The Geometry of the South Leading Carpathian Thrust Line and the Moesia Boundary: The Role of Inherited Structures in Establishing a Transcurent Contact on the Concave Side of the Carpathians

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Abstract The NW-most corner of Moesia offers the possibility to unravel the structural architecture as well as the kinematic characteristics of a highly-bent contact between an orogenic nappe pile and its foreland plate. The major fault system, dominantly transcurent that accommodated during the Tertiary the displacement and rotation of the Latest Cretaceous Carpathian orogenic wedge around the Moesian corner had originated from a passive margin stage when W-E to WNW-ESE extensional faulting predated the formation of the Late Jurassic Severin oceanic crust. In the NW-most Moesia, these old structures are cut by an E-W-trending major normal fault system which accommodated the Late Oligocene (?) - Burdigalian dextral movements of the Carpathian units along the Timok lineament. Structural evidence shows that this initially rather straight N-S dextral transfer fault evolved into a curved anastomozed system parallel to the present-day shape of the orogen not earlier than the Middle Miocene. This was at the time when the Carpathian units commenced to rotate around the Moesian corner along the original Timok and one of the major E-W-trending normal faults. Farther ENE- to E-wards displacement of the Carpathian units along the northern margin of the Moesian plate induced an oblique inversion of the Mid-Tertiary extensional basin by peeling-off E-SE-wards its sedimentary fill. Overall, the inversion created a duplex-style system that changes E-wards to a major plan-view wedge bounded by a NW-SE dextral tear fault passing gradually to the thin-skinned Subcarpathian nappe. In this contribution we stress the role of inherited structural weaknesses within the foreland plate in the creation of a transcurent contact.

Keywords. Transcurent fault, Thrust belt, Plate boundary, Carpathians, Moesia, Timok Fault

1 Introduction

One of the most arcuate segments of the Alpine chain is represented by the South Carpathians where the strike of the orogen changes from E–W to N–S and then again E–W to the Balkans (Fig. 1). The present-day structure of the Carpathian system is the result of a long-lasting evolution that included periods of:

a) lithospheric stretching and break-up;
b) plate convergence and collision;
c) orogen-parallel extension and core-complex formation;
d) rotation and wrenching;
e) basin opening and inversion (e.g. Sandulescu, 1984).

Following the Mid-Cretaceous subduction of the entire Severin oceanic crust which had separated during at least Late Jurassic-Early Cretaceous two pieces of lithosphere derived from the European margin (Dacia and Moesia), the ongoing contraction led eventually to the overthrusting of the Supragetic/Getic/Severin nappe assemblage onto the distal Moesia (exposed presently as the Danubian Autochthonous unit). It also generated duplex formation inside the latter by Late Cretaceous times (e.g. Sandulescu, 1984; Iancu et al., 2005). The further Tertiary kinematics is rather complex, however the overall picture of mechanisms of the tectonic transport of the Carpathian units towards the present-day position around the Moesia corner is generally accepted (e.g. Ratschbacher et al., 1993; Schmid et al., 1998).

The present-day South Carpathians are flanked by a deep foreland basin that has been deformed in response to the progressive movement of orogenic slices around the Moesian western corner. This foreland basin differs significantly from typical foredeeps because the flexural loading of the foreland lithosphere played only a subordinate role in its subsidence (Rabagia and Matenco, 1999; Tarapoanca, 2004).

In this contribution we focus on the South Carpathians Thrust Belt / Moesia boundary and especially on the NW corner of Moesia (Fig. 1), aiming to describe new details concerning the geometry of the contact as well as the tectonic evolution. Our study is mainly based upon the interpretation of new seismic lines acquired mid-2005 across the northern part of the Timok lineament and inside the neighboring basin. They are supplemented by re-interpreted information from older surveys and wells previously drilled within a concession currently explored by Rompetrol. The subsurface data were particularly useful as the contact between the South Carpathians and Moesia is

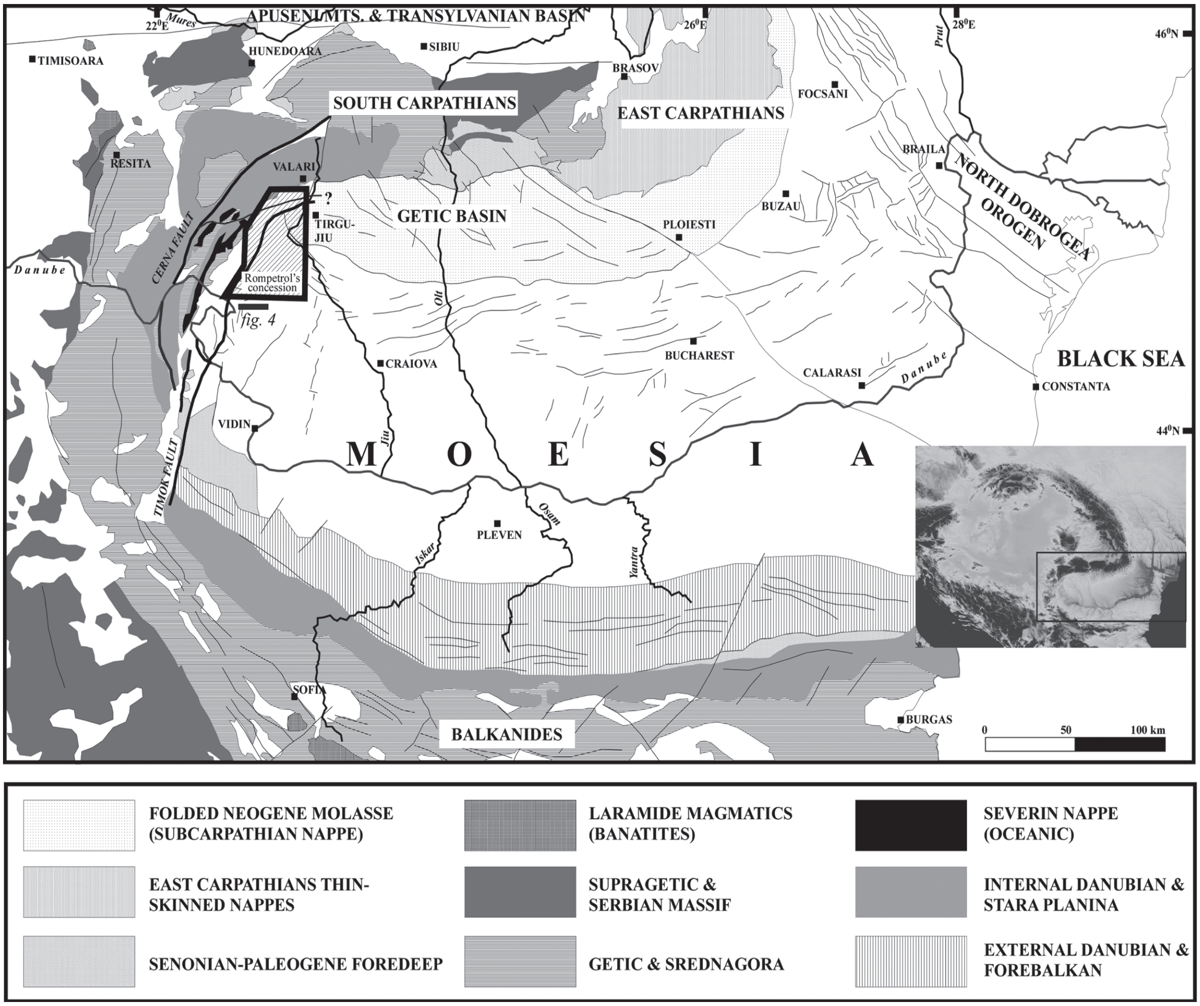


Fig. 1. Major structural units of the Carpato-Balkan thrust belt (modified from Sandulescu, 1988; Tari et al., 1997 and Iancu et al., 2005). The structures from Getic Basin are schematically drawn after Rabagia and Matenco (1999) and those from Moesia (north of Danube River) are taken from Tarapoanca (2004). The Pliocene fill over Moesia and Carpathians was ignored. The thick E-W black line in the westernmost part of Moesia represents the location of the interpreted seismic line shown in Fig. 4. The inset map only shows the topography of the East Alpine-Dinarides-Carpathians realm. The location of our study (NW Moesia) is indicated by the outline of the Rompetrol's concession.

hidden by the Neogene sedimentary fill which onlaps onto a Getic klippe to the south and directly onto the Danubian Autochthonous to the north (Fig. 1).

We shall argue that the geometry of the contact between the orogen and foreland is largely controlled by an extensional fault system formed presumably prior to the creation of the oceanic lithosphere (Severin domain). The integration into a regional tectonic framework of the architecture of this older system will result in our sense in a significant advancement to the knowledge of the relationship between the South Carpathians and Moesia. We have devoted particular attention to the impact of the transcurent displacement of the orogenic units upon the Moesian foreland, particularly the opening of an extensional basin during the Late Oligocene (?) – Burdigalian (hereinafter named Mid-Tertiary). Eventually, the structural setting of the NW Moesian basin is briefly discussed from the standpoint of petroleum systems aiming to shed light on further exploration options.

