

## Miocene to Quaternary deformation, stratigraphy and paleogeography in Northeastern Slovenia and Southwestern Hungary

### Deformacije, stratigrafija in paleogeografija severovzhodne Slovenije in jugozahodne Madžarske od miocena do kvartarja

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*Ključne besede:* razlamljanje, gubanje, pogrezanje, dvigovanje, paleomagnetizem, rotacija, napetostno polje, sedimentacijsko okolje, neogen, Panonski bazen, Slovenija, SW Madžarska

#### Abstract

The Mura-Zala basin was formed due to ENE-WSW trending crustal extension in the late early and middle Miocene (~19 – 11 Ma). Marine sedimentation occurred in several more or less confined depressions (half grabens), then in a unified basin. The rifting phase was probably connected to uplift and brittle-ductile deformation of metamorphic basement at the eastern part of the Pohorje and Kozjak hills. During the late Miocene thermal subsidence, deltaic to fluvial sediments were deposited.

After sedimentation, the southernmost Haloze-Budafa sub-basin was inverted. Map-scale folds, reverse and strike-slip faults were originated by NNW-SSE compression during the latest Miocene(?)–Pliocene. After this folding, Karpatian sediments of the Haloze acquired magnetization. During the late(?)Pliocene to Quaternary(?), the whole Mura-Zala basin, including the folded Haloze, suffered ~30° counterclockwise rotation as a relatively rigid block. This rotation affected a wider area from Slovenia to western Hungary and northern Croatia.

#### Kratka vsebina

Mura-Zala bazen je nastal v času od poznega zgodnjega do srednjega miocena (~19 – 11milj. let) z raztezanjem zemeljske skorje v smeri ENE-WSW. Najprej je sedimentacija potekala v depresijah (poljarkih), zatem pa v enotnem bazenu. Rifting je verjetno spremljalo dvigovanje, razlamljanje in plastično deformiranje metamorfne podlage na vzhodnem delu Pohorja in na Kozjaku. Riftingu je v zgornjem miocenu sledilo termalno pogrezanje. Tedaj enotni bazen so zapolnjevali deltni in na koncu rečni sedimenti.

V najpoznejšem miocenu(?) ali pliocenu se je začelo stiskanje bazena iz smeri NNW-SSE. Med inverzijo južnega dela bazena, tj. Haloze-Budafa subbazena, so nastali reverzni in zmični prelomi ter gube. Po gubanju so bili karpatijski sedimenti na novo namagneteni. Zatem pa se je celotni Mura-Zala bazen od poznega(?) pliocena do kvartarja(?) zasukal za ~30° v nasprotni smeri od urinega kazalca skupaj s severno Hrvaško, zahodno Madžarsko in vzhodnim delom Vzhodnih Alp.

## INTRODUCTION

The present paper gives a short description of the results of the bilateral cooperation project between Slovenia and Hungary during the years 1999-2000. More detailed descriptions are in preparation. The project was initiated by our joint work in Northern Slovenia and Hungary during the years 1992-1996, including an inter-governmental project in 1995-1996 (Fodor et al., 1996; Jelen et al., 1998). This work demonstrated stratigraphical and paleogeographical similarities between the North Slovenian and North Hungarian-South Slovakian Paleogene basin segments, which represent dismembered parts of a formerly unique basin (Kázmér & Kovács, 1985; Báldi, 1986; Jelen et al., 1992; 1998). Their deformation started in early Miocene and resulted in important dextral strike-slip displacement, mainly along the faults of the Periadriatic-Mid-Hungarian shear zone, like the Donat-Balaton zones (Balla, 1985; Csontos et al., 1992; Tari, 1994; Fodor et al., 2000). Strike-slip deformation was also associated with important rotations, whose sense and angle are varying in different tectonic blocks (Márton & Jelen, 1997; Fodor et al., 1998).

In the present project, we aimed at constraining the age of the youngest rotation in NE Slovenia and SW Hungary and at determining its geographical extent. Thus we carried out paleomagnetic studies on Karpatian through Pontian rocks (17,5 – 6 Ma).

The other question was the structural mechanism which made the rotation possible. Particularly, we wanted to check 3 possible theoretical solutions: the rotation (1) affected the whole region as a rigid block, (2) occurred in shear zones and represent local rotations of small intra-shear blocks, (3) affected only a relatively thin upper block above a sub-horizontal detachment surface.

