On the formation and evolution of the Pannonian Basin: Constraints derived from the structure of the junction area between the Carpathians and Dinarides

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[1] The large number and distribution of rollback systems in Mediterranean orogens infer the possibility of interacting extensional back-arc deformation driven by different slabs. The formation of the Pannonian back-arc basin is generally related to the rapid Miocene rollback of a slab attached to the European continent. A key area of the entire system that is neglected by kinematic studies is the connection between the South Carpathians and Dinarides. In order to derive an evolutionary model, we interpreted regional seismic lines traversing the entire Serbian part of the Pannonian Basin. The observed deformation is dominantly expressed by the formation of Miocene extensional detachments and (half) grabens. The extensional geometries and associated synkinematic sedimentation that migrated in time and space allow the definition of a continuous and essentially asymmetric early to late Miocene extensional evolution. This evolution was followed by the formation of few uplifted areas during the subsequent latest Miocene–Quaternary inversion. The present-day extensional geometry changing the strike across the basin is an effect of the clockwise rotation of the South Carpathians and Apuseni Mountains in respect to the Dinarides. Our study infers that the Carpathian rollback is not the only mechanism responsible for the formation of the Pannonian Basin; an additional middle Miocene rollback of a Dinaridic slab is required to explain the observed structures. Furthermore, the study provides constraints for the pre-Neogene orogenic evolution of this junction zone, including the affinity of major crustal blocks, obducted ophiolitic sequences and the Sava suture zone.

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1. Introduction

[2] Extensional back-arc basins develop in the hinterland of active convergent areas in response to retreating subduction boundaries, their architecture being controlled by a large variety of parameters such as the age of subducted lithosphere, the subduction direction, the type of underlying crust or the uplift of the orogenic/magmatic arc [e.g., *Dewey*, 1981; *Doglioni et al.*, 2007; *Mathisen and Vondra*, 1983; *Uyeda and Kanamori*, 1979]. These parameters control the large variety of back-arc basins of various ages presently overlying different types of crust, such as the Caribbean, Banda-Sunda back arcs or the Black Sea Basin [e.g., *Hall*, 2011; *Meschede and Frisch*, 1998; *Munteanu et al.*, 2012; *Spakman and Hall*, 2010].

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[3] The Pannonian Basin of Central Europe (Figure 1a) is a classical back-arc basin, which is still underlain by highly thinned continental lithosphere that formed during Miocene times in response to the rapid rollback of a slab attached to the European continent [e.g., *Balla*, 1986; *Horváth et al.*, 2006; *Horváth*, 1993; *Royden*, 1988]. The rollback is partly responsible for the creation of the highly arcuate geometry of the Carpathian Mountains (Figure 1) [e.g., *Matenco et al.*, 2010], a process that is common with many other Mediterranean orogens [e.g., *Faccenna et al.*, 2004; *Jolivet and Faccenna*, 2000]. Evolutionary models of the Pannonian Basin assume the onset of extension at ~20 Ma, subsequently followed by a peak tectonic activity along normal faults during Middle Miocene times, which was subsequently followed by a post-rift, thermal sag phase starting in late Miocene times [e.g., *Tari et al.*, 1999, and references therein]. A latest Miocene–Quaternary contractional event has subsequently overprinted the basin during the translation and counterclockwise rotation of the Adriatic indenter [*Bada et al.*, 2007; *Fodor et al.*, 2005; *Horváth*, 1995; *Pinter et al.*, 2005].

[4] The timing of extension in the Pannonian Basin is best constrained in the area of the ALCAPA unit in the north,

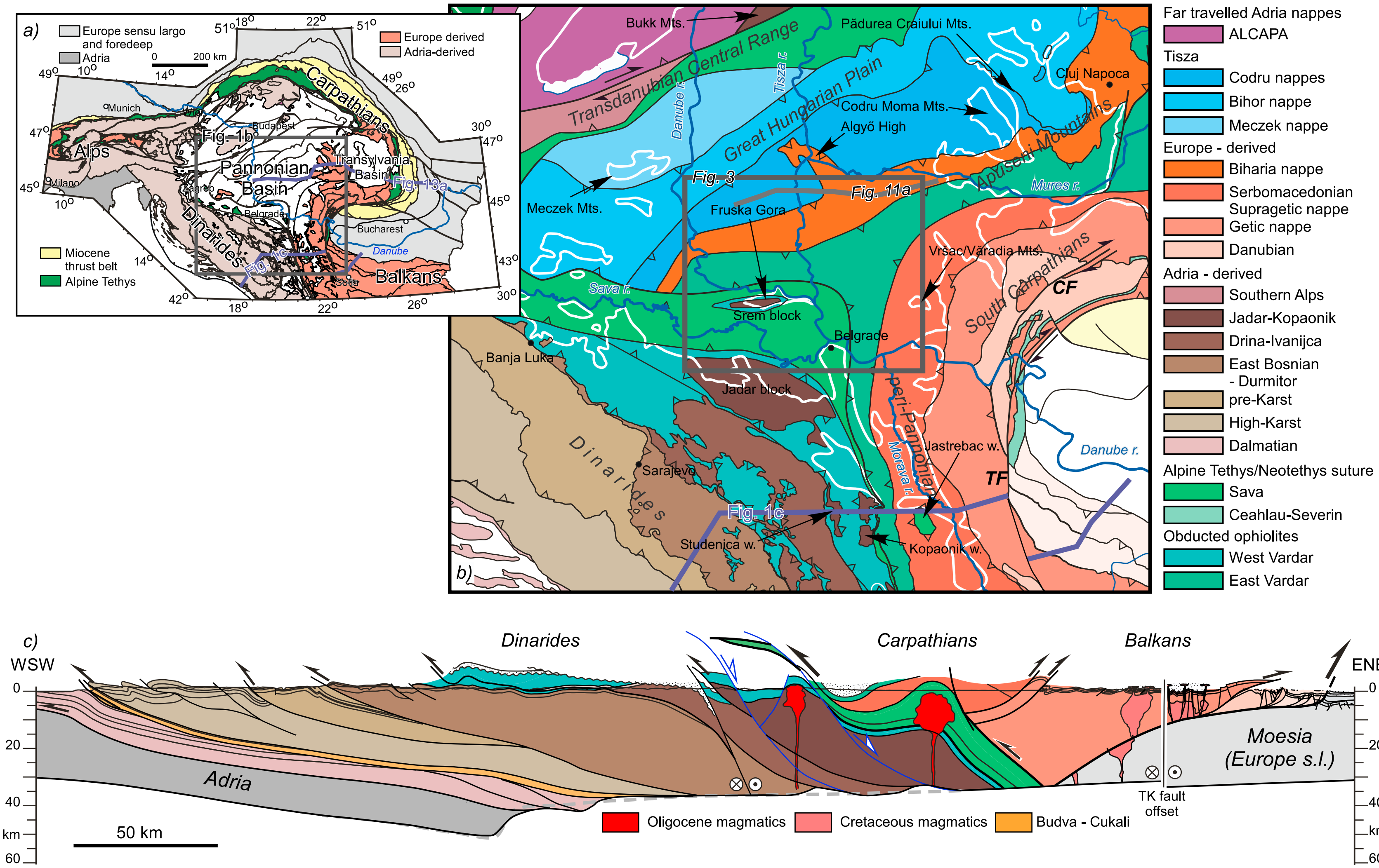

Figure 1. (a) Tectonic map of the Alps–Carpathians–Dinaridic system (simplified after *Schmid et al.* [2008]) with the extent of the large Pannonian and Transylvanian back-arc basins and the location of other Miocene basins superposed over the Dinarides and Carpathians structures. The thick blue line is the location of the cross section in Figures 1c. (b) Detailed tectonic map of the connection between the Dinarides, South Carpathians and Pannonian Basin (modified from *Schmid et al.* [2008] by S. M. Schmid). The white line is the extension of the Miocene sediments of the Pannonian Basin. The gray rectangle is the location of Figure 3; CF, Cerna-Jiu Fault; TF, Timok Fault. (c) Cross section over the Dinarides and Balkanides system (modified after *Schefer* [2010], *Schmid et al.* [2008], and *Šumanovac* [2010]). Note the thick orogenic root situated in the front of the Dinaridic system and Miocene extensional features (blue lines) situated near the contact between Dinarides and Dacia. The legend is the same as for Figure 1b.

while fewer data are available for the southern Tisza and Dacia domains (Figure 1a). The extension of the ALCAPA unit was triggered both by the lateral extrusion of blocks from the Eastern Alps and by Carpathian slab rollback, processes that started in latest Oligocene to early Miocene times [e.g., *Frisch et al.*, 2000; *Ratschbacher et al.*, 1991]. Although undefined, it is plausible to assume that the Tisza–Dacia block was extruded from the Dinaridic collision zone under similar geodynamic conditions to those of the ALCAPA terrane [*Horváth et al.*, 2006]. Large uncertainties still exist in the Tisza-Dacia block in what concerns the timing, geometry and succession of extensional events, as well as the moment when this extension ceased. For instance, although late Miocene normal faults have been observed in the Pannonian Basin and middle–late Miocene extensional detachments have been rather intuitively defined in its SE part, the amount of coeval stretching has been generally considered limited and, therefore, the thermal relaxation is considered to be the main mechanism acting during late Miocene times [*Horváth et al.*, 2006; *Kováč et al.*, 1995; *Magyar et al.*, 2006; *Tari et al.*, 1999; *Tari and Horváth*, 2006; *Windhoffer et al.*, 2005]. Furthermore, when compared with the ALCAPA unit, much less is known on the role of the clockwise rotation of the Tisza-Dacia unit on the formation of the Great Hungarian Plain part of the Pannonian Basin (and its connection with the Dinarides and Carpathians (Figures 1a and 1b).

[5] The SE part of the Pannonian Basin in Serbia is a critical area that has received little attention in terms of kinematic studies (Figure 1b). Although a mature exploration province with a high density of high-quality subsurface data (seismics and wells) described in a number of mostly local publications [e.g., *Čanović and Kemenci*, 1988, 1999; *Pigott and Radivojević*, 2010; *Šolević et al.*, 2008, and references therein], studies analyzing fault patterns and their effects on the evolution of the basin fill are still not available. This is highly relevant because this key junction area is the place where the transition between the Late Jurassic–Eocene orogenic structures of the Carpathians and Dinarides and the Miocene formation of the Pannonian Basin unit can be accurately quantified (Figures 1b and 1c) [e.g., *Schmid et al.*, 2008]. Due to the Miocene cover, the kinematic connection between the underlying obducted ophiolites, suture zones, nappe structure and basement affinities in this junction area between Dacia, Tisza and Dinarides units (Figure 1b) is poorly known in literature outside the biostratigraphic and paleogeographic work of *Čanović and Kemenci* [1988].

[6] We address these uncertainties by interpreting regional seismic transects across the Serbian part of the Pannonian Basin that are calibrated by a high density of exploration wells. The interpretation allowed the correlation between the patterns of extensional deformation recorded at the junction between Dacia, Tisza and Dinarides. Although the quality of seismic data decreases significantly beneath Miocene sediments, the correlation with exploration wells and existing studies enabled a number of key inferences for the pre-Neogene orogenic evolution.

