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

Deformacije, stratigrafija in paleogeografija severozemljih Slovenije in jugozahodnih Madžarske od miocena do kvartarja

László FODOR1, Bogomir JELEN2, Emo MÁRTON2, Helena RIFELJ2, Marijan KRALJIĆ4, Renata KEVRIĆ4, Péter MÁRTON5, Balázs KOROKNAI6 & Mária BALDI-BEKE6

1 Geological Institute of Hungary, Stefánia 14, H-1143 Budapest, Hungary, fodor@mafi.hu
2 Geološki zavod Slovenije, Dimičeva 14, SI-1109 Ljubljana, Slovenia
3 Eötvös Loránd Geophysical Institute of Hungary, Paleomagnetic Laboratory, Columbus 17-23, H-1145 Budapest, Hungary
4 Nafta Lendava, Rudarska cesta 1, SI-9220 Lendava, Slovenia
5 Eötvös Loránd University, Department of Geophysics, Pázmány Péter setány 1/C, H-1083 Budapest, Hungary
6 2046 Üröm, Rákóczi 42, Hungary

Key words: faulting, folding, subsidence, uplift, paleomagnetism, rotation, paleostress, depositional environment, Neogene, Pannonian basin, Slovenia, SW Hungary

Abstract

The Mura-Zala basin was formed due to ENE-WSW trending crustal extension in the late early and middle Miocene (~11 – 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 pozega zgodnjega do srednjega miocena (~11 – 11mil. let) z raztezanjem zemeljske skorje v smeri ENE-WSW. Najprej je sedimentacija potekala v depresijah (poljarkih), zatem pa v enotnem bazenu. Rifting je verjetno spremenil dvigovanje, razlamljanje in plastično deformiranje metamorfne podlaje na vzhodnem delu Pohorja in na Kozjak. Rifting je v zgornjem miocenu sledilo termalno pogrezanje. Tedač enotni bazen so zapolnjevali delni in na koncu rečni sedimenti.

Zatem pa se je celotni Mura–Zala bazen od pozega(?)-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-
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 different stress states (Angelier & Manoussis, 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 & Žnidarič, 1977; Aničić & Juriša, 1985; Žnidarič & Mioč, 1988; Mioč & Markovič, 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 biochrono-marker 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 Donal zone.

The early Badenian is inferred from the occurrence of planktonic and benthic foraminifera Praeorbulina glomerosa circularis, Globigerinoides bisphericus and Uvigerina macrorcarinata. Paleo-water depth curve shows that middle bathyal depth around 900m was reached very fast again in the very beginning of the Uvigerina macrorcarinata 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 neudorfiensis 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 understand (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 (Durasek, 1988). Seismic sections demonstrate that delta progradated generally from NW to SE (Pogácsás et al., 1988; Durasek, 1988; Újszázi & Vakaars, 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 counterclockwise 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–Kožjak 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; Plenčar, 1973, Korőssy, 1988; Plenčar 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 Schmidti v 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 (Volgyi, 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 (Koróssy, 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, Lovázi, represented on earlier maps and publications (Pávai Vajna, 1926; Papp, 1939; Strausz, 1943; Dank, 1962; Horváth & Rumpler, 1984; Aničić & Jurriša, 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 Haloze.
Mura-Zala basin (Goričko, Slovenske Goricce, 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...
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, an 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; Durasek, 1988; Újszásvi & Vakárce, 1993). Sedimentation changed in style and decreased in amount in the latest Miocene, the Pliocene and Quaternary is characterised by thin terrestrial or fluviatile 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 magnetostatigraphic 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 (Újszászi & Vakárce, 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 (Podor 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 (Mártton et al., 1999, and in press), the Transdanubian Range (Mártton & Fodor, 2003) and the eastern part of the Eastern Alps (Mártton et al., 2000) and eventually the Istria peninsula (Mártton & 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 (Mártton, 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.

ACKNOWLEDGEMENTS

The research was carried out in the frame of a bilateral Slovenian-Hungarian research project (Slo-6/98) financed by the Hungarian Ministry of Education and Slovenian Ministry of Science and Technology. Seismic reflection lines and other data from the Mura Basin were kindly provided by the company Nafta Lendava. The research was supported by the Hungarian National Science Fundation T 22119 of Emo Mártón and T29798 of László Fodor and Slovenian Ministry of Science and Technology PO-0502-0215/99-00 of László Fodor and Slovenian Ministry of Education and Slovenian Ministry of Science and Technology (Slo-6/98) financed by the Hungarian National Science Fundation T 22119 of Emo Mártón and T29798 of László Fodor and Slovenian Ministry of Science and Technology PO-0502-0215/99-00 of László Fodor and Slovenian Ministry of.