Any of these structural mechanism would have consequences for the formation of the Mura-Zala basin, one of the largest and deepest depressions of the Pannonian basin system. Based on our combined paleomagnetic and structural work we intended to give a new model for the formation, and subsequent deformation of this basin which still holds major hydrocarbon production of Slovenia and keep to serve production in Hungary and Croatia.

Paleomagnetic and structural work is not possible without good stratigraphical data. Missing data, particularly microbiostratigraphical ones, were also obtained in the framework of the research. Characteristic paleoenvironmental features of the thick piles of sediments were also investigated.

## METHODS OF THE RESEARCH

The Slovenian part of the study area, the Mura-Zala basin, its present-day rim were first examined for cross sections and exposures which can yield good combined paleomagnetic, structural and stratigraphic results. The most promising sites were selected, following the requirement for uniform distribution as much as possible. Information for the Hungarian side of the basin was derived from the existing literature.

### Stratigraphy

For the stratigraphic part of the research, cross-sections were considered of primary importance. Unfortunately, continuous ones are rare. In the late Miocene and Pliocene rocks only scattered outcrops were available for observations. Therefore, to reconstruct stratigraphic successions, time consuming stratigraphic constructive modelling was applied using all field informations. Results derived from the field observations for the early and middle Miocene were satisfactory, while results for the late Miocene and Pliocene were largely depended on seismic sections. Lithofacies, foraminiferal biofacies and sedimentary structures were newly studied. Foraminiferal, nannoplankton, and sequence stratigraphy were used to establish chronostratigraphic subdivisions and their calibration to geochronologic time scale for the lower and middle Miocene. In the consideration of the late Miocene and Pliocene stratigraphy existent molluscs, ostracods and palynological data were searched for information. During the stratigraphic considerations we wanted to remain independent of the previous stratigraphic interpretations.

Many new informations on the paleoenvironment were derived from the quantitative analysis of the foraminiferal biofacies. For this research, stratigraphic and paleoen-

vironmental data obtained during the last five years were employed.

### Paleomagnetism

Paleomagnetic samples were collected and processed from the Haloze (Karpatian, 10 localities, total of 74 independently oriented cores), and from the Slovenske Gorice-Goričko area (12 localities, Sarmatian through Pontian age, total of 116 independently oriented cores).

The paleomagnetic measurements and the low field magnetic susceptibility measurements were carried out in the Paleomagnetic Laboratory of the Eötvös Loránd Geophysical Institute of Hungary, the remanence anisotropy measurements at the Geophysics Department of the Eötvös University, Budapest. The paleomagnetic measurements consisted of the measurement of the natural remanent magnetization and the low field susceptibility of each sample in the natural state, the thermal or alternating field demagnetization of the samples till the magnetic signal was lost, from remeasurement of the natural remanent magnetization after each demagnetization step, remeasurement of the susceptibility after each heating step. To help identification of the magnetic minerals, magnetic mineralogy measurements were also carried out.

### Structural works

Field structural measurements were carried out in the Pohorje-Kozjak hills and in the Haloze-Slovenske Gorice-Goričko areas in 62 outcrops. Measurements included all brittle structures, joints (with or without mineral coatings), faults, slickenside lineations, fold axes, fractured pebbles.

Paleostress calculations were performed from the field data using computer methods (Angelier, 1984). Estimation of stress axes was made when kinematic indicators for faults were scarce, using the model of Anderson (1951). If faults belong to more than one stress tensor, computerised automatic and "hand-made" separation was applied to differentiate stress states (Angelier & Maoussis, 1980).

Age of deformation (stress state) was estimated from a relative chronology between different phases, the age of deformed and undeformed rocks, and using projected datings from surrounding areas. Seismic sections were also used in few cases to determine more precisely the duration of syn- or post-sedimentary deformations.

Surface structural observations were compared to structures observable on seismic reflection lines in the Mura depression. A number of Miocene structures were identified on a network of seismic sections in the Mura depression, particularly in the area where poor late Miocene outcrops prevented surface structural observation. Interpretation was made together with colleagues of the company Nafta Lendava, which kindly provided the seismic lines.

Observations on brittle structures were used to characterise the kinematics of major mapable faults. All these data permitted the analysis of deformation pattern and the description of structural events. Structural maps were constructed on the basis of observations during the present project and the existing Slovenian (former Yugoslavian) geological maps (Fig. 1). (Mioč & Žnidarčič, 1977; Aničić & Juriša, 1985; Žnidarčič & Mioč, 1988; Mioč & Marković, 1998).

At some outcrops of metamorphic rocks of the Pohorje and Kozjak hills, signs of ductile deformation, like mineral lineation was also measured. For their better characterisation, thin sections and polished surfaces of samples were analysed.