2. The Evolution of the Junction Area Between the Carpathians, Dinarides and Pannonian Basin

[7] In the western and central part of the studied area (Figure 1), the Dacia block is essentially a piece of European continent that broke off during latest Middle to late Jurassic times and was gradually sutured backward during the Cretaceous closure of the Ceahlău-Severin Ocean and a more easterly oceanic to thinned continental remnant that closed in Miocene times, i.e., the Carpathian embayment [*Balla*, 1986; *Săndulescu*, 1988]. The Dacia unit consists of a thick-skinned nappe stack that formed during late Early to late Cretaceous times, its overall geometry being that of a large antiform exposed in the East and South Carpathians [*Fügenschuh and Schmid*, 2005; *Iancu et al.*, 2005; *Kräutner and Krstić*, 2003; *Kräutner and Bindea*, 2002]. Adjacent to the studied area, the Getic/Supragetic nappe sequence contains medium to high-grade metamorphic Neoproterozoic to Early Paleozoic basement, locally overlain by Paleozoic successions affected by a low degree of metamorphism, and a late Paleozoic–Mesozoic nonmetamorphosed sedimentary cover [e.g., *Balintoni et al.*, 2009, 2010; *Iancu et al.*, 2005, and references therein]. In the studied area, this cover has a dominantly continental to shallow water facies. The structurally highest units are the Biharia nappe and the Serbo-Macedonian “Massif” (assigned to Dacia in Figure 1b), characterized by a medium to high-degree metamorphic sequence that is scarcely overlain by mostly proximal sediments of various Mesozoic ages [e.g., *Dimitrijević*, 1997]. During late Jurassic times these two units became tectonically overlain by obducted oceanic crust containing ophiolites and genetically associated island arc volcanics, rocks that are grouped under the name of East Vardar ophiolites [e.g., *Robertson et al.*, 2009; *Schmid et al.*, 2008]. These crop out in the East Carpathians, Apuseni Mountains, central southern Serbia and are buried by Neogene sediments in the Transylvanian Basin and the SE part of the Pannonian Basin (Figure 1) [e.g., *Čanović and Kemenci*, 1999; *Hoeck et al.*, 2009; *Ionescu et al.*, 2009; *Nicolae and Saccani*, 2003; *Robertson et al.*, 2009; *Săndulescu*, 1975; *Săsăran*, 2005; *Schmid et al.*, 2008, and references therein].

[8] In the NW part of the studied area, Dacia is juxtaposed against the Tisza unit (Figure 1b), a block that displays mixed European and Adriatic (or Mediterranean) affinities. This block experienced large amounts of translations and rotations during its Mid-Jurassic separation from the European continent, movement southward to a position adjacent to Adria, and realignment with blocks with European affinity during the closure of a branch of the Neotethys Ocean in Cretaceous times [e.g., *Csontos and Vörös*, 2004; *Haas and Péró*, 2004; *Márton*, 2000; *Pătraşcu et al.*, 1992; *Vörös*, 1977]. Various high-grade Variscan metamorphic series are overlain mainly by continental Permian deposits and a Germanic Triassic cover that shows significant lateral and temporal changes to a Middle Triassic massive carbonate buildup or an Upper Triassic Halstatt-type of facies [*Bleahu et al.*, 1981; *Burchfiel and Bleahu*, 1976; *Haas and Péró*, 2004]. The last orogenic deformation affecting the contact between Tisza and Dacia continental units took place in Late Cretaceous times, the intra-Turonian event created a sequence of four presently NW facing nappes that are, from bottom to top, the Meczek, Bihor, Codru and Biharia nappes (Figure 1b) [*Balintoni et al.*, 1996; *Bleahu et al.*, 1981; *Haas and Péró*, 2004]. The highest Biharia has been recently reassigned to the Dacia unit (Figure 1b) [*Schmid et al.*, 2008].

[9] In the SW part of the studied area, the Dinaridic units with Adriatic affinity outcrop in the Jadar block that consists of a nonmetamorphosed to slightly metamorphosed Paleozoic

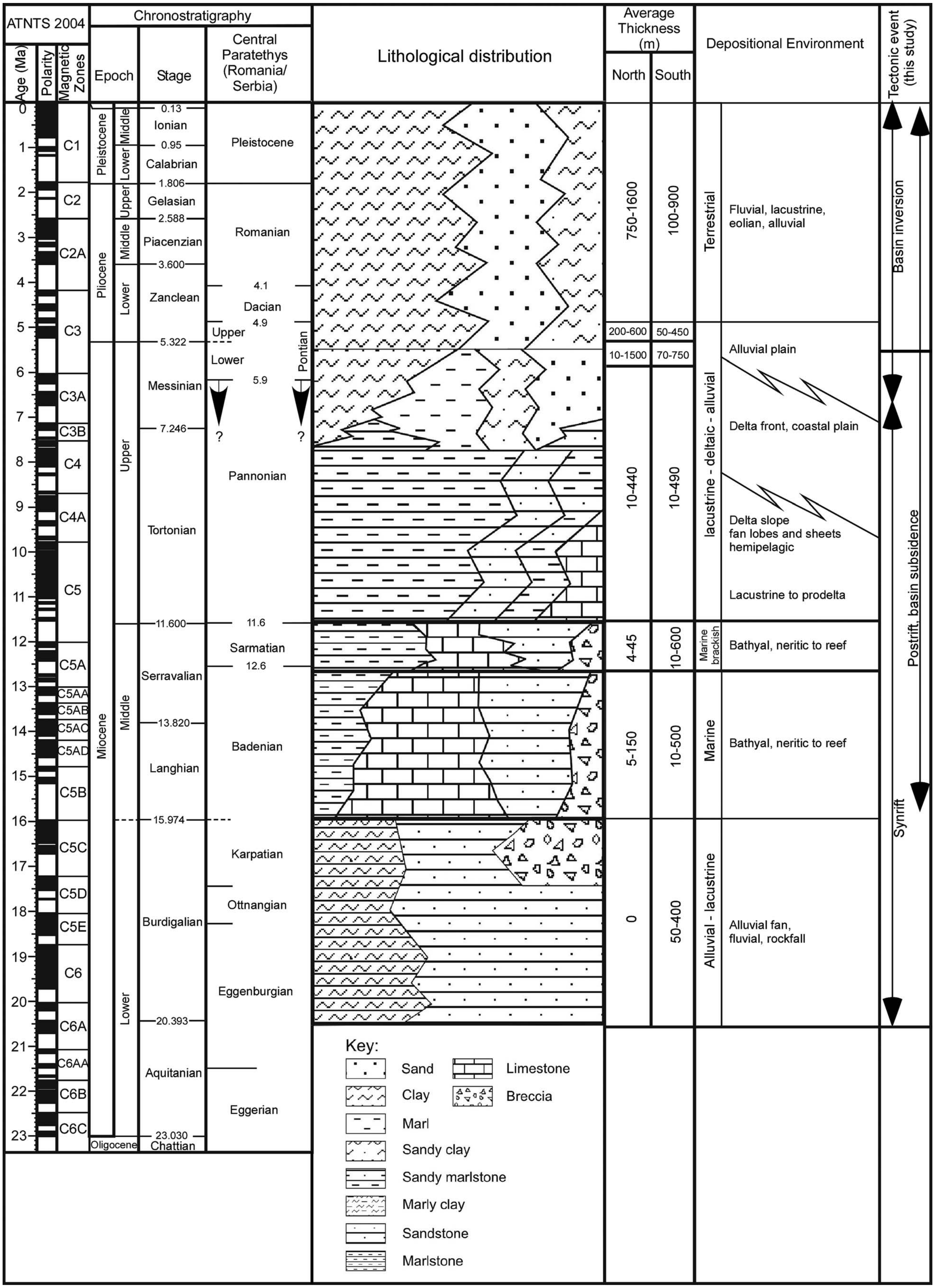
ATNTS 2004
Age (Ma)
Polarity
Magnetic Zones
Chronostratigraphy
Epoch
Stage
Central Paratethys (Romania/ Serbia)
Lithological distribution
Average Thickness (m)
North
South
Depositional Environment
Tectonic event (this study)
C1
C2
C2A
C3
C3A
C3B
C4
C4A
C5
C5A
C5AA
C5AB
C5AC
C5AD
C5B
C5C
C5D
C5E
C6
C6A
C6AA
C6B
C6C
Pleistocene
Pliocene
Miocene
Oligocene
Middle
Lower
Upper
Ionian
Calabrian
Gelasian
Piacenzian
Zanclean
Messinian
Tortonian
Serravalian
Langhian
Burdigalian
Aquitanian
Chattian
0.13
0.95
1.806
2.588
3.600
5.322
7.246
11.600
13.820
15.974
20.393
23.030
Pleistocene
Romanian
Dacian
4.1
4.9
Pontian
5.9
Pannonian
11.6
Sarmatian
12.6
Badenian
Karpatian
Ottnangian
Eggenburgian
Eggerian
750-1600
100-900
200-600
50-450
10-1500
70-750
10-440
10-490
4-45
10-600
5-150
10-500
0
50-400
Terrestrial
lacustrine - deltaic - alluvial
Marine brackish
Marine
Alluvial - lacustrine
Fluvial, lacustrine, eolian, alluvial
Alluvial plain
Delta front, coastal plain
Delta slope fan lobes and sheets hemipelagic
Lacustrine to prodelta
Bathyal, neritic to reef
Bathyal, neritic to reef
Alluvial fan, fluvial, rockfall
Basin inversion
Postrift, basin subsidence
Synrift
Key:
Sand
Limestone
Clay
Breccia
Marl
Sandy clay
Sandy marlstone
Marly clay
Sandstone
Marlstone

Figure 2

sequence covered by an Alpine Triassic-Jurassic shallow water carbonatic to deep water radiolaritic sequence, which is similar to various other tectonic slices displaced westward in the Medvenica Mountains of Croatia or northward in the Bükk Mountains of Hungary [*Filipović et al.*, 2003; *Pamić*, 2002; *Schmid et al.*, 2008; *Tomljenović*, 2000]. To the SE, this unit is laterally continuous with the Kopaonik metamorphic series [*Dimitrijević*, 1997], which are the metamorphosed equivalents of the Jadar Paleozoic and its Triassic-Jurassic sequence [*Schefer et al.*, 2010]. The Jadar-Kopaonik unit is interpreted as a unit with Adriatic affinity based on facies arguments and biostratigraphical dating, and it carries the West Vardar (or Dinaridic, or External Vardar subzone) ophiolites in a higher tectonic position; these were obducted during late Jurassic–earliest Cretaceous times [*Dimitrijević*, 1997; *Karamata*, 2006; *Pamić*, 2002; *Schmid et al.*, 2008]. This early obduction was followed by the closure of an intervening Neotethys oceanic segment at the end of Cretaceous times, located between Europe- and Adriatic-derived units, which created the Sava suture zone [*Pamić*, 2002; *Schmid et al.*, 2008; *Ustaszewski et al.*, 2009]. The closure of this ocean is marked in particular by a Maastrictian (Eocene?) suture containing dominantly deep-water turbidites (i.e., flysch) deposits [*Dimitrijević*, 1997; *Schmid et al.*, 2008]. Ophiolites previously obducted over both Europe-derived (Serbo-Macedonian and Biharia) and Adriatic-derived (Jadar-Kopaonik) margins are juxtaposed by the subsequent Cretaceous–Eocene orogenic collision in the studied area against the Sava suture zone (Figure 1b).

2.1. The Extension and Inversion of the Pannonian Basin

[10] The evolution of the Pannonian Basin is generally related to rollback subduction and collisional processes taking place at the exterior of the Carpathian chain [*Cloetingh et al.*, 2006; *Horváth et al.*, 2006]. The Miocene extension was partly coeval with the gradual uplift of the SE European mountain chains that separated the Pannonian back-arc basin from the main Tethyan area. Part of the Paratethys realm, the Pannonian Basin is characterized by an endemic biostratigraphy (Figure 2) [*Rögl*, 1999; *Senes*, 1973]. Furthermore, Carpathian uplift toward the end of middle Miocene times [*Matenco et al.*, 2010] separated the lacustrine Pannonian Basin from other endemic areas of Paratethys located more eastward [*Harzhauser and Piller*, 2007; *Magyar et al.*, 1999a].