REFERENCES

Anderson, E.M. 1951: The dynamics of faulting. 2nd ed. – Oliver & Boyd, 206 pp., Edinburgh.

Angelier, J. 1984: Tectonic analysis of fault slip data sets. – J. Geoph. Res., 89, B7, 5835-5848, Richmond.

Angelier, J. & Manoussis, S. 1980: Classification automatique et distinction de phases superposée en tectonique cassante. – C. R. Acad. Sc., 290, 651-654, Paris.

Anićić, B. & Jurjiša, M. 1985: Geological map of SFRJ 1:100 000, Sheet Rogatec. – Geol. Surv. of Ljubljana., Ljubljana, Geol. Inst., Zagreb, Federal Geol. Surv., Beograd.

Bada, G., Cloetingh, S., Gerner, P. & Horváth, F. 1998: Sources of recent tectonic stress in the Pannonian region: inferences from finite element stress modelling. – Geophys. J. Int., 134, 87-101, Oxford.

Báldi, T. 1986: Mid-Tertiary Statiigraphy and Paleogeographic Evolution of Hungary. – Akadémiai Kiadó, 293 pp. Budapest.

Balla, Z. 1985: The Carpathian loop and the Pannonian Basin: a kinematic analysis. – Geophy. Transactions, 30, 313-333, Budapest.

Bodzay, I. 1968: Stratigraphische und Palao-

geo graphische Skizze der Miocanablagenungen in Südwest-Ungarn anhand der Angaben von Tiefbohrungen auf Kohlenwasserstoffe. – Földtani Köz lóny, 92, 76-90, Budapest.

Csontos, L., Nagymarosy, A., Horváth, F. & Kovác, M. 1992: Tertiary evolution of the intra-Carpathian area: a model. – Tectonophysics, 199, 73-91, Amsterdam.

Dank, V. 1962: Sketch of the deep geological structure of the south Zala basin. – Földtani Köz lóny, 92, 150-159, Budapest.

Durasek, S. 1988: Some Results of Contemporary Geophysical Exploration for Oil and Gas in SR Slovenia (1963-1987). – Nafta, 39, 6, 211 – 326, Zagreb.

Flower, B. P. & Kenett, J. P. 1994: The middle Miocene climatic transition: in: East Antarcti c ice sheet development, deep ocean circulation and global carbon cycling. – Paleo 3, 108, 537-555, Amsterdam.

Fodor, L. & Koroknai, B. 2000: Tectonic position of the Transdanubian Range unit: A review and some new data. – Vjesti Hrvatskoga geolo{kog dru{tva, 27, 38-40, Zagreb.

Fodor, L., Jelen, B., Mártón, E., Skaberne, D., Čar, J. & Vrabec, M. 1996: Miocene tectonic evolution of the Periadriatic Zone and surrounding area in Slovenia: repeated dextral transpression. – Mitteilungen Gesellschaft Geol. Bergbauanst. Oesterreich, 41, 106, Abstracts, Wien.

Fodor, L., Jelen, B., Mártón, E., Skaberne, D., Čar, J. & Vrabec, M. 1998: Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic Line and surrounding area: a new model of Alpine-Carpathian extrusion–subduction. – Tectonics, 17, 690-709, Washington.

Fodor, L., Márton, E., Jelen, B., Báldi Beke, M., Kázmér, M. & Rifelj, H. 2000: Connection of the eastern Periadriatic and Mid-Hungarian zones and its implication to Paleogene palaoeography, Miocene extrusion tectonics. – Slovak Geol. Magazine, 6, 296-299, Bratislava.

Gosar, A. 1995: Modelling of seismic reflection data for underground gas storage in the Pečaroči and Dankovec structures–Mura depression. – Geologija, 37-38, 483-549, Ljubljana.

Haq, B., U. Hardenbol, J. & Vail, P. R. 1987: Chronology of Fluctuating Sea Levels since the Triassic. – Science, 235, 1156-1161, New York.

Horváth, F. & Rumpler, J. 1984: The Pan nonian basement: extension and subsidence of an alpine orogene. – Acta geol. Hung., 27, 229-235, Budapest.