## RESULTS

### Stratigraphy and paleogeography

Based on the occurrence of biochronomarker foraminifer *Uvigerina graciliformis* the Neogene marine sedimentation started in the Karpatian. Underlying undated deposits are coarse-clastics of which thickness do not exceeds ~60m. In places these coarse-clastics were found to contain in fine-grained intercalations *in situ* (not reworked) foraminifera. The biostratigraphic data set shows that, during Karpatian, marine sedimentation remained restricted to the Mura depression. The paleobathymetric study us-

ing van der Zwan et al. (1990) equation and the benthic foraminifera taxa distribution as an approximation to the paleo-water depth indicate upper to middle bathyal depth for the Karpatian. The paleo-water depth of 700m was reached in a very short time after the beginning of Karpatian. The maximum water depth of 900 – 1000m (geometric mean is 840m) was reached at the beginning of the late Karpatian. Benthic and planktonic foraminiferal fauna reflect deep and confined basins with restricted hydrological exchange with the open seas – conditions associated with the initial stage of the Karpatian extension. Deep-water depositional system is represented by gravity mass movements. Submarine fan divisions have been recognised on the basis of the internal sedimentary structures, but not studied in detail. Paleobathymetry and paleogeography indicate that present-day structural features, like Radgona and Ljutomer depressions (half grabens) already existed in the Karpatian.

The lower Karpatian is correlated with the transgressive system tract, upper Karpatian with the highstand system track of the Haq's et al. (1987) TB 2.2 sequence. The Karpatian/Badanian boundary is marked by the Styrian unconformity, which is correlated with the Burdigalian-5/Langhian-1 sequence boundary. During the Karpatian, sedimentation was restricted to deep and narrow basins. The great early Badenian transgression reached far outside these basins, overstepping also the Donat zone.

The early Badenian is inferred from the occurrence of planktonic and benthic foraminifera *Praeorbulina glomerata circularis*, *Globigerinoides bisphericus* and *Uvigerina macrocarinata*. Paleo-water depth curve shows that middle bathyal depth around 900m was reached very fast again in the very beginning of the *Uvigerina macrocarinata* Range-zone. A maximum of 1000m (geometric mean 880m) was reached in the upper part of the biozone. The deep-water depositional system is represented by fine-grained turbidites. Very favourable biotic conditions, particularly for the plankton, were controlled by the highstand of the TB 2.3 sequence and by the renewing of the equatorial tropical-subtropical circulation through the Mediterranean Sea (Flower & Kennett, 1994) that also reached the Central Paratethys (Rögl, 1998).

The early Badenian/middle Badenian boundary was located at the first occurrence of *Uvigerina venusta* and *Uvigerina cf. pygmaea*. The deep-water depositional system changed to sand-rich turbidites, which, together with the dramatic decrease of the presence of planktonic foraminifera, indicate the formation of restricted basins. It might be correlated with the Langhian-2/ Serravallian-1 sequence boundary at 14.8 Ma and the lowstand of the TB 2.4 of Haq et al. (1987).

After the middle Badenian it is difficult to follow the development of the depositional systems of the study area because of bad outcrop conditions. A small peak of planktonic foraminifera within the *Pappina neudorfensis* and *Velapertina indigena* Range-zones (= upper Badenian) may indicate the highstand of the TB 2.4 sequences. This system tract falls between the Langhian-2/ Serravallian-1 and the Serravallian-2 sequence boundaries. The turbiditic system was preserved at depocentres of the basins during the Sarmatian. However, the depositional systems and the stratigraphy of rather thin Sarmatian in comparison to the thickness of other chronostratigraphic units are still poorly understood (e.g., in the well Ljutomer-1: Sarmatian ~300m with respect to Pontian ~1700m, Pannonian ~900m, and Badenian ~600m, Karpatian ~1000m; in the well Kog-5: partly eroded Sarmatian ~215m, with respect to Badenian ~750m, Karpatian ~1000m (Rijavec, 1976); in the well Vučkovec: Sarmatian ~170m, Pannonian ~470m and Badenian ~1000m, Karpatian ~1000m; (Seljan & Parlov, 1995)).

