2020. Nem volt megállapítható, hogy a feltolódások eredetileg észak vagy dél felé mozogtak

formation. No obvious bed thickening could be observed in the succession along faults, which could be decisive in this case. However, the appearance of normal faults in a concave curvature, like the one above the 1 m sign in *Figure 7A*, point to syn-sedimentary movement.

Despite the narrow stratigraphic range of the normal faults, their original, backtilted orientations show quite large scatter even in this relatively small area (*Figure 6*). This does not necessarily mean that they were created during separate deformation events. An explanation for this may be the different competence of the marls and the sands. Another factor that complicates the picture is that the sand pit lies on the front of a basement block projecting south from the main body of the mountains, between the Pécsbánya embayment in the west and the mountain foreland in the east (*Figure 1*). This geometry caused different folding (tilting) directions in the Neogene sediments around the basement block, the strike orientations of tilted beds show an arcuate pattern (*Figure 2*). Although the backtilting of earlier faults with the local bedding dips should eliminate the effect of different folding directions, the irregular mountain front geometry still could have caused locally varying orientations of earlier fault groups as well. This setting warns us not to differentiate too many deformation events based on small differences in fault orientations.

Strike-slip? faults

In the western corner of the northern wall, steep, subparallel faults with westerly dips were observed (*Figure 8,*

Figure 6B). Their apparent displacements attain a maximum of a few tens of cm. Some of them have normal, some others reverse sense; this may refer to strike-slip movement for the whole fault array. It is uncertain which fault group and deformation event they belong to. They are located very close to the tilted normal faults of the western wall, but they have different orientations (*Figure 6*). In case these two fault groups are coeval, the strike-slip faults could have acted as tear faults between normal ones. They could have formed posterior to tilting as well, but their orientation does not fit into a common stress field with the reverse faults.
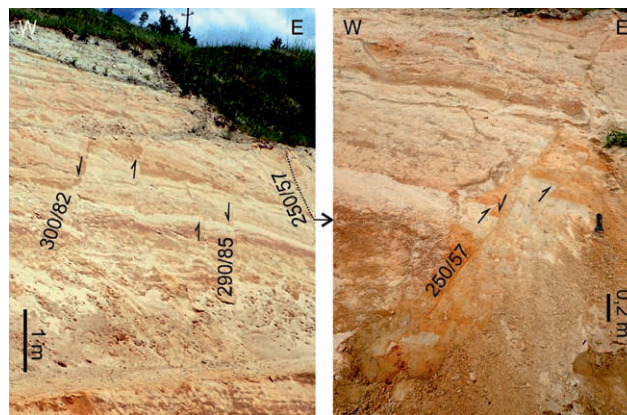

Figure 8. Possible strike-slip faults near the western end of the northern wall. Stereoplots in *Figure 6A*. Note the varying apparent reverse and normal separation along the set

8. ábra. Valószínű eltolódások az északi fal nyugati végében, változó irányú látszólagos elvetéssel. Sztereogram a 6. A ábrán

Reverse faults

Reverse faults were observed in the Pannonian deposits, both in marls and sands. Their size is variable, the smallest ones crosscut only a few layers, while the largest ones displace sediment packages with tens of metres of thickness.

Small faults can be observed in the Pannonian calcareous marls, which crosscut layers and often terminate at bedding planes (*Figure 9*). They appear as normal faults in their present position, in the subvertical marl layers. However, the rounded shape of the striations ("soft striae") refers to an early formation of the faults, before the complete lithification of the deposit. If backtilted with the local bedding dip (170/80), they point to SSE-vergent thrusting. A minor sinistral component is indicated by the slickenlines. No tensional features have been observed that post-date the large-scale folding and tilting of the succession, and the backtilted orientation of the studied faults fits the compression direction for the area, so they are most probably reverse faults that formed at the onset of shortening, before the folding of the succession.