Jelen, B., Anićić, B., Brezigar, A., Buser, S., Cimerman, F., Drohne, K., Monostori, M., Kedves, M., Pavlovec, R., Pavšič, J. & Skaberne, D. 1992: Model of positional relationships for Upper Paleogene and Miocene strata in Slovenia. In: A. Montanari, R. Coccioni, G-S. Odin (eds.), Interdisciplinary Geological Conference on the Miocene Epoch with Emphases on the Umbria-Marche Sequence. – Abstracts and field trips, 71-72, International Union of Geological Sciences, Subcommission on Geochronology, Ancona.

Jelen, B., Márton, E., Fodor, L., Báldi Beke, M., Čar, J., Rifelj, H., Skaberne, D. & Vrabec, M. 1998: Paleomagnetic, Tectonic and Stratigraphic Correlation of Tertiary Formations in Slovenia and Hungary along the Periadriatic and Mid-Hungarian Tectonic Zone (Preliminary Communication). – Geologija, 40, 325-331, Ljubljana.
Miocene to Quaternary deformation, stratigraphy and paleogeography in Northeastern Slovenia... 113

Kázemer, M. & Kovács, S. 1985: Permian-Paleogene Paleogeography along the Eastern part of the Intraoceno-Periadriatic Lineament system: Evidence for continental escape of the Bakony-Drau- zug Unit. – Acta geol. Hung., 28, 71-84, Budapest.

Kroli, A., Flügel, W. & Weber, F. 1980: Stereoches Becken – Südburgenlandsche Schwellen, Reliefkarte des präkarien Untergangs. 1:200 000. – Geol. Bundesanstalt, Wien.

Márton, E., Kuhlemann, J., Frisch, D. & Tomljenović, M. 1985: Tying the basalts from the Late Miocene Lake Pannon deposits. – Acta geol. Hung., 42, 5-31, Budapest.

Márton, E. 1985: Tying the basaltic from the Transdanubian Central Mountain to the standard polarity time scale. In: M. Kretzoi, M. & M. Pécsi (eds.), Problems of the Neogene and Quaternary. – Akadémiai Kiadó, 99-106, Budapest.

Márton, E. 1985: Tying the basalts from the Late Miocene Lake Pannon deposits. – Acta geol. Hung., 42, 5-31, Budapest.

Márton, E. & Fodor, L. 2001: Tertiary rotation sand faulting in the Transdanubian Range, Hungary. In: J. Szendroi J. (eds.), PANCARDI 2001, PO-64, 155-159, Bratislava.

Márton, E. & Jelen, B. 1997: Tertiary paleomagnetic results from S. Slovenia. – Annales Geophysics, Suppl. I vol., 15, C 108, Abstracts, Paris.

Márton, E. & Veljović, D. 1983: Paleomagnetism of the Istria peninsula, Yugoslavia. – Tectonophysics, 91, 73-87, Amsterdam.

Márton, E., Pavlic, D., Tomljenović, B., Pamic, J. & Márton, P. 1999: First paleomagnetic results on Tertiary rocks from the Slavonian Mountains in the Southern Pannonian Basin, Croatia. – Geologica Carpathica, 50, 273-279, Bratislava.

Márton, E., Kuhlemann, J., Frisch, W. & Dunkl, I. 2000: Miocene palaeomagnetic results in the Eastern Alps – paleomagnetic results from intramontane basin sediments. – Tectonophysics, 323, 163-182, Amsterdam.

Márton, E., Pavlic, D., Tomljenović, M. & Pavlic, R. 1999: Role of unconformity-bound units in the stratigraphy of the continental record: a case study from the Late Miocene of western Pannonian Basin, Hungary. In: B. Durand, L. Jolivet, F. Horváth, M. Séranne, (eds.): The Mediterranean Basins: Tertiary extension within the Alpine Orogen. – Geol. Soc. Spec. Publ., 156, 237-300, London.

Papp, S. 1939: The oil and gas exploration of the Magyar Amerikai Olaj Reszvénytársasag (Hungarian Oil Industrial Company Ltd.). – Bán- yásszati und Kiházasati Lapok, 72, 200-241, Budapest.

Pávai Vajna, F. 1926: A magyar szénhidrogénkutatás eddigi tudományos eredményei. – Bán- yásszati und Kiházasati Lapok, 59, 415-418, Budapest.

Placec, L. 1998: Structural meaning of the Sava folds. – Geologija, 41, 191-221, Ljubljana.

Plenčar, M. 1973: The possibility of oil deposits in the Hrvoje and Slovenes Goric hills. – Rudarsko-metalurški zbornik, 3, 192-195, Ljubljana.