Unconformity at the Sarmatian/ Pannonian boundary is correlated with the Serravallian-3 sequence boundary. During the subsequent Pannonian transgressive/ subsidence phase the highest parts of tilted blocks were flooded (Turk, 1993). The approaching delta front is recognised in the basins, while in the deepest parts in front of the slopes turbiditic sedimentation still prevailed (Đurasek, 1988). Seismic sections demonstrate that delta progradated generally from NW to SE (Pogácsás et al., 1988; Đurasek, 1988; Újszászi & Vakarc, 1993). Accommodation spaces initiated in the Karpatian were completely filled up with delta sediments by the end of the Pontian.

It is to note that the chronostratigraphic correlation of local lithostratigraphic suc-

cessions, i.e. lower and upper Pannonian, lower and upper Pontian, and Pliocene with the regional geochronologic time scale needs to be nonbiologically calibrated (Magyar et al., 1999; Sacchi et al., 1999). This is due to overcome the problem of biostratigraphic continuity and iteration, dispersal and terminal niches versus time equivalence in the very diversified and changeable environment of the Lake Pannon.

### Paleomagnetic results

#### Haloze

Except two localities, statistically well-defined paleomagnetic directions were obtained for all. Negative tilt test proves that the paleomagnetic signal is of secondary origin (post-tilting age) for 7 localities. This signal suggest that the area rotated about 30° in the counterclockwise sense with respect to the present north, after the deformation (Fig. 1). Magnetic fabric (expressed by the orientation and intensity of the low field magnetic susceptibility anisotropy) connected to mafic minerals is basically of sedimentary origin (minima are perpendicular to the bedding). Weak deformation is also evident in this fabric; this is reflected in the low degree of anisotropy, in the grouping of maxima, not only at locality level, but also regionally. In contrast, the fabric of the magnetic minerals, expressed by the anisotropy of the remanence, is of post-tilting (post-folding) origin. This suggests that it is not only the remanence, which is of post-tilting age, but also the mineral carrying the remanence.

#### Slovenske Gorice – Goričko area

Four localities yielded statistically good paleomagnetic directions. Two of them from the Ormož-Selnica anticline point to clockwise rotation. Two other sites, one within the anticline and one north from it, show counterclockwise rotation (Fig. 1). These rotations, as the source rocks are of Pannonian-Pontian age, are constrained to be very young; they reflect neotectonic movements. Additional three localities, all north of the Ormož-Selnica antiform, indicate counter-

clockwise rotation, but the statistics is too poor to express the results quantitatively.

### Structural results

Samples of metamorphic rocks directly below the Karpatian sediments show very intense ductile deformation. The locally mylonitised rocks show extensional deformational features and top-to-ENE shear sense in section parallel to the ENE-SWS trending stretching lineation (this lineation was observed by Mioč (1977) but interpreted in a different way). This ductile extensional direction is sub-parallel to brittle tensional direction. Non-metamorphosed Permo-Mesozoic rocks are always located above the described low-angle shear zones. The sequences are always tectonically truncated. Similar occurrences were bored in the Mura depression (Gosar, 1995). This shows that the non-metamorphosed rocks represent extensional allochton(s) over the metamorphosed Pohorje nappe units (Fodor & Koroknai, 2000).

Brittle deformation of Karpatian sediments in the eastern Pohorje-Kozjak hills, Maribor and Cmurek/Mureck sub-basins is characterised by ENE-WSW to E-W tension (Fig. 1). The resulting normal faults defined half grabens which were partly described in earlier publications (Vončina, 1965; Pleničar, 1973, Korössy, 1988; Pleničar et al., 1990). The edge of tilted blocks are the South Burgenland Swell (Kröll et al., 1988), the Murska Sobota and Hahót highs and the south-western margin of the Transdanubian Range. The grabens/sub-basins are the Radgona-Vas, the Ljutomer-Haloze-Budafa, the Eastern Mura-Orség, the Maribor, and the Cmurek/Mureck sub-basins (Fig. 1).

On reflection seismic lines both high and low-angle normal faults can be seen (Gosar, 1995). The latter ones are in the crystalline basement, but locally are associated with high angle normal faults bounding small Karpatian-Badenian grabens. This geometry is similar to that observed by Tari et al. (1992), at the northern Vas graben.