Reverse faults crosscut the sands both in the western and in the northeastern wall of the sand pit (*Figure 4*). They occur at irregular intervals. Due to the lack of slickenlines, it is not possible to measure the exact slip direction along them; their visible displacement is usually only a few tens of cm. Most of the reverse faults must have formed when the layers had already reached their present-day (tilted) position. There was a group of reverse faults in the NE wall that enclose acute angles (20–30°) with the bedding (*Figure 4C, G*). If completely backtilted with the bedding, their orientation is still asymmetric (*Figure 4H*). They become symmetrical at an intermediate stage of tilting between the original and the present bedding dip; thus, these can be syn-tilt features.
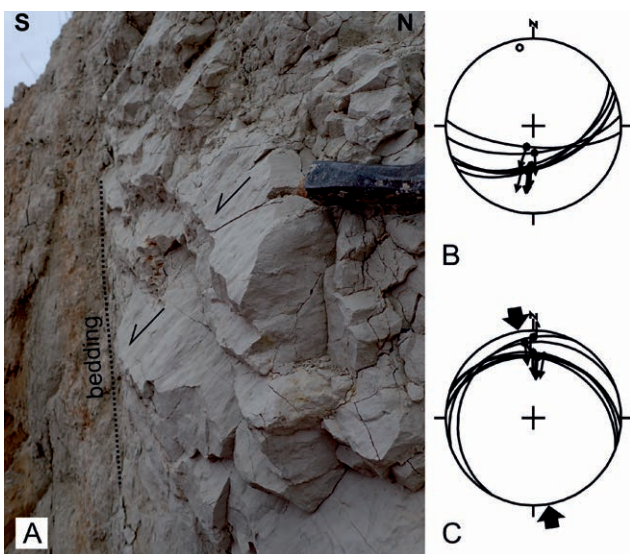

Figure 9. Small faults in the calcareous marls. A) Field photo of the originally reverse, now tilted faults; B) their orientation in stereoplot; C) orientation backtilted to supposed original position

9. ábra. Kis vetők mészmárgában. A) Az eredetileg rátolódásos, kibillent vetők terepi képe; B) sztereogramjuk; C) visszabillentett, eredeti helyzetük sztereogramja

The upper part of the Pannonian marls seems to be most affected by reverse faulting. In most cases outcrop conditions did not allow us to follow the exact trace of faults, but it was possible to notice displacement or repetition of layers. Slip planes often include bedding planes along parts of their lengths (*Figure 7*, *Figure 10B*). A few m thick intervals were observed to be repeated in the uppermost marl and silt layers, where slip happened mostly along bedding planes (*Figure 7*). The vergency of thrusting – whether originally north- or south-vergent – could not be identified. Differences in the thickness and the number of beds in the sedimentary succession at various locations in the sand pit also refer to partly bedding-parallel thrusting. The interval between a tuff layer (205 according to bed numbering in Sebe et al. 2021) and the transitional, yellowish marl and calcareous silt interval capping the "white marls" (from layer 218) is 9 m thick in the centre of the sand pit, and includes two green clay – sand – green clay packages (*Figure 10A*). It is only 5.5 m thick in the NW part, with one clay-sand-clay package and another clay layer missing there. In the seemingly conformable succession brecciated intervals occur from place to place, and apparently continuous and undisturbed layers may change their thickness or disappear along strike (*Figure 10A*). A major thrust fault was exposed by excavations in the central part of the sand pit in 2012, along which a wedge-like body of the succession is repeated (*Figure 10A* (background) and *C*, marked with arrows). The fault plane has a dip of approximately 60° towards the SE in its present orientation, while backtilting with local bedding dip gives an original dip towards the NE at the time of its formation. Drag of layers along the plane indicates presently top-to-SE normal, originally SW-vergent reverse movement.