2 Disruption of the Cretaceous Carpathian Areas: Synthesis of the Tertiary Tectonics

We shall describe in this section the main deformation stages taking place in both the westernmost Moesian realm and the Carpathian nappe pile after they became welded together in Late Cretaceous times. Significant advances in the understanding of many

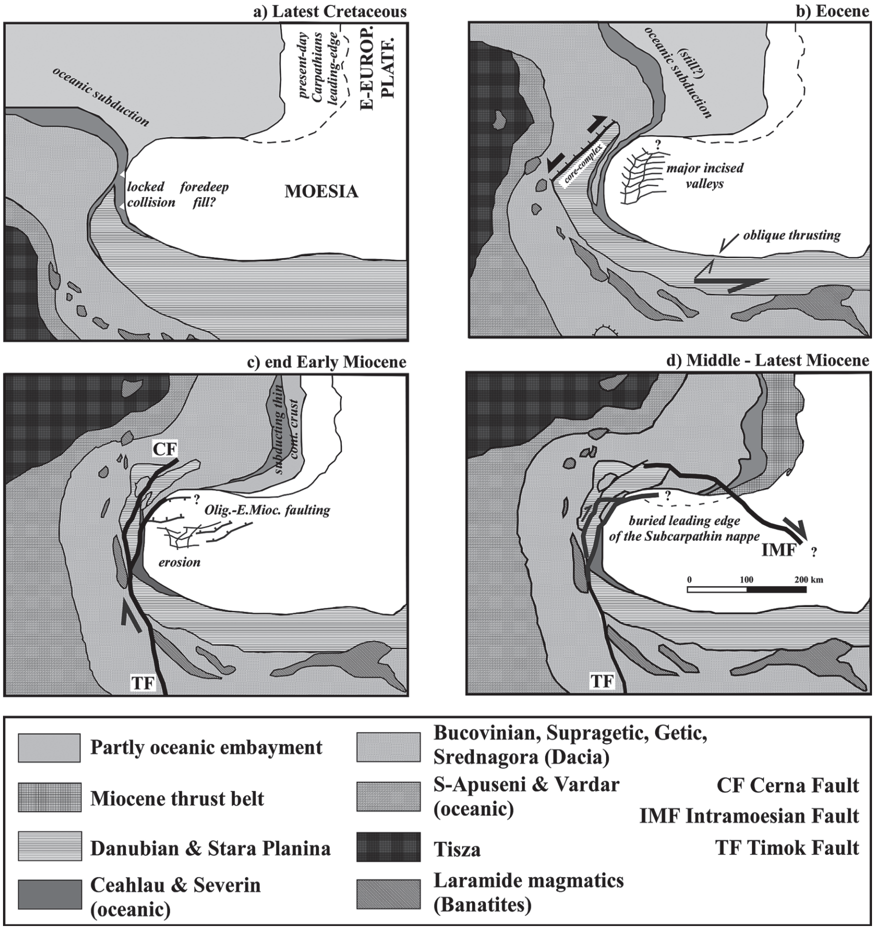


Fig. 2. Schematic reconstructions of the Carpathians / Moesia major events postdating the Latest Cretaceous collision. The figures are largely based upon Fig. 9 of Fugenschuh and Schmid (2005) with additional information on Moesia from Tarapoanca (2004) and present contribution.

of the peculiarities of this curved orogenic boundary were published in the last decade and derive mainly from structural and fission-tracks studies carried out in the South Carpathians by, e.g., Ratschbacher et al. (1993), Schmid et al. (1998), Matenco and Schmid (1999), Rabagia and Matenco (1999), Willingshofer et al. (2001), subsequently integrated at orogenic scale by Fugenschuh and Schmid (2005). Their regional picture is employed as the main source for the next overview of the Tertiary evolution.

Palinspastic restoration of the Tertiary convergence brings the Carpathian units next to the westernmost part of Moesia by the Latest Cretaceous, facing to the north an oceanic embayment which was completely subducted during the Paleogene (Fig 2a). Remnants of the associated Latest Cretaceous-Paleocene foredeep are found exposed to the SW and N (Fig. 1) as well as in the subsurface of the Getic Basin, while in westernmost Moesia they were largely removed by the subsequent erosion. This erosion which created deep canyons (Paraschiv, 1997; Tarapoanca, 2004) was presumably mostly Eocene in age and coeval, possibly genetically-related, with an orogen-parallel extension leading to core-complex formation in the Carpathians (Fig. 2b) and with the sinistral shortening in the E-W segment of the Balkanides (Doglioni et al., 1996).

The tectonic transport of the Carpathians around the Moesian corner during the Oligocene was mostly accommodated by dextral wrenching of some 35 km along the Cerna Fault (Berza and Draganescu, 1988, Fig. 2c). The movement continued during the Early Miocene when the accommodating structure became the more externally Timok Fault. The Timok Fault took over some 65 km of dextral displacement (cf. Moser, 2001 in Fugenschuh and Schmid, 2005). Contemporaneously to the transcurrent movements of the orogenic slices, normal faulting and basin opening occurred in the northern Moesian margin (Rabagia and Matenco, 1999) when still some erosion was probably active on the distal, southern Moesia (Tarapoanca, 2004). Moreover, the orogenic nappe pile itself seems to be severely affected by normal faulting as well (Matenco and Schmid, 1999; Fugenschuh and Schmid, 2005).

Starting with the Middle Miocene, the transport of the Carpathian units has further changed to a more ENE-to-E-wards orientation (Hippolyte et al., 1999), with several E-W and NW-SE dextral faults cutting through the nappe pile and the foredeep fill (Matenco et al., 1997; Rabagia and Matenco, 1999; Matenco and Schmid, 1999). Overall, the Getic Basin or the "Getic Depression" as known in older Romanian literature (i.e., the early foredeep fill of the South Carpathians) has undergone oblique shortening culminating with the emplacement of the Subcarpathian Nappe (Fig. 2d).

3 Geometry of the Orogen / Foreland Boundary and Overview of the Basin Structure

The structural pattern of the NW-most Moesia, as shown in Fig. 3, mainly resulted from the interpretation of several hundreds of kilometers of 2D seismic lines including 250 line km acquired in the summer of 2005. The most striking feature is represented by the sizeable difference in elevations of the base Tertiary (Fig. 3a) across the Timok Fault that ranges from several hundreds of milliseconds to more than 2 seconds TWT (corresponding to around 2.5–3 km!). The Timok Fault system is parallel to the present concave bend of the South Carpathians and marks the western limit of a basin that hosts several kilometers-thick sediments mostly of Neogene age. In our study area, the basin floor represented by the regional erosional unconformity that is developed on top of the dominantly carbonatic (Upper Jurassic - Cretaceous) Moesian platform, deepens from around 1.3 s (~ 1.5 km) in the south to more than 5 s (~ 6.5 km) in the NE.

To the east of the Timok Fault, two roughly perpendicular, normal fault systems are mapped:

1. The E-W-oriented one that has the largest offsets at the basin bottom (Fig. 3a) and is mostly Mid-Tertiary in age;
2. The N-S to NE-SW older system (Fig. 3b) that originates presumably from the Permo-Triassic rift-