Plenčar, M., Hinterlechner-Ravnik, A., & Faninger, E. 1990: Some tectonic elements and tectonic events on the SW margin of the Pannonian Basin. International symposium on the Geodynamic evolution of the Pannonian Bas- in. – Academic Conferences, 62. Dept. Natural and Math. Sciences, 4, 161-170, Serbian Acad. of Sciences and Arts, Beograd.

Pogácsás, Gy., Lakatos, L., Ujészászi, K., Vakarcs, G., Várkonyi, L. & Várnai P. 1988: Seismic facies, electro facies and Neogene sequences chronology of the Pannonian basin. – Acta geol. Hung., 31, 175-207, Budapest.

Rifelj, H. & Jelen, B. 2001: Do the Kar- patian and Badenian microforaminiferal faunas of Slovenia reflect global climatic and tectonic changes? – Geološki zbornik, 76, 34-41, Ljubljana.

Rijavec, L. 1996: Biostratigraphy of Miocene Beds from Slovenes Goric. – Geologija, 19, 53-82, Ljubljana.

Rögl, F. 1998: Paleogeographic Considerations for Mediterranean and Panthalassa seaways (Oli- gocene to Miocene). – Ann. Naturhist. Mus.Wien, 99A, 279-310, Wien.

Sacc, M., Horváth, F. & Magyari, O. 1999: Role of unconformity-bound units in the stratigraphy of the continental record: a case study from the Late Miocene of western Pannonian Ba- sin, Hungary. In: B. Durand, L. Jolivet, F. Horváth, M. Séranne, (eds.): The Mediterranean Basins: Tertiary extension within the Alpine Orogen. – Geol. Soc. Spec. Publ., 156, 237-300, London.

Sachsenhofer, R.F., Dunkl, I., Hasen- huttl, C. & Jelen, B. 1998: Miocene thermal history of the southwestern margin of the Styrian Basin: vitrinite reflectance and fission–track data from the Pohorje/Kozjak area (Slovenia). – Tecto- nophysics, 297, 17-29, Amsterdam.

Seljan, D. & Parlov, B. 1995: Strukturtene-ktenski odnosi na lokalitetima Vučkovec i Vuka- kozhcel. – Földtani Közlöny, 73, 649-651, Budapest.

Tari, G. 1994: Alpine tectonics of the Pan- nonian basin. – Ph.D. thesis, Rice University, 501 pp., Houston.
Tari, G., Horváth, F. & Rumpler, J. 1992: Styles of extension in the Pannonian Basin. – Tectonophysics, 208, 203-219, Amsterdam.

Tomljenović, B. & Csontos, L. 2001: Neogene-Quaternary structures in the border zone between Alps, Dinarides and Pannonian basin (Hrvatsko zagorje and Karlovac basin, Croatia). – Int. J. Earth Sci. 90, 560-578, Stuttgart.

Turk, V. 1993: Reinterpretation of chronostatigraphic and Litostratigraphic positions in the Mura depression. – Rudarsko-metalurški zbornik, 40, 145-149, Ljubljana.

Ujszászi, K & Vakár, G., 1993: Sequence stratigraphic analysis in the South Transdanubia region, Hungary. – Geophys. Transactions, 38, 69-87, Budapest.

Van der Zwaan, G.J., Jorissen, F.J., de Stigter, H.C. 1990: The depth dependency of planctonic/benthic foraminiferal ratio: Constraints and applications. – Marine Geol., 95, 1-16, Amsterdam.

Vončina, Z. 1965: Geotectonic division of the Mura-river depression. – Nafta, 1, 1-3, Zagreb.

Völgyi, L. 1956: Miocén uledékek kifejlődése a Lováski mélyfúrásokban. – Földtani Közlöny, 86, 139-150, Budapest.

Vrabec, M. 2000. Late Miocene to recent tectonics south of the Periadriatic line: strike-slip deformation of Central Slovenia. – Vjesniki Hrvatskoga geološkog društva, 37, 3, 130-131, Zagreb.

Vrabec, M. 2001: Strukturna analiza cone Savskega preloma med Trstenikom in Stahovico. – Ph.D. thesis, Univ. Ljubljana, 94 pp., Ljubljana.

Znidarčič, M. & Mioč, P. 1988: Geological map of SFRJ 1:100 000, Sheet Maribor and Leibnitz. – Geol. Survey of Ljubljana, Ljubljana, Federal Geol. Survey, Beograd.