Folds

Folds are not widespread in the sand pit, but some features point to large-scale folding. Bedding dips in the entire sand pit give the general view of a large south-vergent asymmetrical anticline, with its southern, subvertical limb making up the northern wall of the sand pit, and a connected syncline within the sand pit, with its lower, subhorizontal limb lying below and to the south of the sand pit (*Figure 2E*, *Figure 11C*). This picture is in accord with the model proposed by Csontos et al. (2002). The fold axis is somewhat curved, as shown by the laterally changing strike of the layers (*Figure 2*). The fold amplitude must exceed 100 m; thus, the curvature of the layers is rarely visible in outcrops of limited size. One such location is in the northern wall, where landslides exposed vertically more extensive outcrops than elsewhere, making the arcuate shape of the calcareous marl layers visible (*Figure 7*). Here only a small section of the fold is exposed, thus the fold can be either an overturned or a recumbent one; it is not possible to exactly assess the position of the axial plane. The dip of the steep sand layers in the western wall also somewhat increases upwards.

In the trench the lower part of the Pannonian marls and the upper Sarmatian deposits have diverse lithologies. These
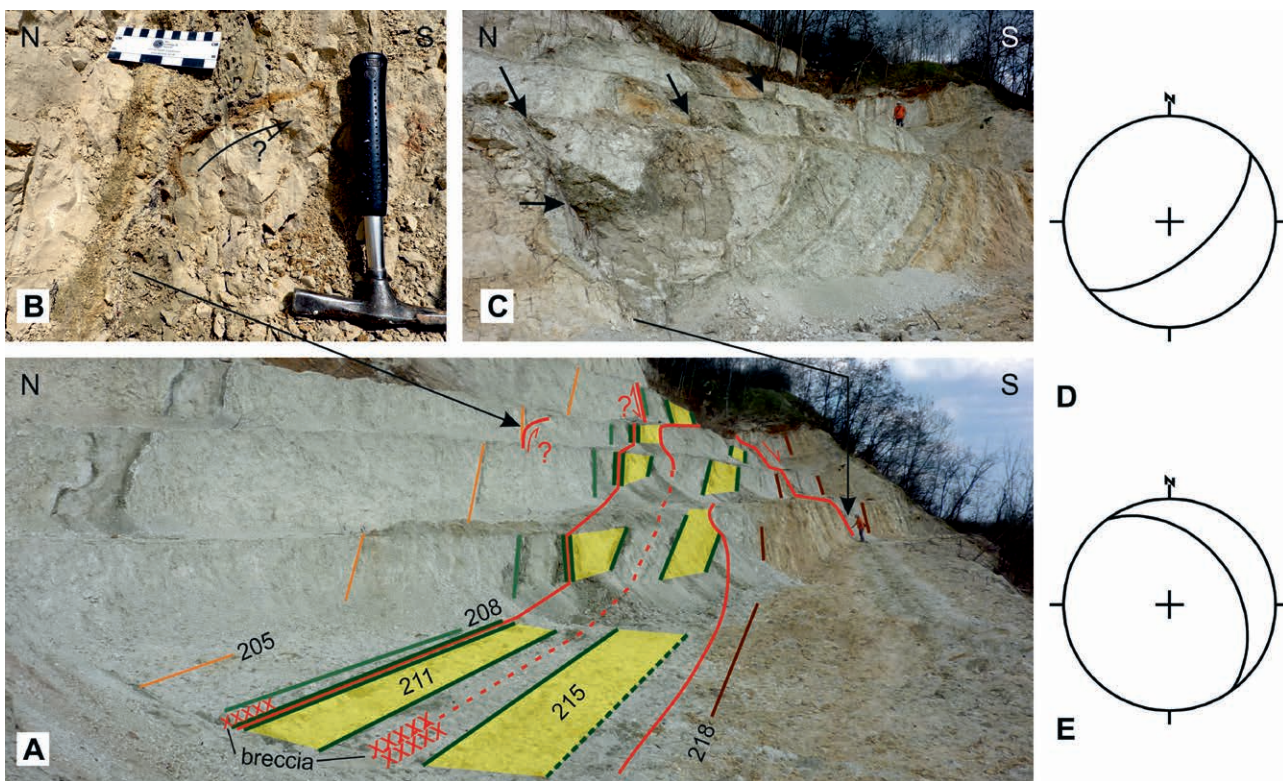
Figure 10. Reverse faults in Pannonian calcareous marls and silts in the central part of the northern wall (A, C: 2012; B: 2016). In fig. C, arrows indicate the location of thrust plane. D) Stereoplot of the major fault plane marked with arrows in A and C. E) The same, backtilted with local bedding dip