[11] Near the transition between the Pannonian Basin and the Eastern Alps, simple shear extension formed core complexes and asymmetric hanging wall basins [*Tari et al.*, 1992; *Tari*, 1996]. Eastward and southeastward, evidences for extension in the larger Great Hungarian Plain are largely of Badenian–(lower) Sarmatian in age, followed by a large thermal sag deposition during Pannonian–Quaternary times [*Fodor et al.*, 1999; *Horváth*, 1993]. In more detail, the timing and style of extension in this part of the basin are rather debated in terms of mechanical effects and style of sedimentation (see discussions by *Fodor et al.* [1999], *Horváth et al.* [2006], and *Tari et al.* [1999]). The latest Miocene–Pliocene indentation and clockwise rotation of Adria inverted the basin and formed large open folds in the Great Hungarian Plain and strike-slip structures in the vicinity of the Transdanubian Central Range (Figure 1b) [*Bada et al.*, 2007; *Fodor et al.*, 2005; *Horváth*, 1995; *Pinter et al.*, 2005].

[12] The Miocene deposition in the Serbian part of the Pannonian Basin (Figure 2) starts with continental alluvial and lacustrine sedimentation that took place during lower Miocene times. The exact age of these sediments is not well constrained, the facies being dominated by rockfall, alluvial fans and fluvial sediments, locally intercalated with volcano-clastic deposits. The onset of a marine transgression is recorded during middle Miocene times. A lower Badenian sequence is observed in almost all areas, with a shallow marine facies (reef limestones and coarse siliciclastic) along structural highs and/or pelagic deep-water sedimentation in the center of extensional grabens, locally associated with volcano-clastic material (Figure 2). Middle–upper Badenian sediments with scarce, nonuniform deposition locally overlie these deposits. Deposited in a marine to gradually brackish facies, Sarmatian sediments have generally lower thicknesses and areal extent. Exception is the SE part of the studied area,

Figure 2. Lithostratigraphic column of the Miocene sediments of the Pannonian Basin in Serbia, evolution of sedimentological environments, tectonic episodes and biostratigraphic correlation chart between standard Tethys ages and the endemic domain of Paratethys. The biostratigraphy follows the Central Paratethys ages as defined in Serbia and Romania corrected with the recent absolute age dating of the same biostratigraphic stages in the Central Paratethys of Pannonian/Transylvania Basins or in the Eastern Paratethys at the exterior of Carpathians [*Rögl*, 1996; *Vasiliev et al.*, 2005, 2010]. The absolute age of the Pannonian/Pontian boundary is less constrained in terms of absolute age, being potentially affected by endemic evolution in the Pannonian Basin before the connection with the Eastern Paratethys, which took place during Pontian times. Note that the biostratigraphic scale is different from the one that commonly uses the Pannonian senso largo time interval in neighboring Hungary (details given by *Magyar et al.* [1999b, 1999c]). The age of lower Miocene sediments is poorly constrained due to rare fossil remnants. The lower Badenian sediments encountered in wells display a diverse fauna in the reef carbonates deposited over structural highs (such as *Lithothamnion*, *Lithophylum*, detritus of bryozoas, forminifers, and echinides), while the structural lows recorded deeper water sedimentation containing abundant pelagic foraminifers (e.g., *Praeorbulina glomerosa circularis*, *Orbulina suturalis*, *Globigerinoides bisphericus, G. trilobus*, *G. quadrilobatus*, *Globigerinopsis grilli*, *Globigerina praebulloides*, *Globigerina bulloides*, *G. concinna)* [*Pigott and Radivojević*, 2010; *Radivojević et al.*, 2010]. The Sarmatian age sedimentation is confirmed by abundant fossil content, in particular, where deposition took place in shallow water conditions (*Quinqueloculina longirostra*, *Q. hauerina*, *Q. akneriana*, *Elphidium aculeatum*, *E. crispum*, *Mactra* sp., *Ervilla* sp., *Modiolus incrassatus*, *Irus gregarius*, *Pirenella picta*) [*Pigott and Radivojević*, 2010; *Radivojević et al.*, 2010]. Note that the deltaic topset-foreset-bottomset formations typically defined in the Pannonian Basin of Hungary (Endrod, Szolnok, Algyő, Ujfalu Zagyva, Nagyalfold Formations) are not used in the lithostratigraphic column due to their diachronous character [*Magyar et al.*, 1999b].

where deposits locally reach thicknesses higher than 600 m, the facies being mainly deep water, fine grained bathyal. Elsewhere, Sarmatian deposits contain reefs and shallow water sedimentation with average thicknesses below 50 m, or are completely eroded (Figure 2).

[13] The Pannonian Basin became an isolated brackish lake during upper Miocene times where sedimentation had a much larger areal extent and took place during a period of gradual basin fill in a lacustrine–deltaic–alluvial depositional environment (Figure 2). The basin was filled by a rapidly prograding sequence, a gradual transition being recorded from deeper water bottomsets (Endrod Formation) and turbidites (Szolnok Formation), deltaic slope foresets (the Algyő Formation) to delta front, coastal plain (Ujfalu Formation) and alluvial plain, fluvial (Zagyva, Nagyalfold Formations) [*Magyar et al.*, 1999b; *Pigott and Radivojević*, 2010]. Note that these formations reflect zone of similar facies in the rapidly prograding depositional environment. Therefore, these are diachronous in various parts of the Pannonian Basin and cannot be used in a strict stratigraphic sense [*Magyar et al.*, 1999b]. In the studied area, the progradation spans throughout Pannonian–Pliocene times [*Magyar et al.*, 2012], being followed by Pliocene-Quaternary terrestrial, fluvial, eolian and alluvial sedimentation (Figure 2).

3. The Miocene Structural Geometry of the Pannonian Basin in Serbia

[14] We have derived the structural geometry of the Pannonian Basin in Serbia by interpreting regional seismic lines calibrated by wells that were acquired by the local petroleum exploration (Figures 3–10). The density of data is particularly high in the area of Serbia located north of the Danube River (i.e., in Vojevodina). The interpretation of two-way travel time seismic lines was converted to depth (Figure 11) by using average interval velocities derived from time-depth relationships in calibrating well surveys (i.e., VSPs), which have a regional distribution across the entire studied area. Although not specifically mentioned, the interpretation was controlled by the stratigraphic intervals traversed by wells displayed in Figures 4–11. The seismic interpretation was correlated with the surface geology outcropping along the Dinaridic basin margin (1:100.000 maps published by the Geological Institute of Serbia) and with recent kinematic, structural and exhumation studies published in or near this marginal area [*Schefer*, 2010; *Schmid et al.*, 2008; *Stojadinović et al.*, 2012; *Toljić et al.*, 2012; *Ustaszewski et al.*, 2010]. Furthermore, our interpretation has been correlated with previously published basement or cover data located in various places across the basin in Serbia and neighboring Hungary, Romania and Croatia [e.g., *Juhász et al.*, 2007; *Magyar et al.*, 2006; *Pavelić*, 2001; *Răbăgia*, 2009; *Saftić et al.*, 2003; *Tari and Horváth*, 2006; *Tulucan*, 2007]. The seismic interpretation uses the sequence stratigraphic terminology common to extensional basins [e.g., *Martins-Neto and Cătunean*, 2010; *van Wagoner et al.*, 1990]. When higher-resolution data were available, the sediments deposited during extension were described by using the tectonic system tract genetic terminology of rift initiation, rift climax and immediate/late stage postrift [see *Prosser*, 1993]. When such a separation was not possible, these sediments were referred simply as synrift, postdating prerift and predating postrift sedimentation.

[15] The reflectivity of seismic lines decreases substantially beneath the Neogene sediments, rendering difficult to interpret in particular structural contacts. However, a number of diagnostic seismic facies types have been defined by the correlation with the high density of exploration wells penetrating the pre-Neogene sequence. For instance, the obducted ophiolites and ophiolitic mélange were picked out by seismic interpretation based on their characteristic low-frequency high-amplitude disconnected reflectors that contrast with the neighboring metamorphic basement (e.g., Figures 8 and 9). This type of reflectivity is otherwise common in buried obducted ophiolitic sequences studied elsewhere [e.g., *Tărăpoancă et al.*, 2010]. One other example is the widespread carbonatic sequence of Triassic age depicted by seismic lines at shallow depths that has a characteristic high-frequency discontinuous signal, higher frequency than the metamorphic basement (e.g., Figures 6, 8, and 9). By testing in wells and subsequent lateral extrapolation, this technique has proven successful to interpret many of the structures buried beneath the Miocene sediments. However, a number of tectonic contacts have remained elusive in particular when only metamorphic basement is involved on both sides of fault zones and have been interpreted with dashed lines in Figures 4–10. Therefore, the interpretation of major tectonic contacts with colored dashed lines in Figure 3 should be considered as tentative. Furthermore, the interpretation of faults crosscutting the metamorphic basement at higher depths is speculative in Figures 4–10 and should be regarded as such.

3.1. The Miocene Extensional Geometry in the Vicinity of the Carpathians and Apuseni Mountains

[16] Two deep (half) grabens have particular large offsets in the SE part of the studied area around the Morava valley and its northern prolongation (Figure 3), which is commonly referred as the peri-Pannonian domain [e.g., *Marović et al.*, 2002, 2007a]. These deep basins are oriented N-S and have the overall geometry of tilted (half) grabens adjacent to large offset east dipping listric normal faults (the Pančevo and Drmno/Zagajica/Plandište depressions, Figures 3–5). Although the normal faults can be easily correlated by seismic interpretation laterally in map view, a number of local Miocene depocenters are observed due to variable fault offsets along their strike (Figure 3).

[17] The western structure (Pančevo Depression, Figures 4 and 5) formed along a system of listric normal faults with bookshelf tilted blocks in their hanging walls that are connected at depth into a singular structure, the Pančevo detachment. Synkinematic reflectors indicate lower Miocene rift initiation sediments, followed by Badenian–early Sarmatian rift climax, while postrift thermal sag sediments were deposited during late Sarmatian–Pontian times (Figures 4 and 5). The eastern structure (Drmno/Zagajica/Plandište depressions, Figures 3–5) has the typical seismic patterns of an exhumed low-angle asymmetric detachment dipping eastward and exhuming a highly eroded footwall. This Morava detachment was crosscut by steeper normal faults that created the present-day graben-like geometry (Figures 4 and 5). One of these faults has a particularly large offset of up to 3 km and was active throughout Miocene times as an

antithetic structure to the main Morava detachment (Figure 5). It created a local subbasin in the vicinity of Vršac/Văradia Mountains (Zagajica Depression, Figure 3). The overall structure is filled with lower Miocene continental alluvial to lacustrine sediments that were deposited during rift initiation, rift climax and immediate postrift deposition continuing throughout middle–upper Miocene times.