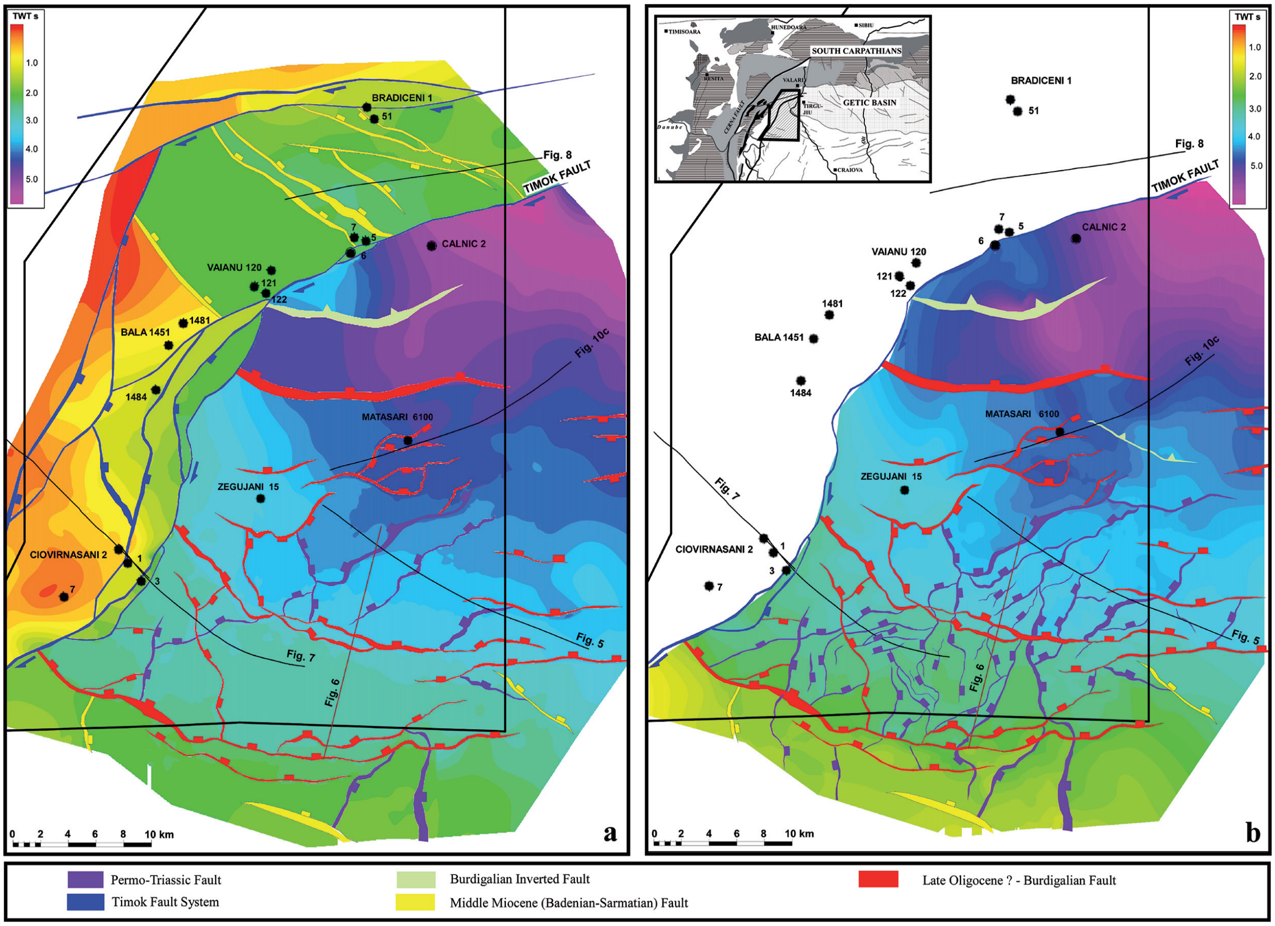


Fig. 3. Structural maps (TWT) of the top of the Moesian platform – base Tertiary unconformity (**a**) and base syn-rift (Paleozoic?) horizon (**b**). Note that the color bar in a. is different from that in b. The location of the seismic lines used in some figures is also shown. Maps location is shown in Fig. 1.

ing associated to a passive margin stage. Some of these old faults were slightly rejuvenated during the younger faulting stage (compare Fig. 3b with 3a). The map at the base of the old syn-rift horizon (Fig. 3b) shows basins sometimes as deep as 1 s (over 1 km).

The superposition of these orthogonal extensional events unsurprisingly led to a highly complicated structural style of the NW Moesia (e.g. Fig. 3b). The detailed structural pattern and formation mechanisms are to be discussed below, with the older system addressed first.

3.1 Western Moesia as a Mesozoic Faulted Passive Margin

The Timok Fault has been for some time proposed as a transcurent, loose boundary between the South Carpathian Cretaceous nappe pile and Moesia (e.g. Sandulescu, 1984, 1988). So far, this boundary has been generally seen as separating (Fig. 1) a piece of the basically undeformed continental lower plate (Moesia) from an assemblage that contains remnants of the upper plate (Supragetic/Getic nappes and Balkanides equivalents), a suture (Severin domain, made up of fragments of oceanic lithosphere and overlying Uppermost Jurassic – Lower Cretaceous flysch sediments) and the so-called Danubian Autochthonous. The last is nothing but the distal underthrust margin of Moesia duplicated in the aftermath of Cretaceous collision (e.g. Sandulescu, 1984; Iancu et al., 2005).

Although any creation of oceanic lithosphere implies previous stretching (rifting) of the continental lithosphere, in this case, Moesia had long time “appeared” as lying far from the ancient locus of the rifting. The closest rift that pre-dated the “Severin” spreading was seen located a few hundreds of kilometers to the SE (central-southern Moesia, Tari et al., 1997) and only the wrenching seemed to be responsible for bringing the South Carpathian nappe pile next to the unstretched Moesia (e.g. Ratschbacher et al., 1993). However, very recently, Matresu and Dinu (2004) identified a series of N-S trending extensional basins (Fig. 4) in the westernmost part of Moesia, developing on a quite limited length of around 25 km. A system of E-dipping normal faults bounds half-graben basins which are capped by an erosional unconformity. Although deep well evidence is scarce enough, Matresu and Dinu (2004) tentatively assigned the syn-rift fill of those basins to a Lower Paleozoic age.

Alternatively, we propose in this paper that the age of the E-W extension is most likely Permian (?) - Triassic as similar to that previously proposed for most of the central Moesia (Tari et al., 1997; Rabagia and Tarapoanca, 1999), supported also by the quite widespread coevally bimodal volcanism (e.g. Paraschiv, 1979). We thus consider the N-S trending extensional basins in the western Moesia as resulting from a regional rifting event that pre-dated the onset of spreading and creation of the Severin oceanic crust. Accordingly, the regional unconformity that develops

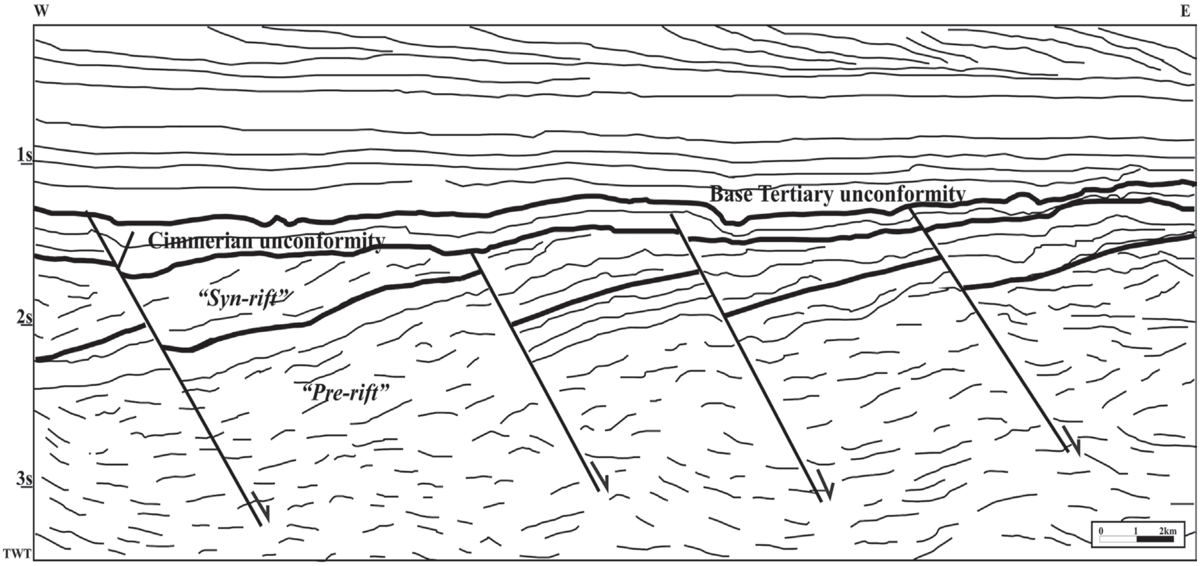


Fig. 4. E-W interpreted seismic line in westernmost Moesia (modified after Matresu and Dinu, 2004). Note that the normal faults bounding the half-grabens are slightly reactivated as proved by the offset of the Cimmerian unconformity. Line location is shown in Fig. 1

in those basins (Fig. 4) should be mostly Lower Jurassic in age being similar to the Cimmerian unconformity of Tari et al. (1997) and supported by the large well database of Moesia (e.g. Paraschiv, 1979). It may represent in fact either a break-up unconformity related to the onset of "Severin" spreading or the expression of a partial inversion and uplift due to slow stretching-related rift migration as proposed for the mid-Norwegian margin by van Wijk and Cloetingh (2002) in an attempt to model the occurrence of local contraction in the context of overall extension.

Significant for unraveling the configuration of the western Moesian passive margin, we have identified the extension farther north of these N-S basins, however in a more complex structural style. They are represented in Fig. 3b by the N-S normal fault system that progressively changes the orientation to NE-SW, which is subsequently truncated by a younger E-W system. Some of these old faults were slightly reactivated in the Mid-Tertiary, as shown in Figs. 4, 5 and 6. Although there are no wells that penetrated the base Tertiary unconformity in our study area from the NW Moesia, the structural style imaged by the seismic lines (Figs. 5 and 6) looks very similar to those shown elsewhere in Moesia. Transfer zones make the transition between E- and W-dipping normal faults (Fig. 3b) giving a general configuration of basins and ranges. It thus appears that the more oriented towards an E-W direction, the more prone to be reactivated were these ancient faults during the later N-S extension.