In the Haloze area, NNE-SSW tension can be attributed to this tensional phase. It affected Karpatian rocks, when beds were still (close to) horizontal (Fig. 1, stereograms at upper right corner). Seismic sections and

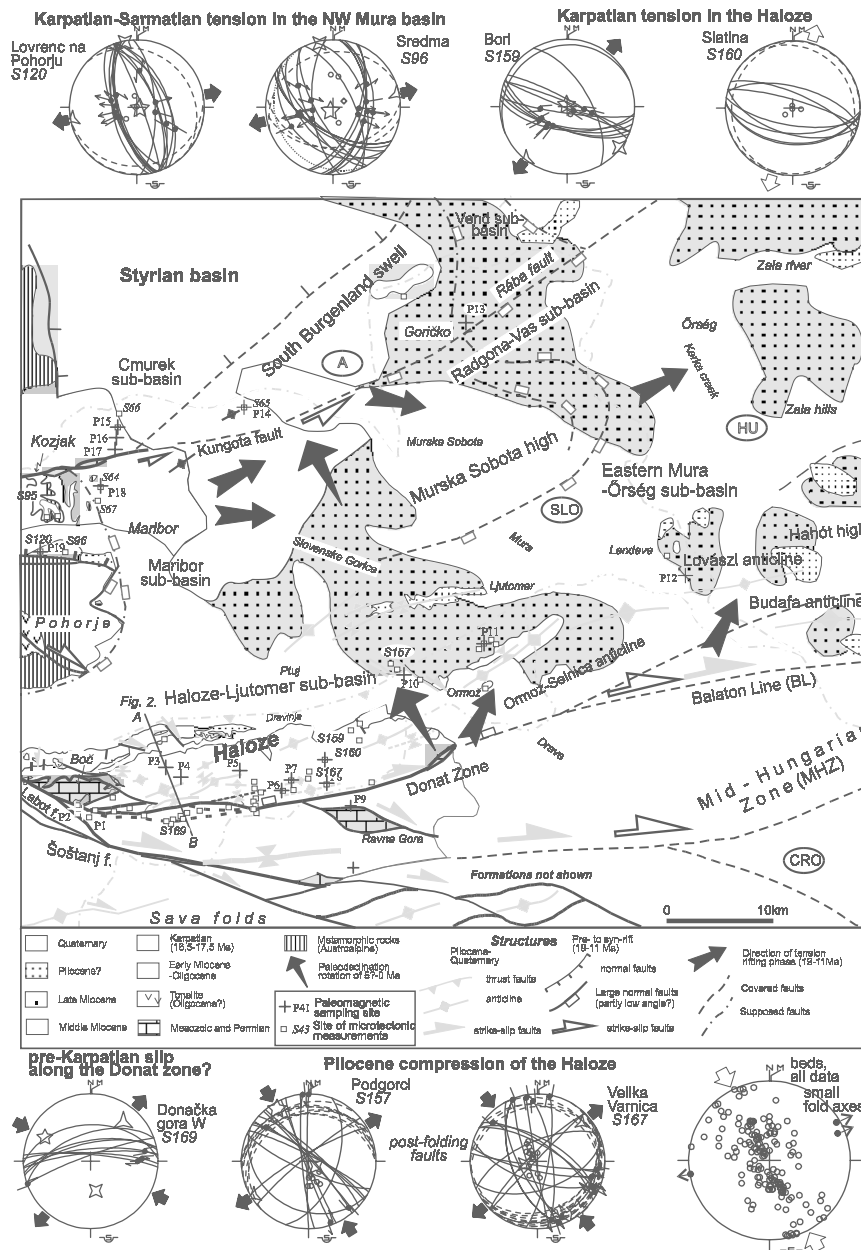


Fig. 1. Main sub-basins and structures of the Mura-Zala basin. Simplified paleostress directions and paleomagnetic declinations are also shown by large black arrows. Stereograms are made on Schmidt-net, lower hemisphere projection. Black and grey arrows show calculated and estimated direction of compression (toward centre of circle) and tension (away from centre of circle), respectively. Small arrows on curves (projected fault planes) show slickensides and motion of the hangingwall.

Sl. 1. Glavni subbazeni in strukture Mura-Zala bazena. Z velikimi črnimi puščicami so poenostavljeno prikazane smeri paleonapetosti in paleomagnetnih deklinacij. Stereogrami so izdelani na Schmidtovi mreži kot projekcije na spodnjo poloblo. Črne in sive puščice na stereogramih kažejo izračunano oziroma ocenjeno smer stiskanja, če so obrnjene proti centru oziroma raztezanje, če so obrnjene stran od centra. Puščice na krivuljah stereogramov (projekcije prelomnih ravnin) označujejo drsne ploskve in smer premika krovnega bloka.

surface cross sections suggest 1 or even 2 km thickness (Fig. 2), similarly what was suggested by Pleničar (1973). 1 km Karpatian thickness was also demonstrated by boreholes in the Budafa area (Völgyi, 1956; Dank, 1962). Borehole and seismic data clearly show that the Karpatian (and partly the Badenian) sediments are completely pinching out in both directions from the graben axis (Korössy, 1988; Horváth & Rumpler, 1984).