[18] The northeastmost part of Serbia, together with the neighboring parts of Hungary and Romania, incorporate large offset extensional structures such as the Szeged

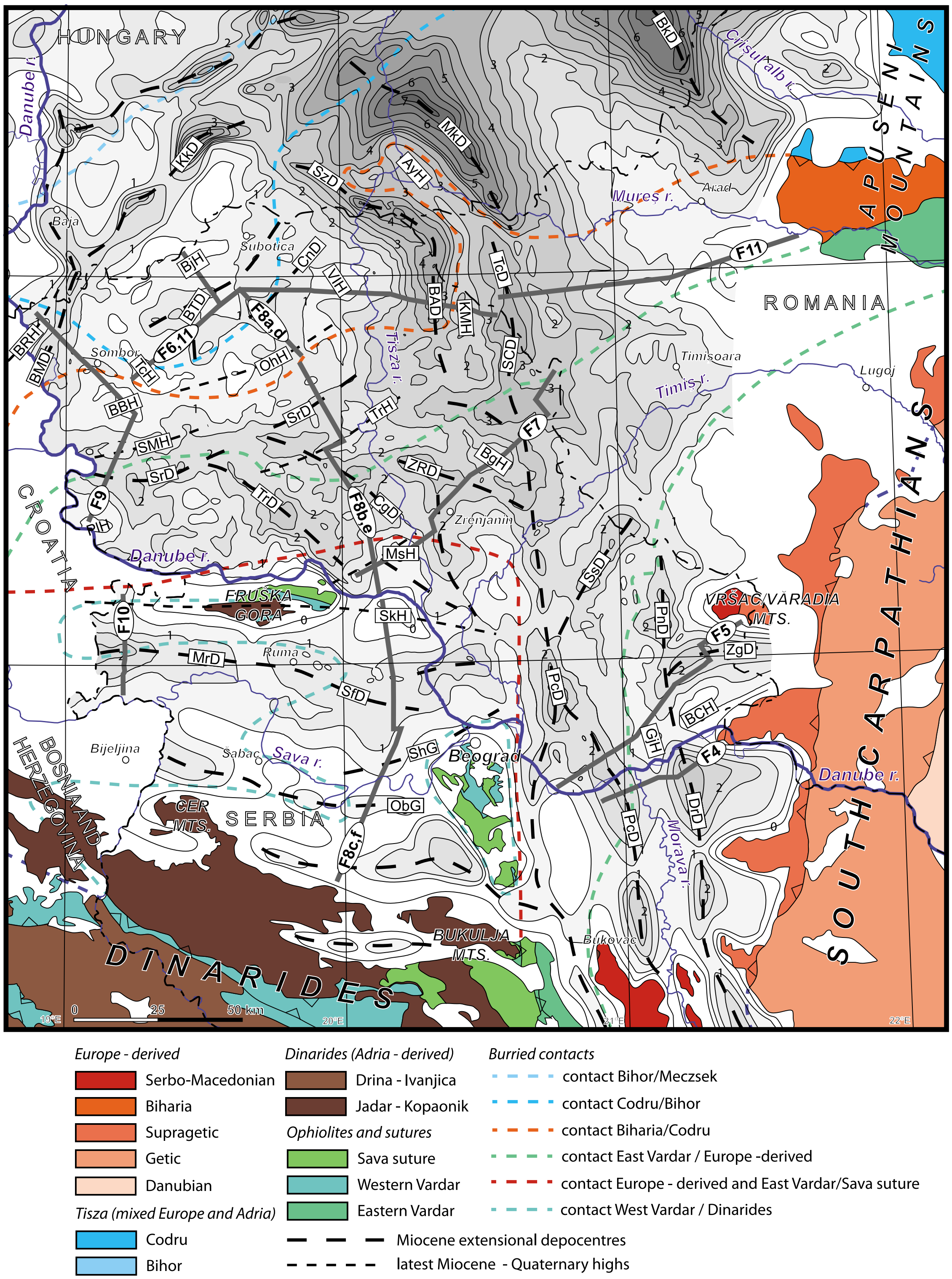

Figure 3

(in Hungary; Banatsko Aranđelovo in Serbia) Depression, the Algyő (in Hungary; Podeanu-Teremia in Romania, Kikinda-Mokrin in Serbia) High and the Makó (Srpska Crnja in Serbia, Tomnatec in Romania) Depression (Figures 3 and 6) [see also *Haas et al.*, 2010; *Magyar et al.*, 2006; *Răbăgia*, 2009; *Tari et al.*, 1999]. These structures are separated by low-angle, large-offset normal faults that show highly eroded footwalls, while the Miocene thickness reaches 7 km in the Makó Depression (Figure 3) [see also *Magyar et al.*, 2006].

[19] The Szeged Depression is an asymmetric half graben controlled by the evolution of a normal fault dipping westward with an up to 3 km offset (Figures 3 and 6). The Miocene fill is tilted against the Szeged fault being truncated by a smaller offset eastward dipping antithetic normal fault (Figure 6). Wells and synkinematic strata demonstrate an extensional evolution in several stages, a rift initiation in Badenian times was followed by an overall unconformity or period of nondeposition during Sarmatian times, a Pannonian rift climax and an upper Pontian–Quaternary immediate to late stage postrift sedimentation (Figure 6). More detailed seismic sequence stratigraphic studies [*Pigott and Radivojević*, 2010] demonstrated gentle Badenian subsidence associated with open to marine waters followed by rapid deepening accommodating the deposition of the Pannonian deep water sediments. This was subsequently followed by a rapid sedimentary infill during the subsequent Pannonian–Pontian deltaic progradation [*Pigott and Radivojević*, 2010]. The overall structural geometry suggests large-scale exhumation of the Algyő High driven not only by the Szeged low-angle normal fault system, but also by exhumation related to the formation of the easterly adjacent structure, the Makó Depression.

[20] The main depocenter of the Makó Depression is located immediately NE of our study area, in Hungary and Romania (Figures 3 and 11a). Only its exhumed western flank is visible in our seismic lines, where an east dipping normal fault of minor importance accommodates Pannonian synkinematic sediments (Figure 6). Seismic interpretations suggested that the ~7 km deep Makó Trough formed along a large-scale eastward dipping detachment (i.e., the Makó detachment) and that the Algyő metamorphic core was exhumed presumably during middle Miocene times [*Tari et al.*, 1999]. However, more recent interpretations demonstrated that the deepest strata drilled in the depocenter of the Makó Trough, down to 5.8 km, are of Pannonian age [*Magyar et al.*, 2006]. This suggests that thick middle Miocene synrift deposits (Badenian-Sarmatian) are only present on the flanks of this depression. These observations point to a strong asymmetry in the extensional system that supports the idea of a detachment, but the main period of extension must be of Pannonian age (Figure 11a), i.e., younger than previously assumed. Correlation of existing wells in the center and the eastern flank of the Makó Trough [*Tulucan*, 2007] indicate that the peak of extension is of Pannonian age, postdating an initial Badenian subsidence event. The pre-Miocene of the Makó Trough and its eastern prolongation contain thick Upper Cretaceous clastics, while these are largely eroded in the flanking highs (Figure 11a). This supports the interpretation of large-scale footwall exhumation during the Miocene extension.

[21] The southern prolongation of the Makó Trough crosses Romania and further south the eastern part of our study area (Figure 3). Extensional deformation is distributed here over a wider area; lower-offset normal faults dipping both westward and eastward form graben and horst-like structures (Figure 7). Hence, the geometry of the Badenian–Sarmatian synrift reflectors demonstrates that this structure is still asymmetric: normal faults with larger offsets dip eastward. The low-amplitude Begejci High marks the western limit of Makó Depression further and the NNE limit of the WNW-ESE oriented Zrenjanin Depression (Figures 3 and 7). The latter contains lower Miocene alluvial to lacustrine rift initiation sediments overlain by thin Badenian–Sarmatian rift climax deposits (Figure 7). Its western boundary is made up by a group of larger offset normal faults dipping NNE that remained active until early Pontian times.

[22] The overall geometry of the N-S (to locally NW-SE) oriented extensional system located along the eastern margin of the Pannonian Basin in Serbia, Hungary and Romania suggests that these depressions are kinematically connected along

Figure 3. Structural map of the pre-Neogene basement of the Pannonian Basin in Serbia and neighboring Hungary and Romania. Note that the map is based on a high-resolution seismic interpretation in areas in Serbia located north of the Sava River and its eastern prolongation along the Danube River (courtesy NIS Gazprom Neft). The contours are also controlled by the entire database of wells drilled in the Serbian part of the Pannonian Basin that have penetrated the pre-Neogene sediments or basement. These wells have a much lower density around and south of the Fruška Gora Mountains and south of the Danube in the vicinity of the Morava River. Therefore, the resolution of the map in these areas is significantly lower. Similarly, the parts of the map located in Hungary, Romania and south of the Sava/Danube River have also a significantly lower resolution (compiled from *Haas et al.* [2010], *Tari and Horváth* [2006], and *Tulucan* [2007]). F4–F11 refer to Figures 4–11, respectively. Isolines numbers are in kilometers. Note that pre-Neogene contacts (color dashed lines) are highly interpretative and locally the map is different than the one of Figure 1b. Not all contacts of Figure 1b were interpreted. AyH, Algyő High; BAD, Banatsko Aranđelovo Depression; BBH, Bački Brestovac High; BCH, Bela Crkva High; BgH, Begejci High; BkD, Békés Depression; BMD, Bački Monoštor Depression; BTD, Bačka Topola Depression; BjH, Bajmok High; BRH, Bački Breg High; CgD, Čurug Depression; CnD, Čantavir Depression; ĐnH, Đurđin High; DrD, Drmno Depression; GjH, Gaj High; KlH, Kljajićevo High; KkD, Kishkunhalas Depression; KMH, Kikinda-Mokrin High; MkD, Makó Depression; MrD, Morović Depression; MoH, Morava High; MsH, Mošorin High; ObG, Obrenovac Graben; OhH, Orahovo High; PcD, Pančevo Depression; PlH, Plavna High; PnD, Plandište Depression; SCD, Srpska Crnja Depression; SfD, Sefkerin Depression; ShG, Sava half graben; SkH, Slankamen High; SMD, Stara Moravica Depression; SMH, Srpski Miletić High; SrD, Srbobran Depression; SsD, Samoš Depression; SzD, Szeged Depression; TcD, Tomnatec Depression; TcH, Telečka High; TrH, Turija High; TrD, Temerin Depression; VlH, Velebit High; ZgD, Zagajica Depression; ZRD, Zrenjanin Depression.

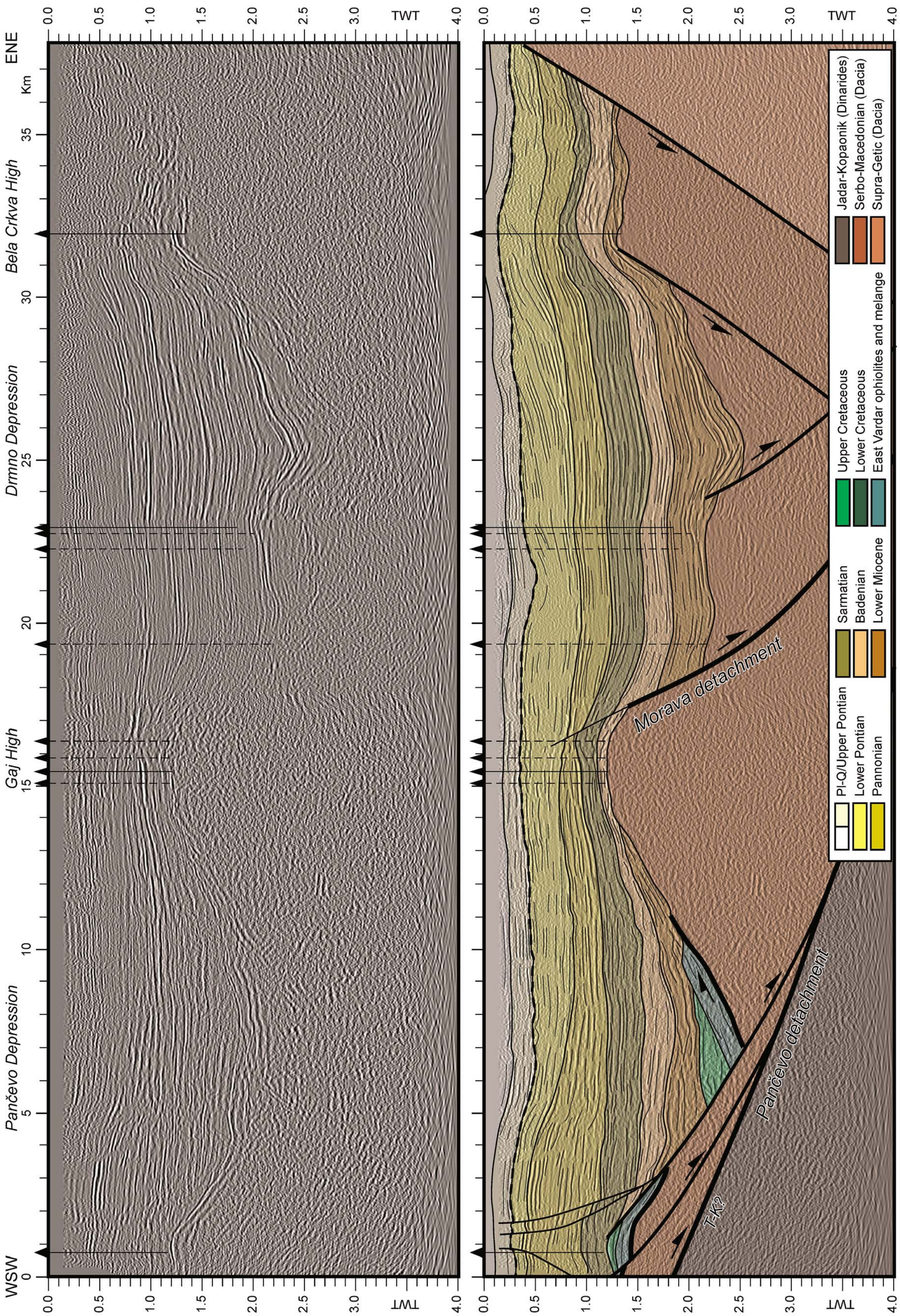

Figure 4. (top) Noninterpreted and (bottom) interpreted versions of a WSW-ENE oriented seismic transect in the southern extension of the Pannonian Basin along the Morava River, immediately south of the Danube River. Location of the cross section is displayed in Figure 3.