10. ábra. Rátolódások a pannóniai mészmárgaösszlet tetejében az északi fal középső részén (A, C: 2012; B: 2016). A C ábrán a nyilak a rátolódási sík helyét mutatják. D) Az A és C ábra nagy, nyíllal jelölt vetősíkjának sztereogramja. E) Ugyanez a helyi rétegdőléssel visszabillentve

preserved signs of bedding-plane shearing, which can be related to folding (*Figure 11A*). Where a competent rock type (hard calcareous marl or limestone) was enclosed by incompetent, soft layers (clays, clay marls), it became dissected by fractures. The produced dominoes got rotated, and the rotation direction is opposite to what would be produced by simple southward thrusting (*Figure 11B*). Instead, it speaks for flexural slip along bedding planes in a fold limb (*Figure 11C*).

Folding is visible in the sands as well (*Figure 3*, *Figure 4*). In the western wall, the same sand layers become somewhat

steeper upwards, i.e., they seem to be gently folded. The northern end of the unconformity surface within the sands is also bent upward, indicating that the uplift and southward thrusting of the hanging wall and the induced folding continued after the formation of the unconformity.

Some previous fold observations need to be reevaluated based on the new observations. The "fold with subvertical axis and several tens of metres of radius" reported by KON-RÁD & SEBE (2010) is now interpreted to have been produced by mining-related landsliding, and the "heavily folded calcareous marl layer in green clay" within the same structure is now explained by pedogenic precipitation instead of deformation.

Discussion

Deformation events

The observed structural features can be arranged in chronological order, and they define several deformation events.

1. Pre-tilt features

The earliest event happened before the tilting and folding of the sediments and is represented by the observed normal fault sets in the marls and sands (*Figures 5, 6, 7*) and the negative flower structure of KLEB (1973, fig. 19) in the sands. These features indicate syn-sedimentary transtension, which
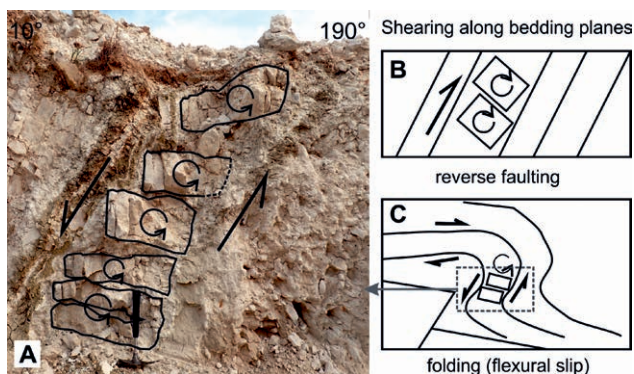

Figure 11. A) Rotated limestone dominoes between clay and marl layers in the eastern wall of the trench; B–C) possible models to explain their formation

11. ábra. Mészkőréteg nyírás hatására elfordult darabjai agyag- és márgarétegek közt a kutatóárok keleti falában; B–C) keletkezésük lehetséges magyarázatának modellje

ceased shortly after the onset of sand accumulation. Based on fault orientations, the main extension direction is estimated to be NNW–SSE to NW–SE. Tentatively, strike-slip faults in the sands (*Figure 8*) can also be assigned to this event.

A part of the shortening-related structures also pre-dates tilting, namely reverse faults in the marls (*Figure 9*). These can be linked to the start of compression (already during sand deposition), with NNW–SSE shortening.