Major structures were formed by NNW-SSE compression in the Haloze, in its northern periphery (Ljutomer depression) and along strike, in the Budafa area. The resulting structural elements are folds, reverse faults with ENE-WSW strike and conjugate strike-slip and local normal faults (Fig. 1, 2). Our observations confirm the existence of anticlines of the Boč-Ormož-Selnica, Budafa, Lovászi, represented on earlier maps and publications (Pávai Vajna, 1926; Papp, 1939; Strausz, 1943; Dank, 1962; Horváth & Rumpler, 1984; Aničić & Jurisha, 1985; Seljan & Parlov, 1995; Mioč

& Žnidarčič, 1996; Mioč & Marković, 1998). Three consecutive steps can be determined on the basis of the relation of structures with respect to bedding. Some faults were formed when the beds were still horizontal. This initial stage was followed by the folding itself, while most of the strike-slip faults occurred after the complete folding. All deformation steps were marked by the same compression, proving coaxial shortening and the lack of rotation. Seismic sections demonstrate folding below the Quaternary of the Ljutomer depression and in the Budafa area (e.g., Horváth & Rumpler, 1984). Surface and seismic observation show that the amount of shortening decreases toward ENE, expressed by the parallel decrease of dip of beds (Pávai Vajna, 1926; Mioč, & Marković, 1998). This deformation phase affected all rocks, even the youngest exposed upper Miocene sediments. The age can be latest Miocene or Pliocene.

On the contrary, no major brittle structures was observed in the main part of the

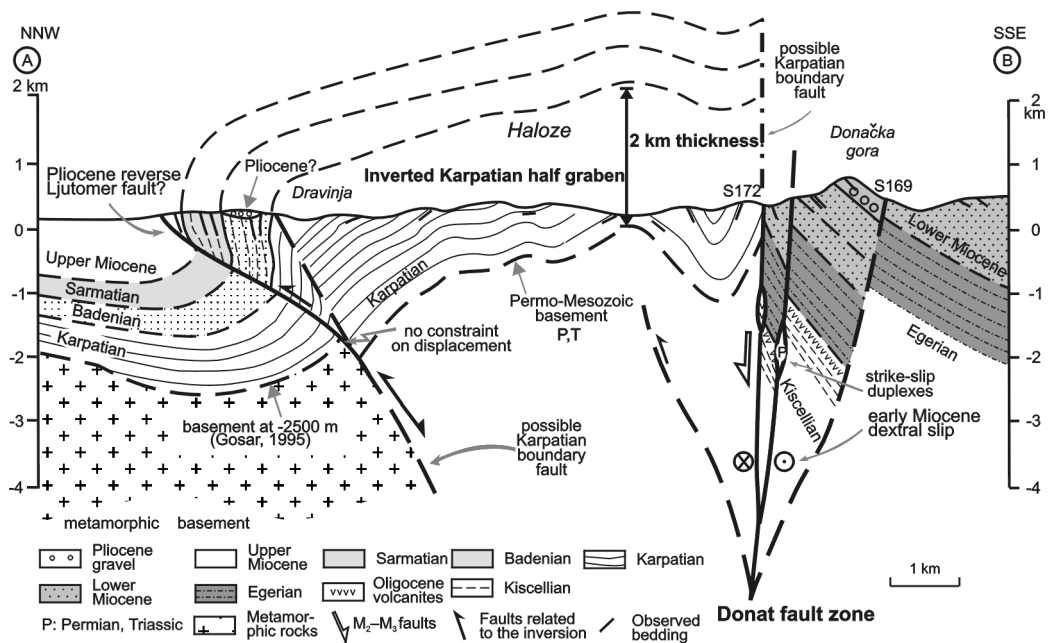


Fig. 2. Cross section through the Haloze showing folding of the thick Karpatian and overlying middle to late Miocene sediments. Note that the boundary faults of the Karpatian graben could be reactivated in different way; reverse slip on the Ljutomer fault, strike-slip on the Donat zone was probable.

Sl.2. Prerez čez Haloze prikazuje nagubane karpatijske, srednje in zgornje miocenske sedimente. Mejni prelomi karpatijskega jarka so bili lahko reaktivirani na različne načine. Ob Ljutomerskem prelomu gre po vsej verjetnosti za reverzni premik, ob Donački coni pa za vzdolžni zmik.