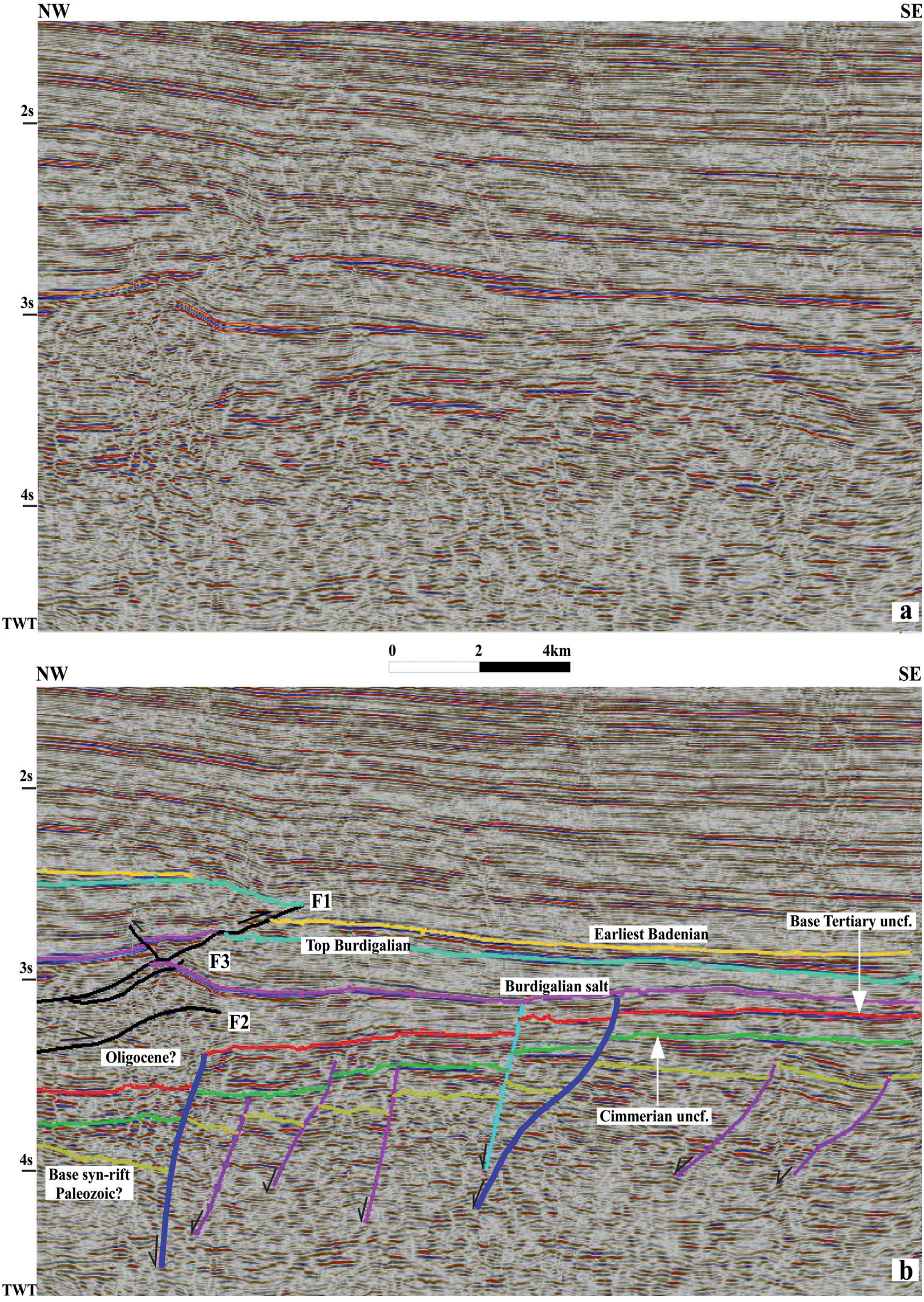
3.2 Timok Fault System and the Edge of the Cretaceous Orogenic Pile

In contrasts to the parallel, outcropping dextral Cerna Fault, which was active mainly during the Oligocene times (Berza and Draganescu, 1988; Ratschbacher et al., 1993), the Timok Fault had a longer tectonic activity. Outcropping only to the south of Danube River, the Timok Fault becomes progressively buried towards north by the Upper Miocene - Pliocene sediments (Fig. 7). It shows up as an impressive flower structure separating the uplifted outer part of the Getic/Severin nappe welded to the Danubian Autochthonous from the deep basin formed onto the Moesian lithospheric plate in the Mid-Tertiary. All the Cretaceous thrust sheets die out at the base Tertiary erosional unconformity. An erosional remnant overlying the base Tertiary unconformity, possibly Badenian in age, correlated also with the thickening of the Sarmatian sequence within the basin witnesses a stage of significant vertical differential movements across the Timok Fault during this time span.

On the map (Fig. 3a), the Timok Fault system has a curved shape, parallel to the belt curvature. However, despite the apparent continuity of the "present-day" Timok Fault, we will show in 3.4 that the curved shape of this system of faults resulted progressively not earlier than the Middle Miocene (Badenian - Sarmatian) by the merging of the original Timok with the northernmost extensional fault into an anastomosed dextral shear zone. Also then, the northern NW-trending faults bounded by the Timok Fault and another roughly E-W strike-slip (Figs. 3a and 8) were formed.

All along the curved contact between the South Carpathians and Moesia (to the north of Danube River), the Timok lineament clearly separates remnants of the Latest Cretaceous orogenic wedge from the Tertiary basin, as further indicated by the seismic line from Fig. 8. The high-amplitude W-wards dipping reflectors are interpreted as the top of the Danubian Autochthonous based upon the correlation with a perpendicular seismic line and farther north, with the outcropping units. To the easternmost part of the line, a thrust of the Getic crystalline is proposed, which would represent the southern prolongation of the Valari klippe (shown in Fig. 1). We believe that the thick reflectors package between the base Tertairy unconformity and Danubian Autochthonous is essentially a deformed pile of Late Cretaceous flysch. Apparently, two other thrust sheets underlie the Getic klippe, which we ten-

Fig. 5. NW-SE oriented seismic line (a. uninterpreted and b. interpreted) in the NW Moesia (location in Fig. 3). The magenta-colored faults are supposedly related to the Permian - Triassic extension (note the tilted block configuration eroded beneath the Cimmerian unconformity and compare with figure 4). A few of them were reactivated in Mid-Tertiary times (dark blue faults) when a new, orthogonal fault system was formed (light blue faults). The Cimmerian unconformity is believed to underlie a Middle Jurassic dominantly shaly (source-prone) sequence followed by an Upper Jurassic - Cretaceous dominantly carbonate platform as elsewhere in western-central Moesia. The base Tertiary unconformity is covered by a sedimentary sequence mostly Early Miocene (Burdigalian) in age. The Burdigalian salt layer is well constrained in a well (Matasari 6100 – the deepest from our study region, see Fig. 3, disposing also of a checkshot) and readily correlable due to its high amplitude and continuity at regional scale. Generally, in the Getic basin (and all along the Carpathian foredeep) the Burdigalian salt (up to several tens of meters-thick, thicker only in diapirs risen in the SE Carpathians bend area) follows an Uppermost Oligocene – Lowermost Burdigalian pelitic sequence. As the syn-rift sequence becomes increasingly thicker towards north (center of the basin), we suppose that the early syn-rift may be represented by Oligocene sediments (also reported all along the northern margin of the basin and also inside the basin farther to the east). Note the low-angle thrust initiated during the Middle Miocene (Badenian) as proved by the age of the piggy-back basin fill. F1, F2, and F3 denote faults which are mapped in Fig. 10d. ▶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Oligocene?
Cimmerian uncf.
Base syn-rift
Paleozoic?
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tatively assign to the Severin nappe and to a duplex inside the Danubian Autochthonous. Nevertheless, the along-arc correlation of the tectonic units is not straightforward made, as they appear highly disrupted and eroded due to the Eocene core-complex formation (Schmid et al., 1998) prior to the onset of wrenching.

We consider that Timok Fault originates from the ancient Permian - Triassic rifting event that pre-dated the creation of the Severin oceanic crust. Giving the roughly N-S orientation of this fault system (Fig. 3b), it is likely to consider that one of them acted as a significant weakness crustal zone that favored the localization of the strike-slip deformation. Moreover, such a fault system (Figs. 4, 5 and 6) would explain why the Triassic deposits that can be found on Moesia (e.g. Paraschiv, 1979; Tari et al., 1997) and the most external part of the Danubian Autochthonous (Fig. 7) are missing on the distal part of the latter where the metamorphic basement is overlain by Jurassic formations only (e.g. Iancu et al., 2005).

3.3 Mid-Tertiary Structural Style: (Another) Basin Opening

A major extensional event took place during the very beginning of the Early Miocene and probably since the Late Oligocene when the E-W-trending normal faults shown in Figs 3a and b were initiated. Steep and generally N-dipping (Fig. 6), these normal faults have sometimes vertical offsets more than 1 s (over 1 km). Crosscutting the ancient rifted passive margin, they are also part of a system with several transfer zones. Many of the Mid-Tertiary faults seem to have cut preferentially through the transfer zones of the older system. Although within the basinal part of the sector from our study area no well has penetrated the entire Early Miocene section, a minimum thickness of 1.5 km is derived from the deepest one (Matasari 6100, Fig. 3). This E-W normal fault system was also identified farther east to our study area beneath the present-day Getic Basin where the Mid-Tertiary basin subsequently underwent inversion (Rabagia and Matenco, 1999). Also, in the region lying approximately between the Jiu and Olt rivers (Figs. 1 and 2c), ENE-WSW normal faults dying-out at the top platform erosional unconformity were assigned to the same Mid-Tertiary rifting event by Tarapoanca (2004).