2. Syn-tilt features

The majority of structures in the sand pit is connected to the large-scale syn-sedimentary compressional deformation of the deposits and fit the model of folding above a blind, south-vergent thrust fault proposed based on scarce data by BENKOVICS (1997) and CSONTOS et al. (2002). Bedding dip directions and reverse fault orientations refer to N–S or NNW–SSE compression during deformation. Folding of the succession caused bedding-plane slip and shearing-related block rotation in the already deposited marl layers (*Figures 7, 11*), while the sand layers accumulating during that time acquired gradually changing bedding dips and tapering shapes, thickening towards the south (*Figures 2, 3*). In the sands some reverse faults formed during the folding process and were then further tilted together with the sediments (*Figure 4C, G, H*). Erosional truncation of the folded succession produced a sharp unconformity surface in the sands. This angular unconformity can be correlated with the one photographed by VADÁSZ (1960, p. 255), BARTHA (1971, p. 144) and JUHÁSZ (1987, unpaginated table after p. 336). Considering the areal extent of the sand pit at that time, the photos were likely taken in the eastern third of the present-day sand pit. The unconformity thus can be followed for approximately 500 m in the E–W direction. As this surface is overlain by the same lacustrine sands that make up the succession below the surface, i.e., subaqueous sedimentation returned, temporary erosion and renewed submergence can be explained at least partly by lake level change and not just by vertical tectonic movements (i.e., lake level fall and rise, or tectonic uplift, then lake level rise). The facts that there are no pedogenic features along the unconformity surface and that the lithofacies of the sands below and above it is identical suggest that emersion and erosional truncation of the lower unit must have been fast.

3. Post-tilt features

Folding continued after the renewal of sand deposition, shown by the upward bending of the unconformity surface. Gently north- and south-dipping reverse faults in the sands indicate that N–S oriented shortening continued after the layers have reached their present-day dips.

Age of deformations

BENKOVICS (1997) and CSONTOS et al. (2002) placed the shortening between the "lower" and "upper" Pannonian, while KLEB (1973) wrote that the unconformity lies within the "upper Pannonian" sands. Based on new palaeontologi-

cal results (BOTKA et al. 2021), now the age of deformations can be confined using time-calibrated mollusk biostratigraphy. The mollusk association in the sand refers to the younger part of the *Lymnocardium conjungens* littoral mollusk biochron (9.6–11.0 Ma; BOTKA et al. 2021). The underlying marls are dated into the youngest part of the *Lymnocardium schedelianum* sublittoral mollusk biochron (11.45–10.2 Ma). Therefore, the age of the sands is estimated to 10.2–10.0 Ma (BOTKA et al. 2021). Extension could have happened at the beginning of this interval, while compression dominated most of the time afterwards. Folding and related features were syn-sedimentary, i.e., still before 10.0 Ma, somewhat earlier than the dating suggested by CSONTOS et al. (2002) ("late Pannonian"). Post-tilt shortening may have happened any time afterwards.

Geodynamic interpretation

The interpretation of the described deformation events in a geodynamic framework is rather complex. The observed pre-tilt NW–SE transtension along the Mecsekalja Fault Zone before or around 10 Ma is in accord with the coeval event along the same fault zone deduced by CSONTOS et al. (2002, fig. 15) from a nearby geological cross-section at Pécsszabolcs, just west of the Danitzpuszta sand pit. Further observations (SEBE & MAGYAR, submitted) show that sedimentation during the earliest Pannonian occurred in fault-controlled subbasins near the mountain fronts in the Mecsek Mts, similarly to the Transdanubian Range (FODOR 2008, FODOR et al. 2021). These could mean that fault-controlled syn-rift extension did not cease in the middle Miocene in the region, as suggested by BALÁZS et al. (2016), but continued into the early late Miocene. Alternatively, the mentioned events may belong already to the post-rift phase, implying that fault activity continued in the region even in this phase generally characterised by thermal subsidence and modest deformation (e.g., HORVÁTH et al. 2006).