Mura-Zala basin (Goričko, Slovenske Gorice, Pohorje, Kozjak and Maribor area). The outcropping late Miocene rocks were not seriously deformed by penetrative faulting. Similar conclusions can be drawn from seismic sections: reflections on upper Miocene sediments are undisturbed, just slight and regional tilting (up to 10°) can be observed, but this could also be due to the compaction of the underlying layers.

## DISCUSSION

### Formation and evolution of the Mura-Zala basin

All the results can be summarised in the following evolutionary scheme for NE Slovenia and SW Hungary (Fig. 3). The Mura-Zala basin was formed due to important stretching of the lithosphere. The ENE-WSW to NNE-SSW tension (present-day direction) resulted in high-angle normal faults, similarly to other basins within the Pannonian basin system (Fodor et al., 1999).

Seismic sections and surface observations suggest that high-angle normal faults merged

to low-angle faults or shear zones at depth. Such shear zones with ductile extensional deformation could be present on the surface, below the Karpatian sediments of the Pohorje-Kozjak hills. These low-angle shear zones might have reactivated earlier detachment surfaces, like Cretaceous thrust planes, or late Cretaceous normal faults. The age of the extensional ductile deformation cannot be determined without radiometric ages. Projection of structural data from the surroundings would suggest either late Cretaceous and/or early Miocene age (Koroknai et al., 1999; Tari, 1996, respectively). Scarce fission track data from the Pohorje-Kozjak would favour Miocene ductile deformation (Sachsenhofer et al., 1998), but further research is still needed.

The high-angle normal faults limited half grabens (tilted blocks). The grabens near the eastern Pohorje (Maribor, Cmurek/Mureck grabens), the Radgona-Vas, the Ljutomer-Haloze-Budafa and the Eastern Mura-Orség sub-basins accumulated very thick Karpatian-Badenian sedimentary pile up to 1 or 1,5 km. The edge of tilted blocks (Murska Sobota and Hahót highs) still remained without sediments during the Karpatian, but

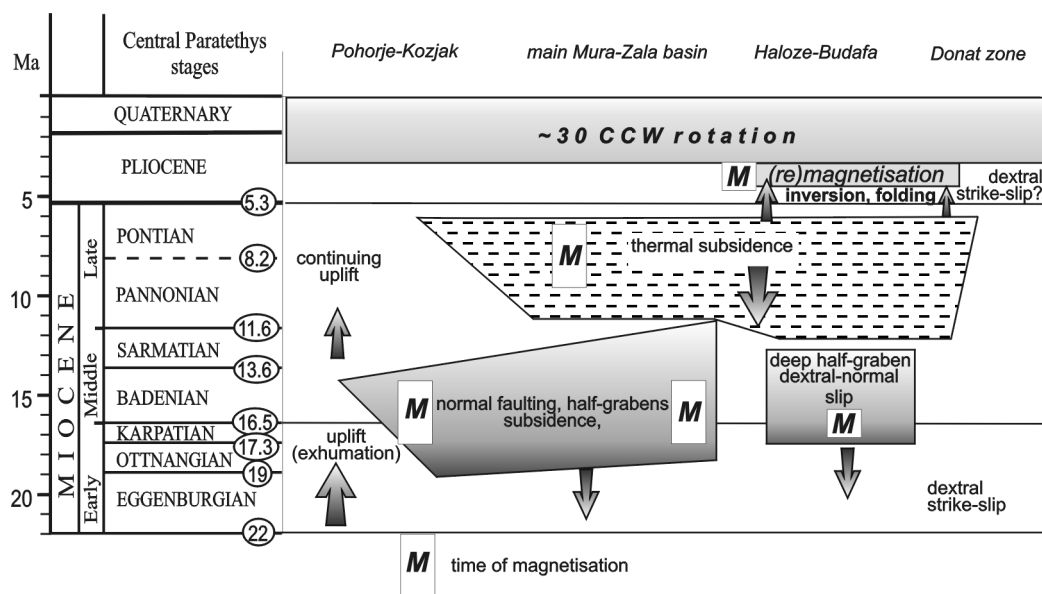


Fig. 3. Main structural and paleomagnetic events in the Mura-Zala basin. Boxes roughly indicate the time interval and spatial distribution of the events.

Sl. 3. Glavni strukturni in paleomagnetni dogodki v Mura-Zala bazenu. Osenčena in šrafirana polja prikazujejo prostorsko in časovno razširjenost dogodkov.



were invaded by the sea during the Badenian and Sarmatian (Bodzay, 1968; Szentgyörgyi & Juhász, 1988; Gosar, 1995). The thickness of these sediments on highs is small.