The western extent of the Mid-Tertiary rifting is clearly stopped by the Timok Fault as shown in Fig. 3a. On the western side of the Timok Fault there are either basically no corresponding Mid-Tertiary sediments or at least thin (much thinner than in the basin) coarse sequences as the few wells propose ambiguous dating due to the lack of fauna. However, to the north of the present Timok system, the Oligocene and Early Miocene sequences were reported (Vaianu and Cilnic wells, Fig. 3), with thicknesses in the order of tens to a few hundreds of meters. Based upon the structural and thickness pattern of the Mid-Tertiary sequence in the neighboring basin, we propose that the Timok Fault functioned during the Early Miocene (and possibly since the Late Oligocene) as a major transfer fault accommodating to the east the displacement of the Carpathian units via a N to NNE-directed extension (Fig. 9). Furthermore, it appears that not only the foreland but also the orogenic pile was then affected by significant faulting, as described by Matenco and Schmid (1999) and Fugenschuh and Schmid (2005). We can thus infer that from the Oligocene to Early Miocene the tectonic transport of the Carpathian units was progressively transferred from the inner to outer accommodating structures, that is, from wrenching along the Cerna Fault to along the Timok Fault.

Within a larger regional framework, the Mid-Tertiary displacement of the Carpathian units was coeval to the north with shortening in the Pienides (Sandulescu, 1984, 1988) and retro-foredeep formation on the Transylvanian northern margin (e.g. Huismans et al., 1997). This would imply a contemporaneously pure dextral strike-slip to oblique shortening in the East Carpathian evolving wedge (as speculated by Matenco, 1997) in contrast to a pure frontal shortening, postulated for a long time (e.g. Sandulescu, 1984, 1988).

3.4 Middle Miocene Onwards: Basin Inversion

The Middle Miocene marks the onset of compression within the Getic Basin (Fig. 1) with a climax in the Middle Sarmatian given by the emplacement of the Subcarpathian Nappe (e.g. Sandulescu, 1984, 1988). This onset is indicated by the deposition of Badenian evaporites in piggy-back basins over large parts of Getic Basin (Rabagia and Matenco, 1999). The inversion of the former basin should be seen as the effect of oblique compression exerted on the northern margin of Moesian lithosphere by the ENE to E-wards displacement of the Carpathian units (Fig. 2d).

Although the Subcapathian Nappe was apparently mapped (e.g. Dicea, 1995; Rosu, 2005; Figs. 10a, b), the definition of its western termination in the vicinity of Jiu valley (Fig. 1) is still a matter of debate. For a long time it was considered as continuing west of Jiu valley more or less parallel to the South Carpathian bend (e.g. Paraschiv, 1979; Sandulescu, 1984, 1988), but recently it was interpreted as terminating towards the NW in a wide and deep-rooted strike-slip zone which displaces also the northern extensional margin (Matenco et al., 1997; Rabagia and Matenco, 1999).

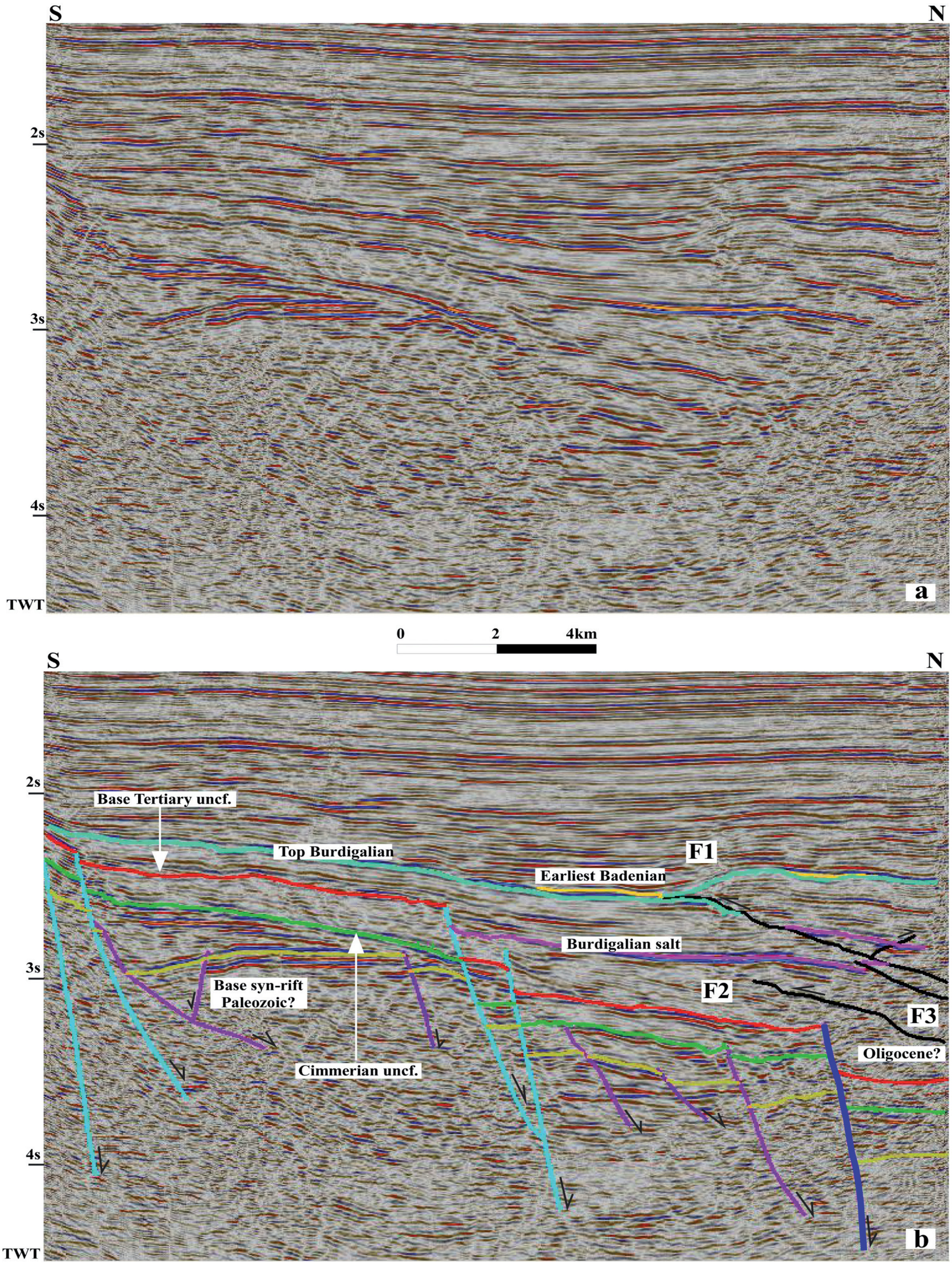

Fig. 6. N-S oriented seismic line (**a** uninterpreted and **b** interpreted) in the NW Moesia (location in Fig. 3). Note the magnitude of the Mid-Tertiary normal faulting (light blue faults). Also note the conspicuous faulted and tilted block eroded under the Cimmerian unconformity. Other symbols as in Fig. 5.