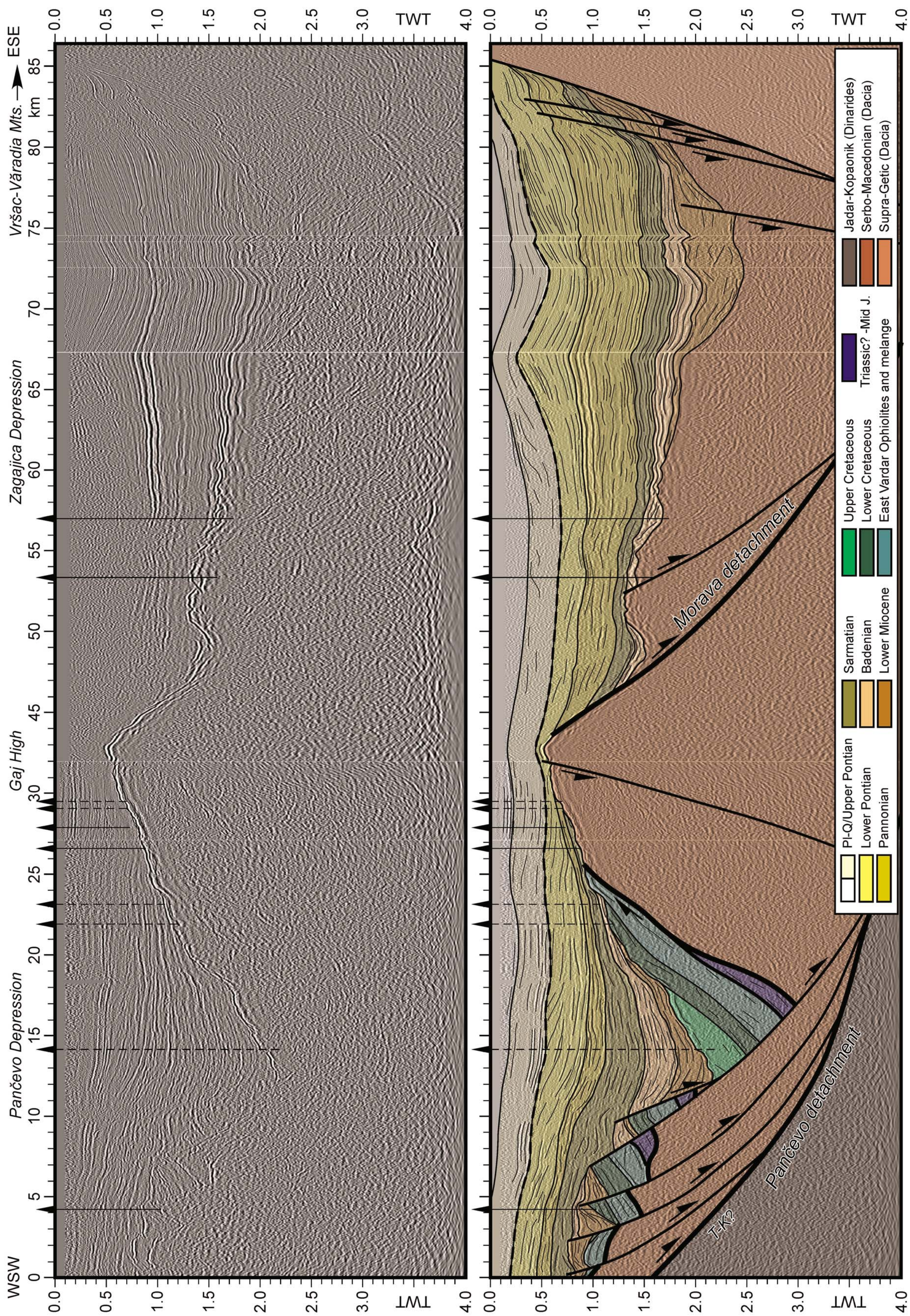

Figure 5. (top) Noninterpreted and (bottom) interpreted versions of a WSW-ENE oriented seismic transect in the SE part of the Pannonian Basin in Serbia, immediately north of the Danube River. Location of the cross section is displayed in Figure 3.

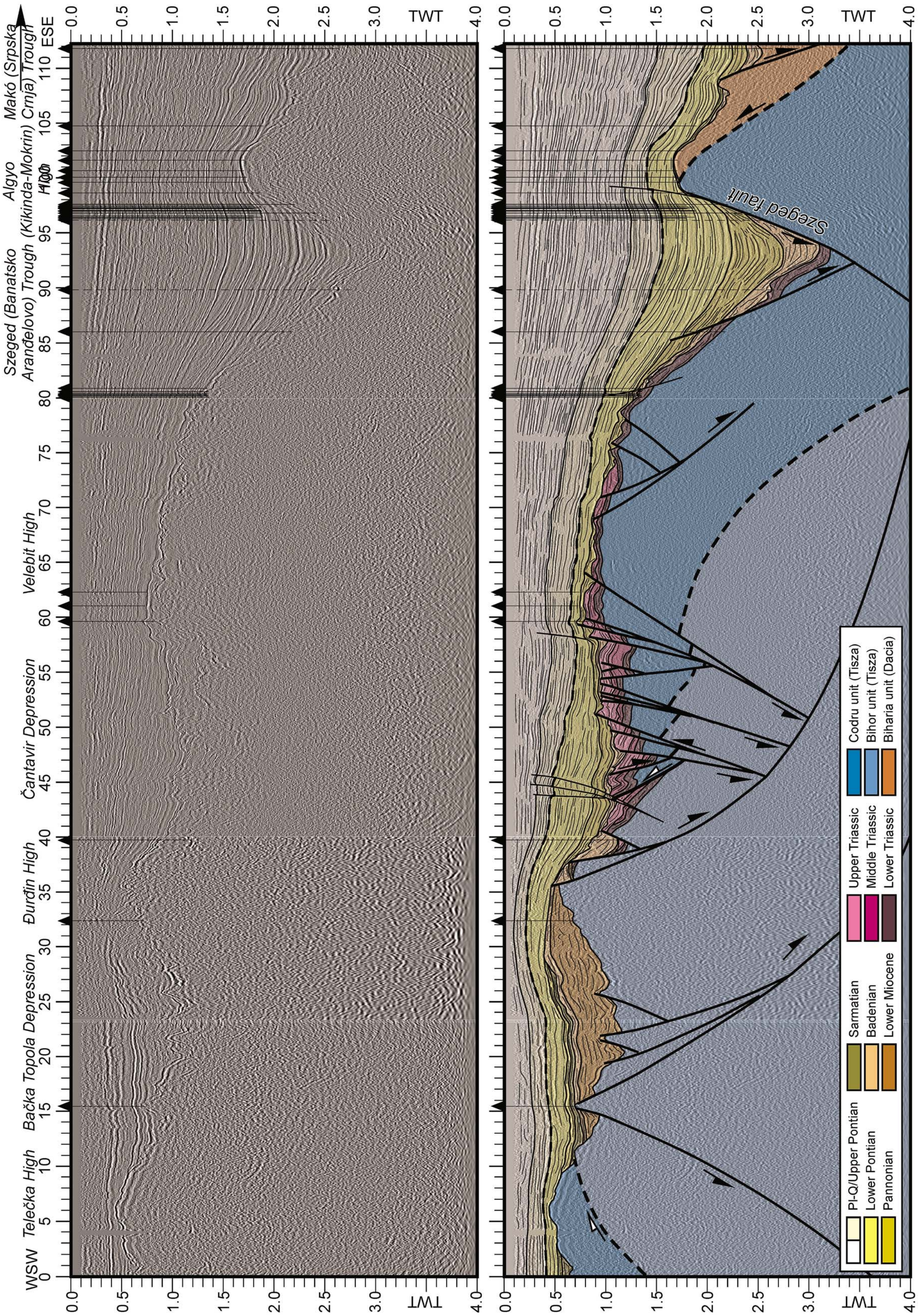

Figure 6. (top) Noninterpreted and (bottom) interpreted versions of a ~E-W oriented seismic transect crossing northern part of Serbia. Location of the cross section is displayed in Figure 3.

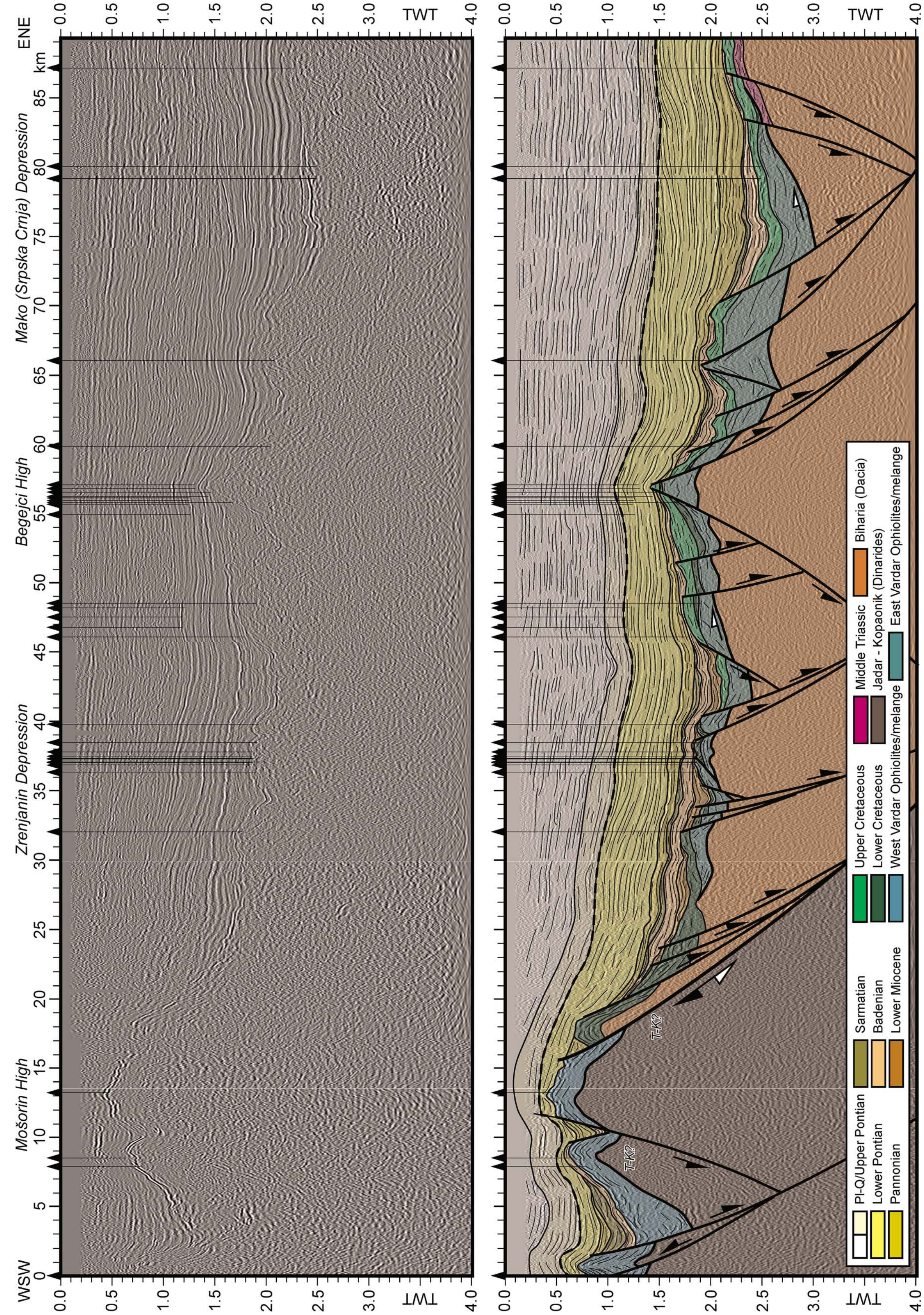

Figure 7. (top) Noninterpreted and (bottom) interpreted versions of a NE-SW oriented seismic transect located in the NE prolongation of the Fruška Gora Mountains. Location of the cross section is displayed in Figure 3.