In the deep grabens depositional depth could reach middle bathyal depth in the Karpatian and early Badenian (Rifelj & Jelen, 2001). Deep basin condition is also indicated by different gravity mass movements. On the highs water depth remained shallow: sedimentation was characterised by algal or sandy carbonates (Bodzay, 1968; Szentgyörgyi & Juhász, 1988).

The southern boundary of this graben-horst system is not known well. The Donat zone might have played a role as basin margin or submarine high. North of the zone, a NNE-SSW tension might have associated with the activity of the basin-bounding Donat zone: this oblique tensional direction would indicate dextral-normal motion (Fig. 1, 2). This motion probably superimposed on early Miocene dextral (transpressional?) slip (Fodor et al., 1998).

Tensional deformation must have continued up to the end of Badenian or to the Sarmatian. However, water depth, marine paleogeographic connections were at least partly governed by eustatic sea level changes which opened (early Badenian) or closed (middle Badenian) ways for fauna migration (Rögl, 1998; Rifelj & Jelen, 2001).

Late Miocene evolution of the basin was marked by thermal subsidence, but no major faulting and/or rotation could be documented, neither on surface, nor on seismic lines (Fig. 2). The basin was filled, like other sub-basin in the Pannonian basin with deltas reaching a relatively deep water lake. Transport direction, as can be judged from seismic sections, was from (N)W to (S)E (Pogácsás et al., 1988; Đurasek, 1988; Újzászi & Vakarc, 1993). Sedimentation changed in style and decreased in amount in the latest Miocene, the Pliocene and Quaternary is characterised by thin terrestrial or fluvial sediments (Mioč & Marković, 1998).

Termination of sedimentation could also be connected to a new deformational phase of NNW-SSE compression (Fig. 1). All sediments were affected by this phase up to the youngest late Miocene ones. The main structural elements are the anticlines and synclines trending ENE-WSW. Parallel reverse

faults are also present, (like the Ljutomer fault) particularly at the northern side of the Boč hill, where Mesozoic rocks are thrust over the Miocene (Aničić & Juriša, 1985).

As indicated by the microtectonic and paleomagnetic data, the deformation was coaxial and no rotation, and probably no major wrenching occurred during this phase. The only exception could be the Donat zone, where renewed dextral slip is probable (Fig. 1, 2). Part of the magnetic fabric was also developed due to this compression, as reflected by the low field susceptibility pattern. The folding of the Haloze-Budafa is part of a wide belt of contractional deformation, from Italy through the Sava folds (Placer, 1998) up to SW Hungary and Croatia (Tomljenović & Csontos, 2001).

Timing of the beginning of folding largely depends on the exact age of the youngest sediments. No direct, calibrated age is known from Slovenia. However, combined seismic stratigraphic and magnetostratigraphic data can be projected from SW Hungary, where folds continue to the Budafa area (Pávai Vajna, 1926; Dank, 1962). Here the youngest folded data can be estimated as 8.7-6.3 Ma (Újzászi & Vakarc, 1993; Sacchi et al., 1999). Slightly younger sediments can be involved in deformation, but this (projected) age of ~6 Ma seem to be a reliable date for the initiation of folding.

In the southern area, in the Haloze, new magnetic minerals were formed and acquired magnetization after the folding (Fig. 3). The whole Boč-Ormož-Selnica antiform suffered ~30° CCW rotation after the folding. Similar rotation was observed in the Goričko area and near Lendava. Together with other published data (Fodor et al., 1998), the whole area of the Mura-Zala basin and their present-day boundaries, suffered this rotation. The rotated area is even larger, it includes NW Croatia (Márton et al., 1999, and in press), the Transdanubian Range (Márton & Fodor, 2001) and the eastern part of the Eastern Alps (Márton et al., 2000) and eventually the Istria peninsula (Márton & Veljović, 1983).

The rotation must have started in the Pliocene. As indicated by the Pliocene basalts in the southern Transdanubian Range, rotation was decreasing during the volcanism, from the early to late Pliocene (Márton, 1985). On the other hand, present-day geo-

dynamic scenario, interpretation of Quaternary fault pattern (Vrabec, 2000; 2001) and contemporaneous stress data (Bada et al., 1998) would also indicate that ongoing CCW rotation of Slovenia and Croatia is still probable. In that case, the rotational deformation can eventually continue up to the present and may have neotectonic significance.

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