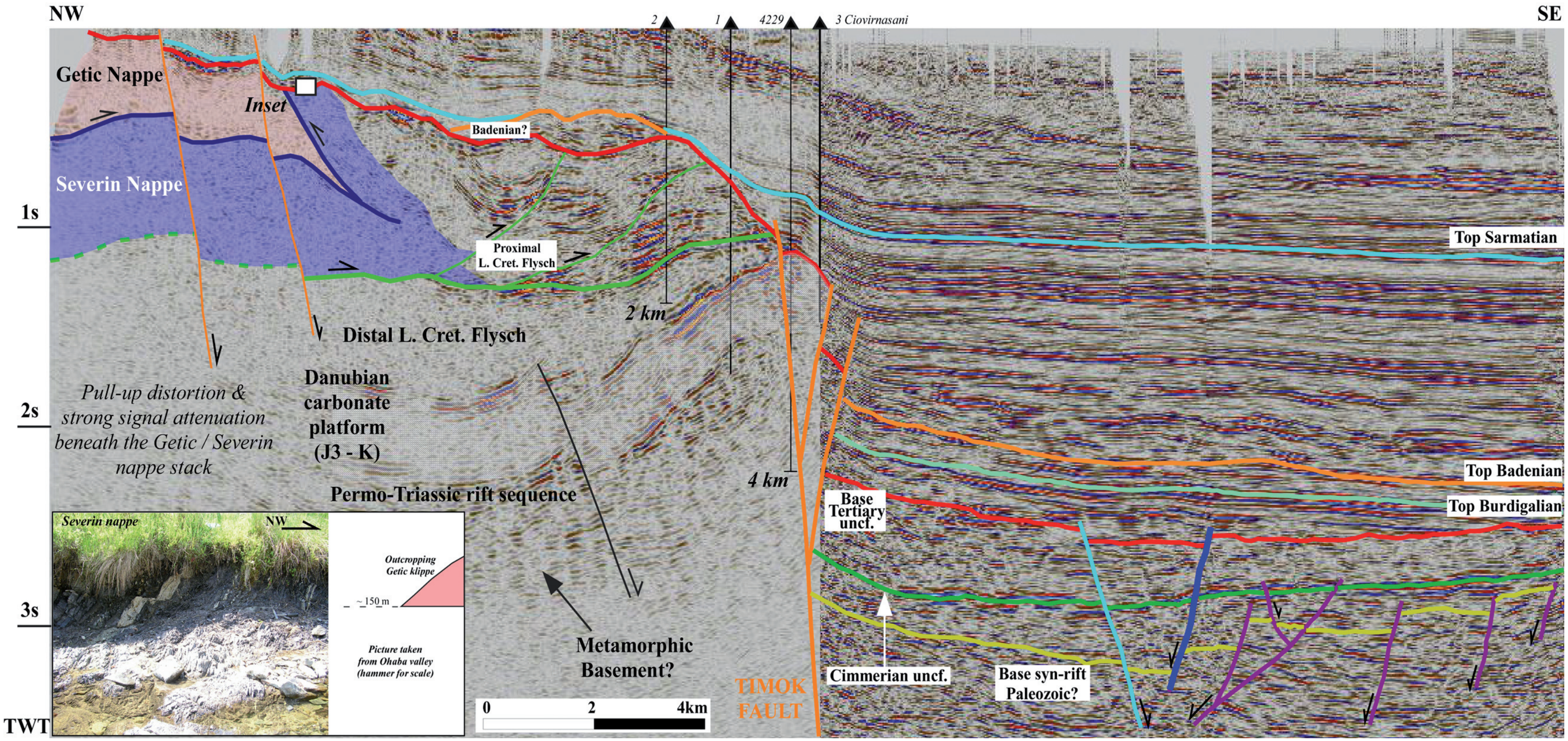

Fig. 7. NW-SE oriented seismic line across the outermost South Carpathians nappe pile, Timok Fault and the deep Moesia (location in Fig. 3). The overthrust sequence labeled as "proximal L. Cret. flysch" onlaps onto a sliver of Severin nappe forming a triangle zone, which can be also observed in outcrops (note the picture taken from a valley at ~ 1 km north from the seismic line). This sequence is made up of predominantly coarse-to-medium grained sediments which were tentatively assigned to either Early Miocene or Eocene age (e.g. Motas, 1981) as no concluding fauna had been recovered. We re-interpret it as a Late Cretaceous proximal sequence thrust over its distal equivalent which is a microfauna-bearing finer sequence. Dark blue and green thrusts are Mid- and Late Cretaceous in age, respectively. Other fault colors as in Fig. 5. Note also the impressive vertical offset across the Timok Fault. Significant movements along the Timok Fault took place mainly during the Early Miocene and Middle Miocene (Sarmatian) indicated by the thickening of these sequences E-wards, inside the basin. The position of the top Badenian reflector is also constrained through correlation with the well Zegujani 15 (located in Fig. 3)

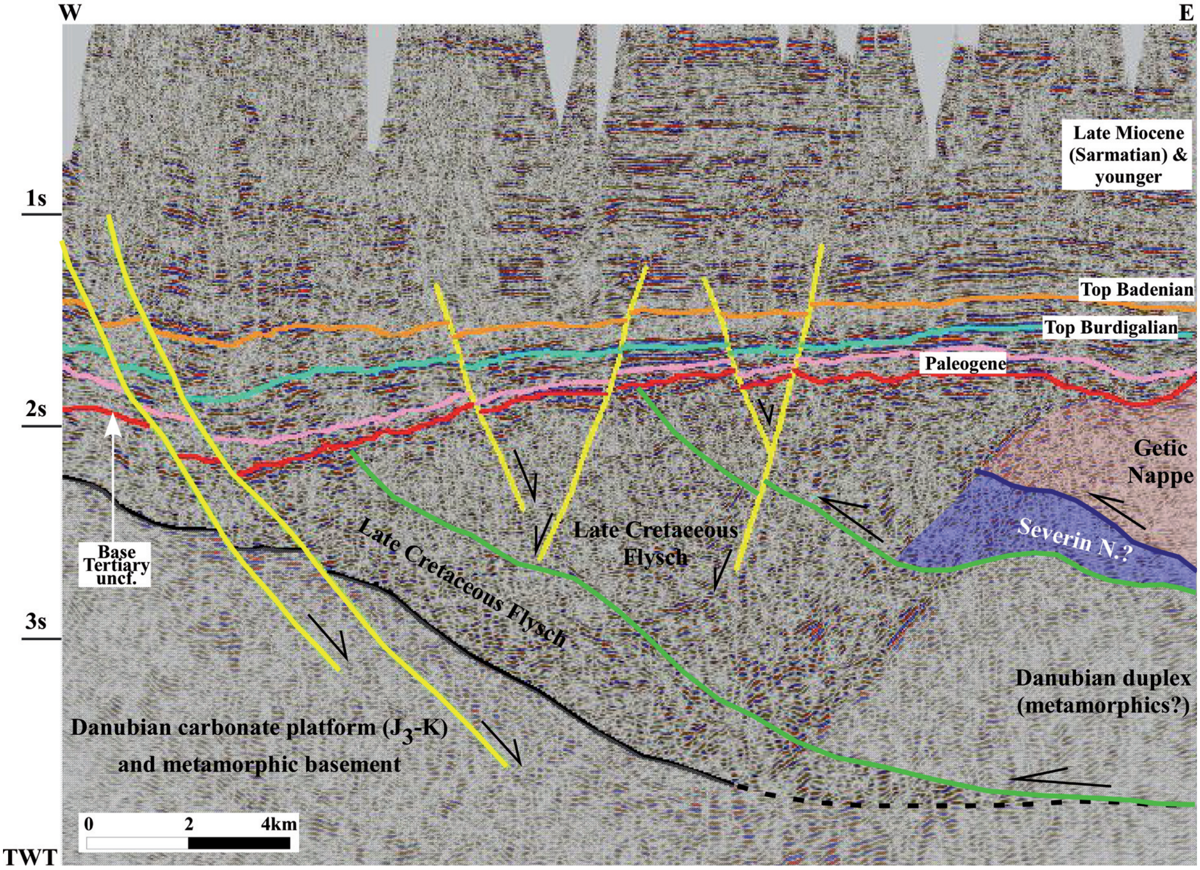

Fig. 8. E-W oriented seismic line, north of the Timok Fault (location in Fig. 3). This line is acquired across the basin margin and images structural units belonging to the Carpathian orogenic pile, similar to those from the western part of line 7. Thrust colors as in Fig. 7. Yellow faults are related to the Middle-to-Late Miocene transtension.

This paper brings new information that differs from the previous cited interpretations. Still supporting the strike-slip model, Fig. 10c shows indeed a major tear fault that represents the westernmost continuation of the Subcarpathian Nappe. However, in our interpretation, it is only a thin-skinned structural feature similarly to the nappe itself. To the NW, this strike-slip fault connects to an E-W former normal fault whereas to the SE, it progressively changes the dip until passing into the Subcarpathian leading thrust.

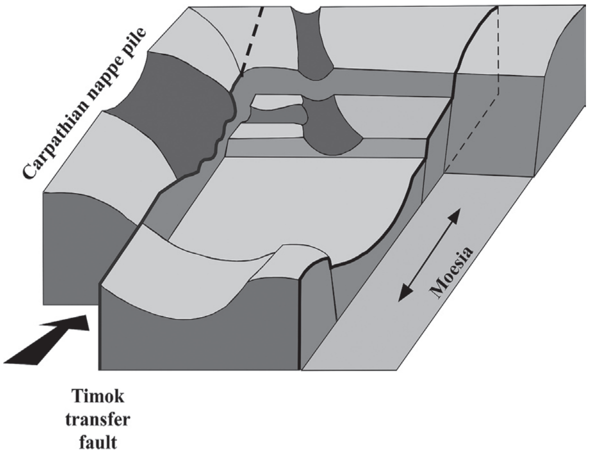

Fig. 9. Sketch of the kinematics of the basin opening during Mid-Tertiary

In premiere, we found evidence of inverted structures as well as of a thin-skinned thrust fault system to the west of the edge of the Subcarpathian Nappe (Figs. 3a and 10d, respectively). Thrust faults involving mostly the Early Miocene (Burdigalian) sediments are also shown in the seismic lines from Figs. 5 and 6. Except for the westernmost one, these thrusts have roughly NE-SW orientation (Fig. 10d). The shortening along the main thrust (the uppermost one, F1) increases from null to almost 1 km towards the NE. There, the structural style becomes more complicated with another thrust (this one WNW-ESE oriented, F4) found beneath, which confers a duplex-type shape (Fig. 10d).