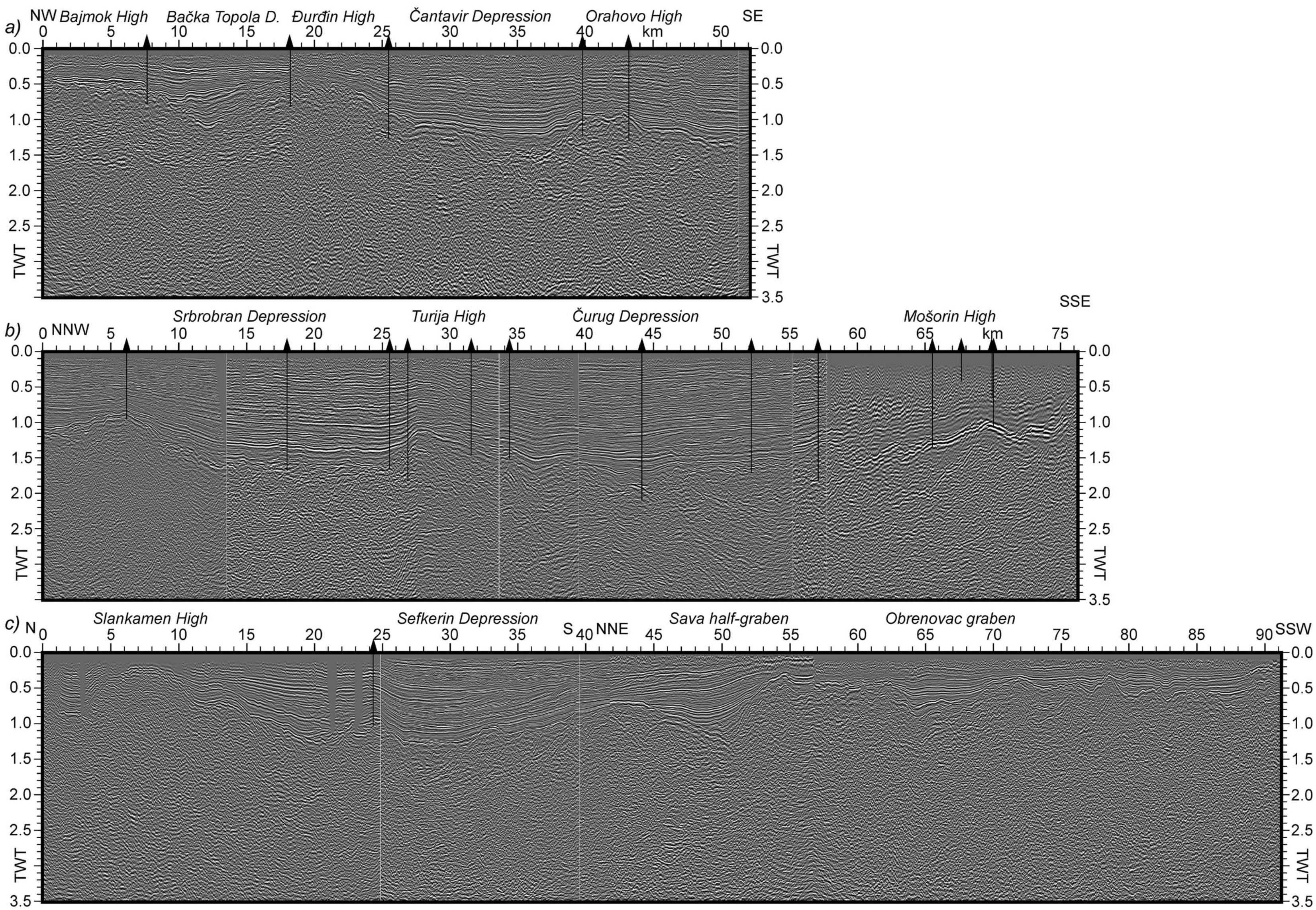

Figure 8. (a–c) Noninterpreted and (d–f) interpreted versions of N-S oriented seismic transect crossing the entire Serbian part of the Pannonian Basin until the connection with the Dinarides. Location of the cross section is partly displayed in Figure 3. Note that Figures 8a–8c and 8d–8f are continuous and are connected into a single transect in Figure 11b.

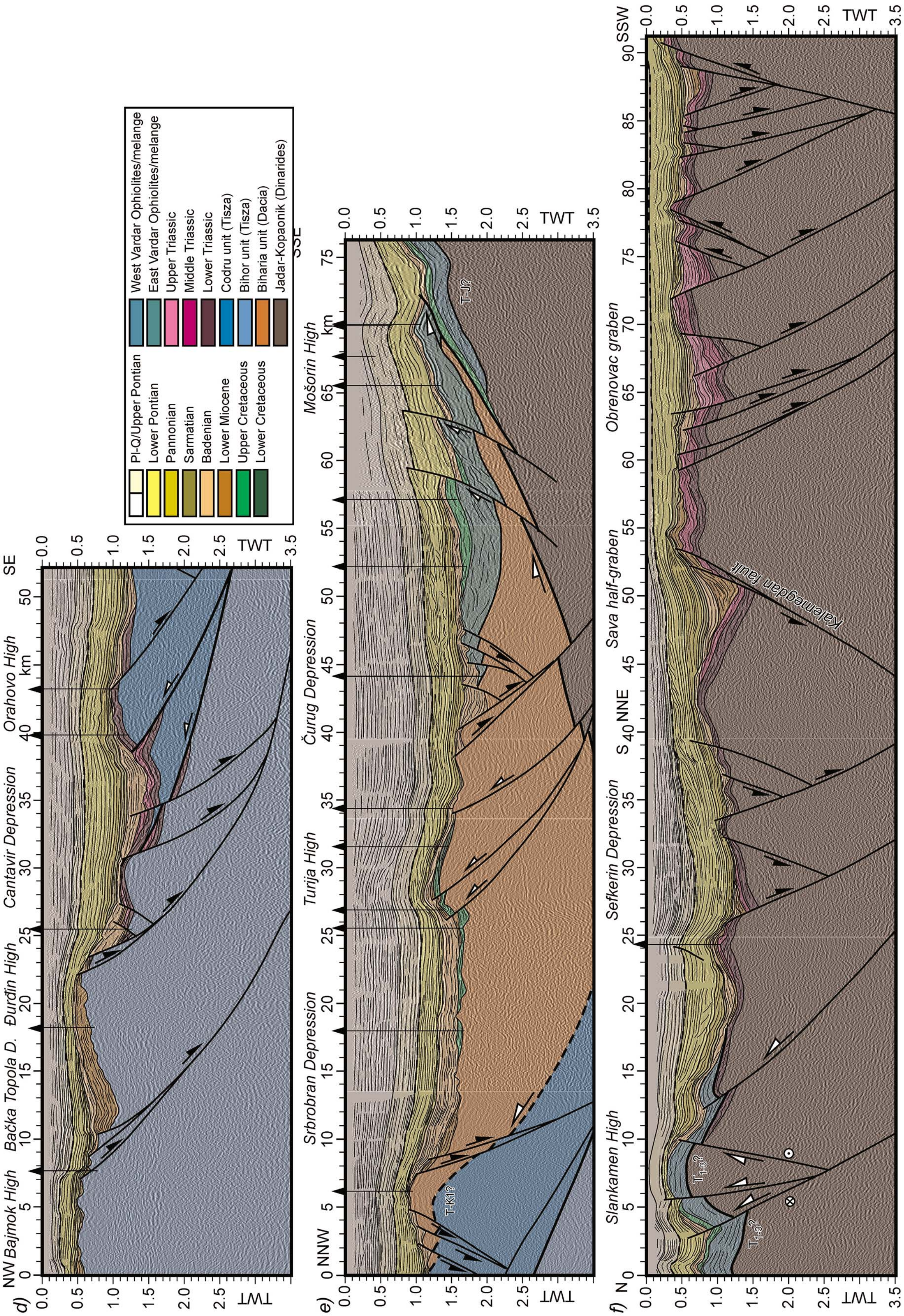

Figure 8. (continued)