The ~N–S compression driving the progressive tilting, folding, truncation and reverse faulting of the sediments started between 10.2–10.0 Ma, and is again difficult to evaluate. The "post-Sarmatian inversion event" proposed by HORVÁTH (1995, 2007) might fit in time with the Danitzpuszta compression features. This short inversion phase was described to be manifested in a basinwide unconformity, folding and uplift of pre-Pannonian rocks, the erosion of Sarmatian deposits and non-deposition of early Pannonian rocks, and placed in time between the latest Sarmatian and the early Pannonian, ~12–9 Ma (HORVÁTH 1995, 2007; FODOR et al. 1999; HORVÁTH et al. 2006). It was attributed to the docking/soft collision of the eastward moving basement of the Pannonian Basin onto the European margin when subduction stopped under the Eastern Carpathians and consequently rifting also ceased in the basin (HORVÁTH 1995, 2007; BALÁZS et al. 2016). In NW Croatia, TOMLJENOVIĆ & CSONTOS (2001) reported late Sarmatian, pre-Pannonian (~12–11 Ma) shortening, while CSONTOS et al. (2002) described folding and erosion at the Sarmatian-

Pannonian boundary in the northern foreland of the Mecsek Mts. However, observations in the Serbian part of the Pannonian Basin, where compressional structures are lacking near this horizon, speak against a basinwide, contemporaneous inversion event (MATENCO & RADIVOJEVIĆ 2012). The 10 Ma event at Danitzpuszta is very close in time to the end of the rifting in the Pannonian Basin as proposed by BALÁZS et al. (2016); i.e., the syn-/post-rift boundary. However, the NNW–SSE compression direction in the Mecsek makes it difficult to regard this the "post-Sarmatian inversion event", which was characterised by E–W shortening (FODOR et al., 1999). Local north-southerly compression (or transpression) could be caused by a right-lateral (constraining) activity of the entire Mecsek transpressive wedge, as proposed for the neotectonic inversion phase due to the Adria push by CSONTOS et al. (2002).

The other candidate, neotectonic basin inversion started ~8.5–8 Ma years ago in the SW Pannonian Basin based on new data and on published ones re-calibrated using mollusk biostratigraphy (SEBE & MAGYAR submitted, based on data from TOMLJENOVIĆ & CSONTOS 2001, FODOR et al. 2005, UHRIN et al. 2009, MATENCO & RADIVOJEVIĆ 2012, SEBE et al. 2020), much later than the deformation documented in the sand pit. Thus, shortening at the Pécs-Danitzpuszta site can be related to the Africa (Adria) – Europe convergence based on the compression direction, but within this process it is difficult to correlate it with other deformation events in the SW part of the Pannonian Basin; it pre-dates the events in the region, which were interpreted to be linked to the onset of neotectonic basin inversion.

Conclusions

The Pécs-Danitzpuszta sand pit exposed numerous structural features – tilted beds, faults and folds – from an interval of the Neogene sedimentary succession of SW Hungary, which is strongly underrepresented in surface outcrops. The measurement of the features and the examination of their relationships allowed us to discern two closely succeeding deformation events, while the dating of the deformed sediments with mollusk biostratigraphy enabled us to constrain their timing. At the beginning of the time interval between 10.2–10.0 Ma, NNW–SSE extension (transtension) created normal fault sets and negative flower structures and possibly strike-slip faults in the Pannonian marls and the lowermost part of the Pannonian sands. Right thereafter, still in the early part of the mentioned time interval, NNW–SSE compression ensued and has continued to dominate the area ever since. Deformations under this stress field started with small-scale reverse faulting in the Pannonian marls. They continued with the folding of the succession, driven by south-vergent thrusting of the mountains towards their southern foreland. Folding created bedding-plane slip and shearing-related block rotation in the already deposited middle and upper Miocene marl layers and continuously varying bedding dips, southward thickening layer shapes and reverse faults in the Pannonian sands. In the formation of an angular unconformity within the sands, lake level changes of Lake Pannon must also have played a role besides compression. Continuing shortening is shown by the bending of the unconformity and additional post-tilt reverse faults.

The observations show that extension- or transtension-related fault activity lasted here up to the late Miocene, though its assignment to the syn- or post-rift phase of the geodynamic evolution of the Pannonian Basin is uncertain. The linkage of the following compressional deformation to the post-rift phase or to the late-stage inversion of the basin cannot be confirmed, either. The compressional event cannot be correlated regionally; it pre-dates basin inversion-related events reported from the region so far.

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