The previously described Timok Fault system (Figs. 3 and 7) appears as being strongly active dur-

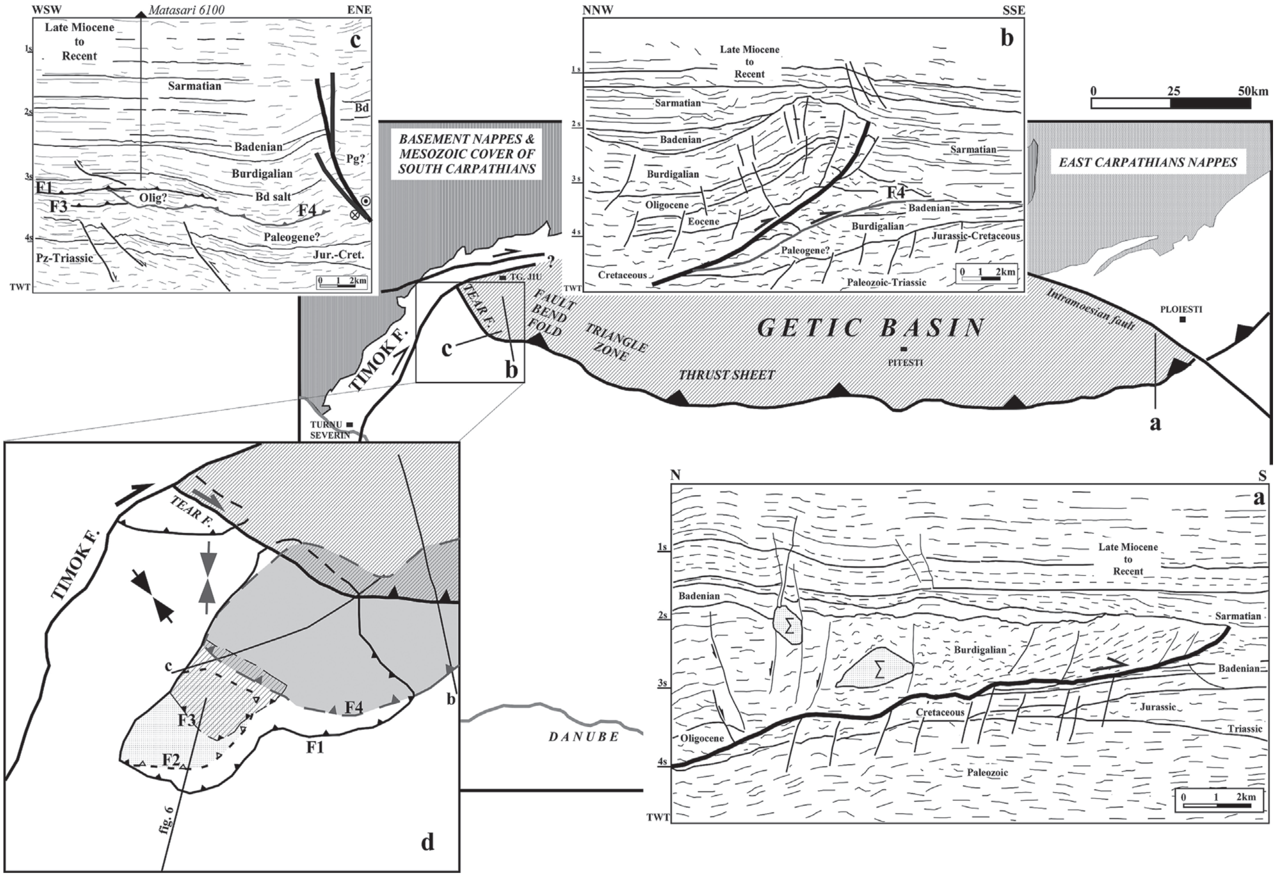

Fig. 10. The structural style of the Subcarpathian Nappe (**a** and **b** are interpreted seismic lines modified from Dicea, 1995 and Rosu, 2005, respectively). Although originally the *line a* was described as imaging the westernmost part of the external thrust sheet of the East Carpathians (Dicea, 1995), in fact it lies to the west of the Intramoesian fault (Tarapoanca, 2004), which is the structural limit between the South and East Carpathians foredeeps. The seismic line shown in **c** evidences a steep shear zone that is interpreted as a dextral tear fault which connects to the leading edge of the Subcarpathian Nappe separating a western domain of relatively minor contraction from an eastern highly shortened one. The subhorizontal thrust planes (barbed thick lines) shown in **c** are faults intersected at small angle by the seismic profile. Also shown in **c** is the deepest well from our study area (bottomed at ~ 5 km). Note in **a** that contraction continued after the Sarmatian main phase of the emplacement of the Subcarpathian Nappe. The map from **d** shows thrust planes mostly organized in a duplex-style to the west of the Subcarpathian Nappe (dashed where covered)

ing the Middle Miocene, particularly during the Sarmatian, indicated by the dramatic change in thickness and elevation of the corresponding sediments across the fault compartments (thin or outcropping to the west and north, over 1.5 km-thick within the basin). Some normal faulting also took place to the southernmost part of the study area (Fig. 3).

We conclude that during the Middle Miocene, the displacement of the Carpathian units took place both along the Timok Fault (formerly acting as a transfer fault) and the northern extensional margin (Fig. 3), thus resulting in a curved anastomozed system. Particularly the movements along the latter, roughly E-W oriented, determined the oblique shortening of the basin fill (Fig. 10d). This is also supported by the continuity of the outcropping ENE-WSW dextral strike-slip system towards the west (fig. 3; for a more detailed view, see the maps published in Matenco and Schmid, 1999 or Iancu et al., 2005). Between the two overstepping strike-slip faults from the north, a series of NW-SE transtensional faults were formed during Middle-to-Late Miocene (Figs. 3a and 8).

The oblique shortening of the basin fill is initiated in the westernmost part of the Getic Basin and created first the NE-SW-oriented thrust faults shown in Fig. 10d (also Figs. 5 and 6). The inversion of a former extensional fault also took place at that time (Fig. 3a). The onset of shortening should be at the very beginning of the Middle Miocene giving the age of deformed sediments and piggy-back sequence. It may be even earlier, however, it is more difficult to ascertain an age for the innermost thrust shown in Fig. 10d, given the limited seismic coverage there.

The deeper, WNW-ESE thrust seems to be formed when the NW-SE strike-slip (tear) fault (shown in Figs. 10c and d) was initiated in response to the farther transport of the Carpathian units. Once the NW-SE strike-slip fault cut through the entire basin fill, it took over all the oblique shortening and left the initial thrusts inactive, thus explaining the major difference in elevations between the structures shown in Figs. 10b and c relative to the ones from Figs. 5 or 6.

As a whole, most of the Mid-Tertiary infill of the Getic Basin was peeled-off to the E-SE as a wedge, with the leading line behaving as a tear fault in the west and changing laterally to a frontal thin-skinned thrust. This orientation may have resulted from the original configuration of the extensional basin, that is, the former relay-ramps or other transferring structures may have exerted a certain control.

It appears that when the Carpathian units started rotating along the Timok Fault system in Middle Miocene times, the old orogenic pile became decoupled from western Moesia, thus leading to accelerated subsidence of the latter. Moreover, this would explain why the westernmost extremity of Moesia records quite minor contractional deformation whereas thrusting proceeded along the belt culminating eventually with the emplacement of the Subcarpathian Nappe by late Middle Miocene (Middle Sarmatian, cf. Sandulescu, 1988; Dicea, 1995; Matenco et al., 1997).

We also speculate that some of the former Mid-Tertiary normal faults inside the Getic Basin farther east, particularly those flanking its northern margin, may have been reactivated in this way during the E-wards displacement of the Carpathian units, thus leading to a highly complex structural style of the inversion, as shown by Rabagia and Matenco (1999).

4 Curved Plate Boundaries: Carpathians / Moesia vs Caribbean / South America

At this point of the discussion, we feel it is worth making a brief analogy of the South Carpathians / Moesia corner with another highly curved tectonic setting which is still developing, namely the Caribbean / South America plates. This was suggested to the first author by H. Doost (personal communication, 2004) and also referred to by Hippolyte et al. (1999). This comparison is useful in picturing how different the foreland plates can deform although the tectonic transport of the upper plates takes place in a rather similar way.

In both cases, there is a plate that dextrally moves and rotates around the corner of another one. The major difference is that the South Carpathians / Moesia NW-most boundary is essentially extensional, with minor contractional deformations taking place at their junction, whereas the Caribbean plate has exerted strong transpression upon the NW corner of the South American plate, leading even to the extrusion and N-wards transport of the Maracaibo triangular continental block (e.g. Pindell., 1991).

We speculate that these contrasting behaviors are mainly related to the presence (and absence, respectively) of weak lineaments within the convex-shaped plate, favorably oriented to the future stresses in the sense of facilitating the tectonic transport of the moving plate. In the case of the Carpathians / Moesia couple, one of the extensional structures inherited from its passive margin stage was likely employed during the future tectonic transport of the Carpathian units and evolved into a major wrench zone.

Furthermore, if one compares the two tectonic plate configurations in terms of shortening within their foredeeps, a similarity concerning the E-wards migration of the contractional deformations could be derived (e.g. Pindell, 1991 and references therein for the Caribbean setting). However, it appears that the time span characteristic of the contractional deformations migration in the Getic Basin is shorter than its counterpart. As shown previously for Carpathians / Moesia, contraction started in the NW-most corner to the end of Early Miocene – beginning of Middle Miocene (Badenian), reached the climax E-wards in the latest Middle Miocene (Sarmatian) and moved to the E-most part in Pliocene, although more diffuse then (Matenco et al., 1997; Hippolyte et al., 1999). In turn, in the Caribbean setting the contraction within the foredeep has started since the Eocene (cf. Pindell, 1991). These comparisons could be of help in directing exploration strategies as both foredeeps host important hydrocarbon reserves.