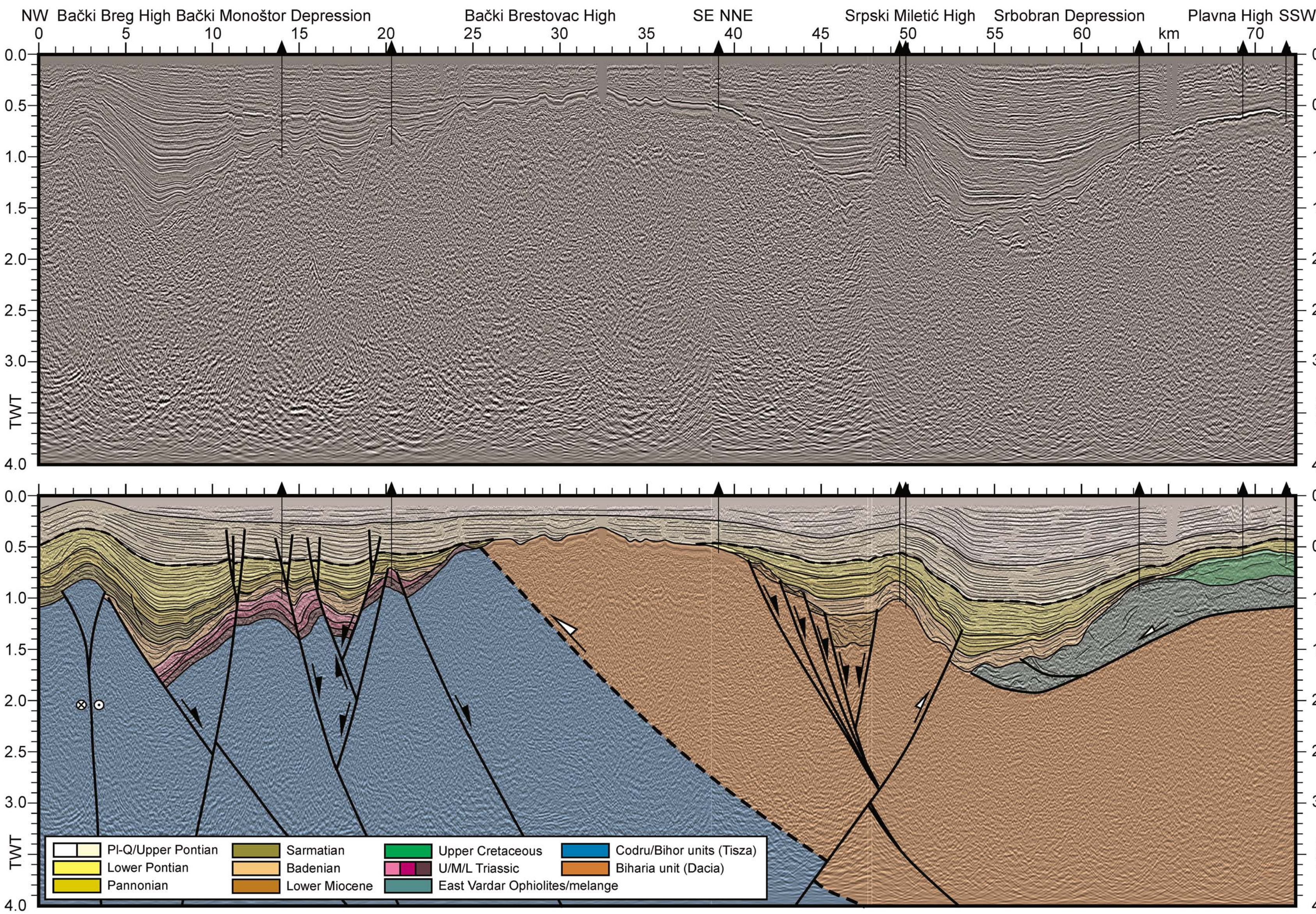

Figure 9. (top) Noninterpreted and (bottom) interpreted versions of N-S oriented seismic transect crossing NW part of Serbia until the connection with the Fruška Gora Mountains. Location of the cross section is displayed in Figure 3.

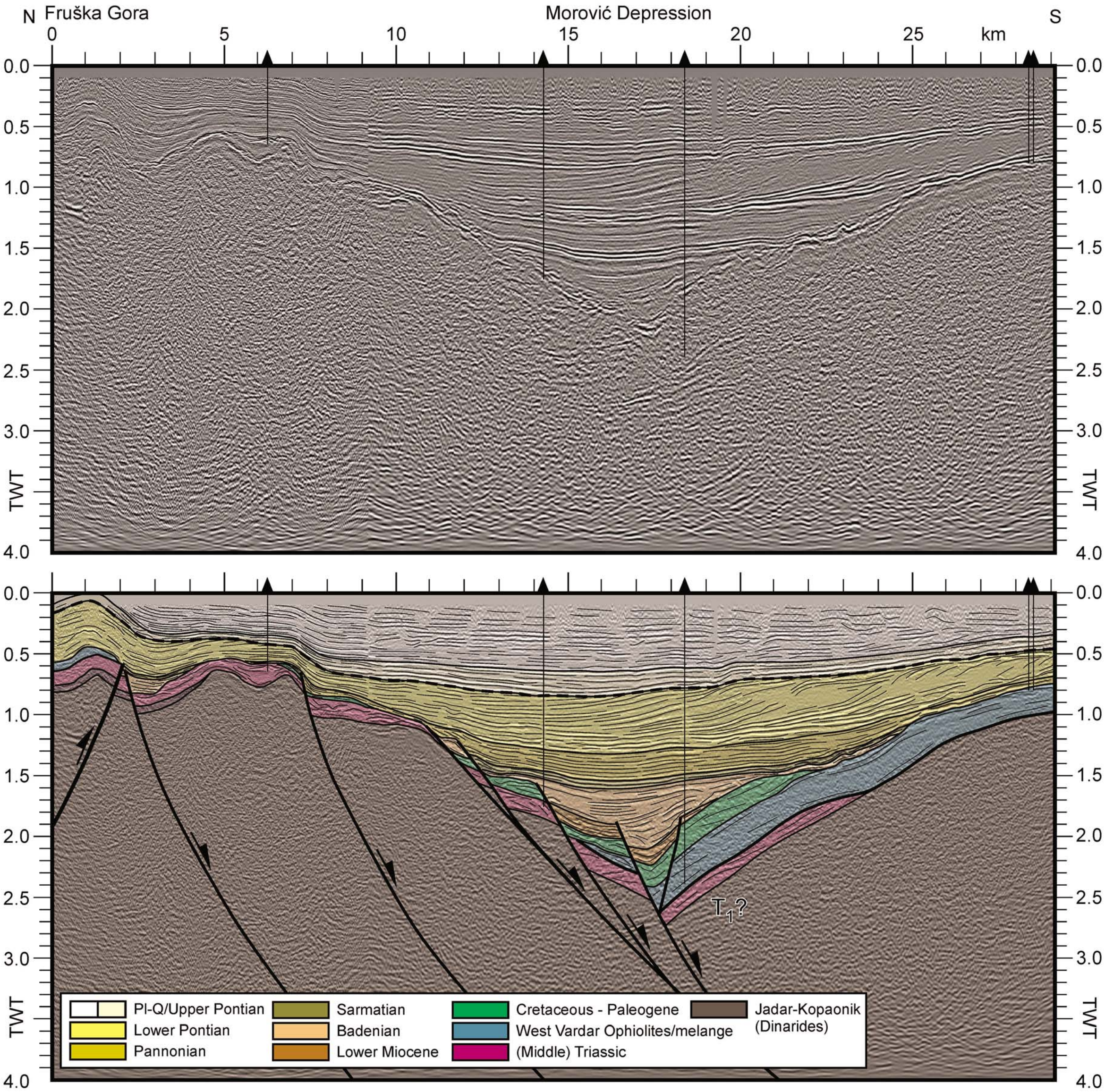

Figure 10. (top) Noninterpreted and (bottom) interpreted versions of a N-S oriented seismic transect located in the SW part of the Fruška Gora Mountains. Location of the cross section is displayed in Figure 3.

their strike (Figure 3). The asymmetric Pančevo Depression and its east dipping detachment (Figures 4 and 5) connect with the Makó Through and its east dipping detachment by exhuming metamorphic cores situated in their footwall (such as Algyő High, Figures 3, 7 and 11a). However, the Szeged and Zrenjanin Depressions are NNW-SSE to WNW-ESE rather than N-S oriented; they are bounded by NNW-SSE to WNW-ESE oriented splay offs from the main N-S striking Pančevo-Makó detachment. The relatively narrow corridor affected by extension south and near the Danube widens northward, the localized Pančevo detachment offset splaying into a large number of normal faults with smaller offsets around the Zrenjanin depression (Figures 3 and 7).

[23] The large offset recorded by the Morava detachment and its associated brittle normal faults is probably transferred from the N-S oriented Drmno/Plandište structures toward north and NE in Romania (Figures 1 and 3). No information is available on this structure beneath the Neogene cover in this area, but one can speculatively assume a prolongation toward a depocenter located south of Timisoara (Figure 3).

3.2. The Miocene Extensional Geometry in NW and Central Part of the Studied Area

[24] The pre-Neogene basement has an overall shallow position in the NW part of the studied area (Figure 3), which affected by a larger number of normal faults with relatively smaller offsets when compared to the regions located more to the east. The Bačka Topola and Čantavir depressions formed along a listric normal fault system dipping SE to SSE associated with few smaller offset antithetic normal faults dipping in the opposite direction (Figures 3, 6 and 8d). In the Bačka Topola Depression, tilted synkinematic reflectors indicate that rift initiation, climax and immediate postrift deposition took place in lower Miocene times, the basin being almost completely filled with lower Miocene alluvial to continental lacustrine sediments. The subsequent Badenian

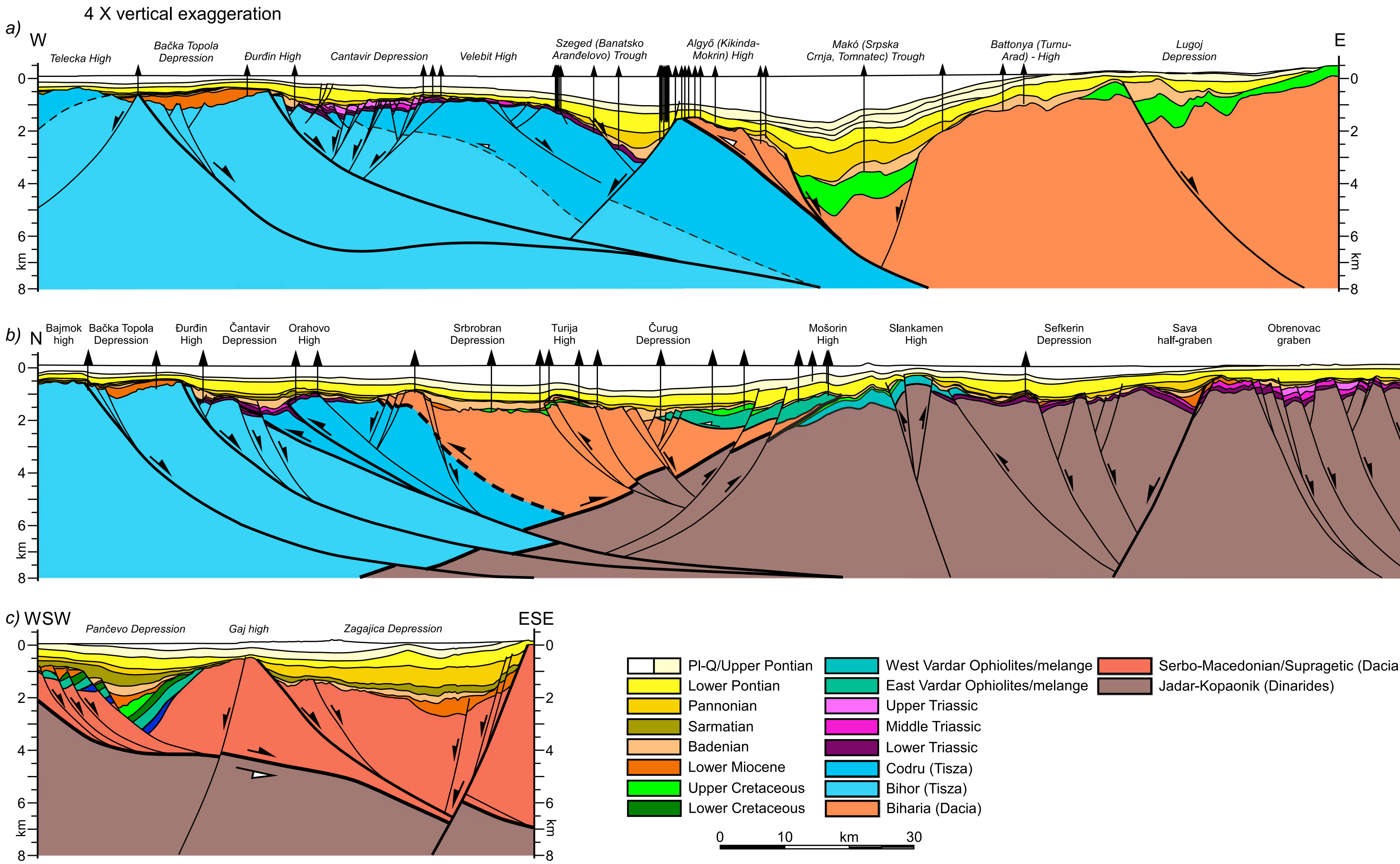

Figure 11. Depth-converted regional transects over the Pannonian Basin of Serbia and Romania. The conversion in depth has used average interval velocities (based on VSP logs) calculated in regionally distributed wells over the studied area. Note that the cross sections are 4 times vertically exaggerated. (a) WSW–ENE regional transect over the northern part of the studied area. The WSW part is the depth-converted interpretation of the seismic transect in Figure 6. The ENE part runs to western limit of the Apuseni Mountains and was compiled from *Răbăgia* [2009] and *Tulucan* [2007]. The location of the transect is displayed in Figures 1b and 3. (b) Depth-converted version of the interpreted seismic transect of Figure 8. (c) Depth-converted version of the interpreted seismic transect in Figure 5.

to Pannonian shallow marine sediments displays only thin postrift deposition. Draping folds are observed at the contact with its NW footwall (i.e., Bajmok High, Figure 8d), suggesting removal by erosion prior to the deposition of thin Sarmatian strata. In the Čantavir Depression, synkinematic reflectors demonstrate a Badenian age of rift initiation and rift climax sequences. These Badenian sediments are overlain by thin Sarmatian or directly by Pannonian postrift deposits (Figures 6 and 8d). The footwall uplift of this structure is observed by the erosional removal of Sarmatian–Pannonian cover along the Đurđin High (Figure 8). In the northwestmost corner of the studied area, the geometry of Bački Monoštor half graben was affected by subsequent Pliocene–Quaternary deformation associated with the formation of the Bački Breg High (Figures 3 and 9). These structures are laterally continuous with larger amplitudes structures in neighboring Hungary, such as the Kishkunhalas Depression (Figure 3). Badenian synkinematic deposits with typical thickness variations are particularly well visible near a large-offset SE dipping normal fault (Figure 9) and are affected by subsequent smaller offset deformation. The Bački Brestovac High and neighboring Telečka High form an area (Figures 3, 6, and 9) that remained under subaerial conditions for the entire extensional evolution, only being covered by a gradual transgression by lacustrine to continental sedimentation during uppermost Miocene–Pliocene times.