5 The Potential of the Western Moesian Passive Margin Petroleum Systems

The passive margins flanking both modern and ancient oceans are generally prone for generating hydrocarbons from source rocks deposited during syn- to post-rift stages. We have thus integrated the structural pattern of the Moesian passive margin described previously into a regional framework aiming to open new perspectives on the petroleum systems.

Most of the reconstructions of the Mesozoic plate setting in the Carpathian realm (e.g. Sandulescu, 1984; Csontos and Varos, 2004) placed the Severin oceanic crust (and its northern equivalents, Ceahlau and Magura +/- Valais) between the fixed Moesia / East European platform and another continental plate that drifted away towards WSW (Fig. 11a). Alternatively,

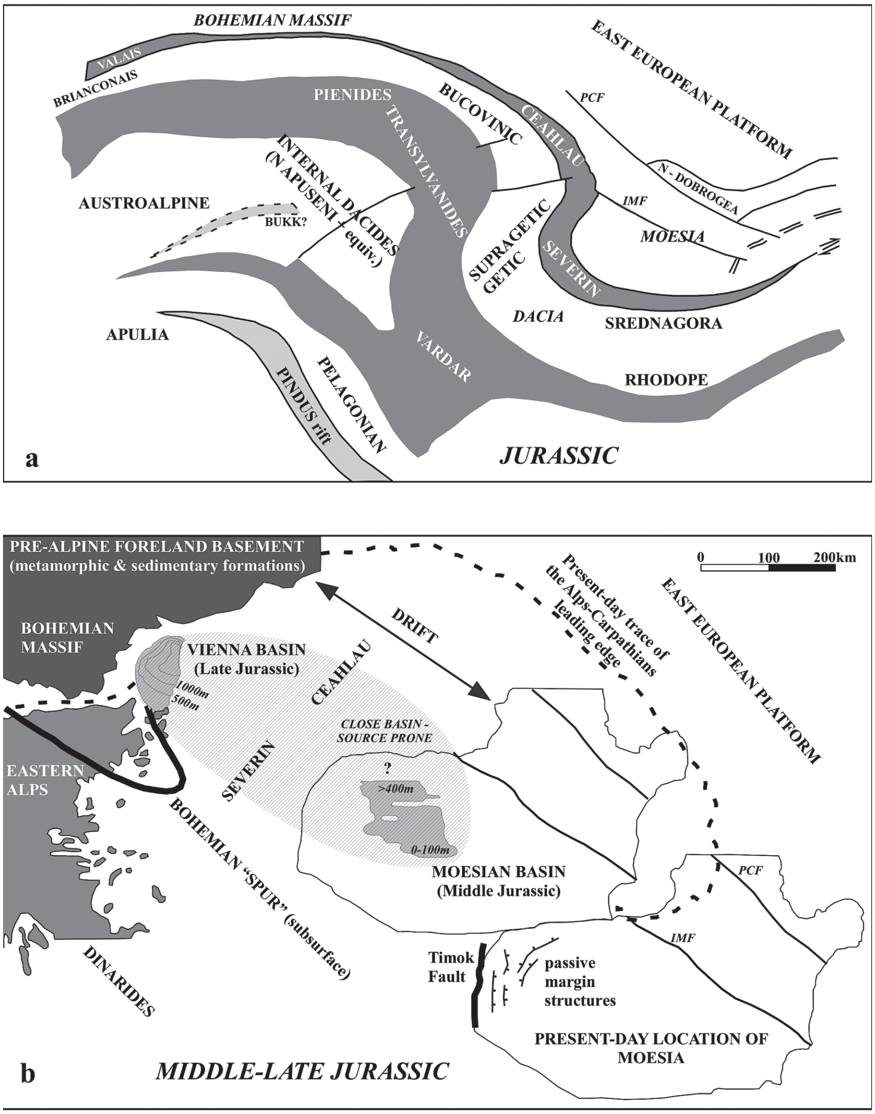

Fig. 11. Plate tectonic models of the Carpathian-Moesian realm prior to the creation of the Severin (and equivalents) oceanic crust (a. from Sandulescu, 1984; b. modified from Tari, 2005). There is no relationship between the gray fills from a. and b. Note that an approximate scale is provided only in b. In b., the thickness maps of the Middle Jurassic (Moesia) and Late Jurassic (Vienna basin) source formations are schematically shown (Tari, 2005 and references therein) as well as the sketch of the rifted passive margin presented in this contribution. We have no intention to discuss the role of the major faults of the foreland plate (IMF Intramoesian fault; PCF Peceneaga-Camena fault) in the Tari's model. Instead, we aim to integrate the Moesian passive margin setting into a larger framework and to provoke further discussions and research on this topic

Tari (2005) proposed that Moesia represents in fact a conjugate plate of the Bohemian segment from the European margin (Fig. 11b). In his model, Moesia is the plate drifted away for over 600 km towards SE during the Middle – Late Jurassic. Very important from the standpoint of hydrocarbon generation, the Middle and Late Jurassic formations known as regional source rocks in western Moesia and the Vienna basin (Tari, 2005 and references therein), appear in this model as deposited within a restricted basin that predated the onset of spreading.

The N-S changing to NE-SW basin structure of the western Moesia, outlined above, seems to sustain Tari's proposed model. These basins appear as remnants of a passive margin that could function indeed in a restricted environment for a while. Although there are no wells that drilled the passive margin sequence presently buried beneath Tertiary sediments, the faulted tilted blocks (e.g. Fig. 5) and their possible syn-to-post rift source-prone fill represents a new attractive potential petroleum system of the NW-most Moesian area. In fact, our findings could extend farther NW the Middle Jurassic-sourced petroleum system located in central-western Moesia (Popescu, 1995).

The hydrocarbon potential of this area is further strengthened by the expected wide distribution of the Late Oligocene shale sequence (Figs. 5 and 6) buried at the oil window depths. This is the proved main source formation all over the Carpathian nappes and foredeep including most of the Getic Basin (Popescu, 1995).

A third, rather highly speculative petroleum system, might be represented in the NW-most Moesia by the pre-rift Silurian shales (e.g. Paraschiv and Baltes, 1983; Popescu, 1995). Although if present, these source rocks are expected to be over cooked within the Tertiary basin area, they might have generated hydrocarbons migrated and preserved upwards in traps from the passive margin setting.

Finally, a prolific petroleum system is represented by the biogenic gas in dominantly stratigraphic traps of the Neogene clastics widespread in the post-Badenian sequences of the entire Carpathian foreland area from Romania to Austria.

6 Conclusions

The information provided by the recent seismic surveys and wells drilled in the NW-most Moesian corner sheds more light upon the structural setting and kinematic evolution of the highly-bent contact zone between the South Carpathians and their foreland plate. This contact is essentially transcurent being represented by the Timok dextral lineament which accommodated during the Mid-Tertiary onwards the displacement and rotation of the Carpathian orogenic units around the Moesian corner. The Timok Fault clearly cuts the South Carpathians structural assemblage from the Moesian foreland plate; north of the Danube River, no proof of Carpathian nappes was found to the east of this bounding lineament.

Two extensional stages overlapped in the NW part of Moesia leading to a complex structural setting made up of orthogonal normal fault systems. The oldest is roughly N-S oriented and originates from the (presumably) Permian - Triassic rifting that predated the creation of the oceanic crust at the western and northern margins of the Moesian realm. After the Latest Cretaceous welding of the Carpathian orogen to Moesia, some of those faults acted as a structural weakness prone to be reactivated in a transcurent manner and became the defined Timok Fault system in the Mid-Tertiary. Genetically related to the N-wards translation of the Carpathian units, the more recent E-W oriented fault system was formed in Late Oligocene – Early Miocene driving the opening of a second extensional basin along the northern margin of Moesia.

The tectonic regime changed to transpression not earlier than the Middle Miocene once the Carpathian units started to rotate around the Moesian corner. Structural evidence shows that only then, the former rather straight Timok Fault merged with one of the northern E-W extensional faults leading to a curved dextral strike-slip system. A duplex thrust system had been formed inside the basin until most of the transpression has been taken over by a NW-SE dextral fault which becomes laterally the thin-skinned Subcarpathian Nappe.

As a whole, the Mid-Tertiary basin has been inverted by progressively peeling-off towards E-SE its sedimentary fill. The thin-skinned character of the inversion and the significant down-throwing of the eastern compartment of the Timok Fault system suggest that by the Middle Miocene the former orogenic pile became fully decoupled from the Moesian foreland plate.

New paths are open for hydrocarbon exploration giving the detailed structural picture highlighted in this contribution. Two main petroleum systems can be envisaged: one is related to the Mesozoic passive margin stage with hydrocarbons possibly sourced from syn- to post-rift Mid-Jurassic sequences and trapped in the rift shoulders; the second is related to the Late Oligocene shales (as in the whole Carpathian foredeep) which could produce hydrocarbons migrated towards either the Mid-Tertiary extensional traps or into those created during the Middle Miocene inversion. The biogenic gas accumulated in stratigraphic traps deserves more explorationists' attention these days when smaller fields could be commercial.

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