[25] An ~E-W oriented corridor located in the center of the studied area and north of Fruška Gora Mountains is characterized by a deeper position of the pre-Miocene basement and cover (Figure 3). The Srbobran Depression is an early–middle Miocene extensional half graben, bounded mainly by SSE dipping low-angle normal faults subsequently distorted by Pliocene–Quaternary thrusting and folding in the area of the Srpski Miletić High (Figures 3 and 9). Rift initiation is made up by lower Miocene continental clastic sediments, extension continuing during early Badenian times, when the footwall located NNW was uplifted and its lower Miocene cover partly eroded, while the hanging wall recorded limited postrift subsidence. More to the east, the northern footwall of the Srbrobran Depression was affected by NNW dipping normal faults with Badenian synkinematic reflectors forming an apparently symmetrical horst (NNW edge of Figure 8e). This symmetry is only apparent, the timing of deformation being different along the two flanks.

[26] More southward, the strike of extensional structures changes to dominantly NW-SE to WNW-ESE oriented, such as the Temerin or Zrenjanin depressions (Figure 3). The Čurug Depression is such a NW-SE oriented (half) graben (Figure 3), where SW dipping normal faults and their antithetic counterparts recorded Badenian synrift deposition (Figures 3 and 8e).

3.3. The Miocene Extensional Geometry in the Vicinity and South of the Fruška Gora Mountains

[27] The Pliocene–Quaternary uplift of the Fruška Gora Mountains has inverted and truncated the predating Miocene extensional structures. Hence, some of the original extensional geometry can be still reconstructed. Miocene strata exposed by the Fruška Gora antiform were deposited in the hanging wall of normal faults that display two orientations [*Čičulić and Rakić*, 1976, 1977]. Normal faults with N-S strike accommodated lower Miocene synrift sedimentation, while subsequent E-W oriented normal faults indicate Badenian–Pannonian synrift deposition [*Toljić et al.*, 2012]. The latter faults are observed on both flanks of the mountains, dipping northward and southward away from the antiform, the overall geometry being the one of a large inverted E-W oriented horst. In the eastern prolongation of the Fruška Gora structure, an asymmetric system of NW-SE oriented normal faults is associated with Badenian–Pannonian synrift sediments that were subsequently deformed by younger shortening (Figures 3 and 7, western flank of the Mošorin High).

[28] South of the Fruška Gora Mountains and north of the Sava River, one ~E-W oriented extensional lineament is made up by two subbasins, the Sefkerin and Morović Depressions (Figure 3). The analysis of synkinematic reflectors in the latter (Figure 10) demonstrates asymmetric synrift deposition of lower Miocene and Badenian strata associated with a series of south dipping normal faults. This was followed by renewed normal faulting during Pannonian times along the northern flank of the depression, accompanied by postrift thermal sag sedimentation during Sarmatian–Pontian times (Figure 10). The latter is absent near the Fruška Gora Mountains, where synrift deposition is connected with south dipping normal faults.

[29] Further southward until the area where the pre-Neogene structure of the Dinarides crop out, a large number of E-W oriented normal faults grouped in both asymmetric and symmetric structures are observed (Sefkerin Depression, Sava half graben, Obrenovac graben and its prolongation southward, Figure 8). The largest structure is the Sava half graben, where a north dipping normal fault accommodates an offset in the order of 1 km and asymmetric tilting/sedimentation. This fault, herewith named the Kalemegdan Fault by association with its lateral prolongation outcropping beneath the Kalemegdan fortress in the city of Belgrade (Figure 3), is associated with lower Miocene-Badenian synrift deposition followed by thin postrift and draping sedimentation during Sarmatian–Pannonian times (Figure 8). It separates the uplifted area located in its footwall south of the Sava River from a northward area that recorded larger subsidence. The only seismic line available south of the Sava River (Figures 3 and 8f) correlated with available surface geological maps indicate an overall E-W strike of the normal faults. These faults are associated with Badenian–Sarmatian synrift deposition. One larger half graben situated in the southern extremity contains lower Miocene continental deposits (Figure 8f).

3.4. Latest Miocene–Quaternary Inversion of the Pannonian Basin

[30] A latest Miocene–Quaternary period of contraction, which created reverse faults or thrusts and large open folds, followed the early Miocene–Pannonian extension. The largest inversion structure is the Fruška Gora Mountains and their prolongation beneath the sediments of the Pannonian Basin along the Slankamen and Mošorin Highs (Figure 3). In outcrops, Pliocene-Quaternary alluvial–continental sediments are gradually tilted, indicating uplift in the center of the mountains and coeval sedimentation in depocenters located along their northern and southern flanks [*Čičulić and Rakić*, 1976, 1977]. The prolongation along the Slankamen High suggests high-angle reverse faults dipping in opposite directions that connect at depth (Figure 8), a geometry that suggests transpression. A high-angle reverse fault is also interpreted along the

southern flank of the same antiformal structure southwest of the Fruška Gora Mountains (Figure 10). The northern flank is truncated by a series of south vergent reverse faults (Figure 8). ENE of the Fruška Gora structure, the seismic interpretation across the Mošorin High suggests a broad anticline flanked by preexisting normal faults, while an inverted normal fault is interpreted westward (Figure 7). Local erosion over the anticlinal culminations and wedge-shaped reflectors along their flanks and demonstrate that inversion started already during lower Pontian times (i.e., uppermost Miocene, Figures 7 and 8).

[31] Inversion structures in the central part of the studied area are associated with synkinematic deposits that indicate an early Pontian age of thrusting onset; deformation continued subsequently until Quaternary times. The Turija High is an ENE-WSW oriented uplifted area along a system of NNW vergent thrusts (Figures 3 and 8e). Westward, the Srpski Miletić High is a similarly ENE-WSW oriented structural culmination that formed due to a SSE vergent trust (Figure 9). Further north, the Orahovo High (Figure 8d) formed in relationship with a north vergent thrust fault that is associated with erosion over the structural culmination and synkinematic reflectors along its flanks. In the northwestmost corner of the studied area, the Bački Breg structure forms a symmetrical open anticline that is located above what appears to be a positive flower structure (Figure 9), which is laterally continuous in neighboring Hungary with the uplifted area NW of the Kishkunhalas Depression (Figure 3).

3.5. Pontian–Quaternary Subsidence

[32] The early to late Miocene (Pannonian) extension was followed by highly variable amounts of postrift subsidence that spans from kilometers thick to no deposition and/or erosion. An initial period of postrift deposition was subsequently followed by large-scale sag subsidence and associated sedimentation during Pontian–Quaternary times, partly coeval with the inversion of the Pannonian Basin. Similar with places outside our study area, such as in Hungary to the north, sedimentation is dominated by large-scale progradations that mark the transition from lacustrine endemic to deltaic and, subsequently, to thick continental alluvial sedimentation [e.g., *Juhász et al.*, 2007; *Magyar and Sztanó*, 2008; *Pigott and Radivojević*, 2010; *Sztanó et al.*, 2012, and references therein]. This large-scale subsidence is the main Tertiary feature that dominates the entire studied area and is visible in all studied seismic lines (Figures 4–10).

[33] The large-scale progradation is characterized by typical topset-foreset-bottomset geometries (e.g., Figure 6). The overall progradation is asymmetric; the main influx was driven from a source area with an arcuate geometry comprising the NW, north and NE (Transdanubia, central part of the Pannonian Basin and Apuseni Mountains, respectively) prograding toward the SE, south and SW. Obviously, the age of progradation is older toward these source areas. This feature is the prolongation of a same progradational geometry dominating the central areas of the Pannonian Basin in Hungary and Romania [e.g., *Juhász et al.*, 2007; *Magyar et al.*, 2012; *Răbăgia*, 2009; *Vakarcs et al.*, 1994, and references therein] and possibly in Croatia. A secondary source with a significantly lower importance is the Dinarides and neighboring South Carpathians. This is visible via progradations in opposite directions, i.e., westward from the South Carpathians margin (eastern part of Figures 4 and 5), northward and eastward from the Dinarides (Figures 5, 8, and 10). This overall geometry demonstrates a strong asymmetry in the alluvial–deltaic system filling the Great Hungarian Plain that was driven by the existence of two major fluviatile systems rapidly filling the basin from the NW, north and NE during Pontian–Quaternary times, possibly representing the precursors of the present-day Danube and Tisza Rivers [see also *Juhász et al.*, 2007; *Magyar and Sztanó*, 2008].

[34] The age of the prograding foresets is almost entirely lower Pontian in the studied area. Older Pannonian foresets with reduced thickness and geometries are observed only near the South Carpathians and Dinarides (Figures 4, 5, 8, and 10). Younger upper Pontian foresets are documented by wells only on the western flank of the Makó trough (Figure 6), suggesting that coeval fluviatile-deltaic sedimentation was present only in this limited area of the Pannonian Basin. This type of sedimentation makes the bulk of the regressive Pannonian Basin fill in the restrictive upper Miocene and subsequent Pliocene–Quaternary lacustrine alluvial environment [e.g., *Sztanó and Mezaros*, 2006, and references therein].

4. Inferences for the Pre-Miocene Evolution Derived From Wells and Seismic Interpretation

4.1. Dacia and Tisza Megaunits

[35] The Dacia, megaunit including its sedimentary cover and eastern Vardar obducted ophiolites, is documented beneath the Neogene cover in the eastern and central part of the studied area (Figures 1 and 3). Late Jurassic obducted ophiolites and/or ophiolitic mélange in the Pančevo Depression were overlain by shallow water Lower Cretaceous (limestones and "paraflysch") and/or deep-water Upper Cretaceous turbidites (Figures 3–5) [see also *Čanović and Kemenci*, 1988]. Wells have penetrated a metamorphic basement that lies eastward directly beneath the Miocene cover. This basement can be correlated southward with the outcropping high-grade metamorphic units of the Serbo-Macedonian Massif (Figure 3). The large high-angle normal fault that bounds the Zagajica Depression to the east (Figure 5) corresponds to the contact between the Supragetic and Serbo-Macedonian units that crops out in the small inselberg of the Vršac/Văradia Mountains (Figure 3). Here, high-grade metamorphic rocks (gneisses, granodiorites, amphibolites) of Serbo-Macedonian affinity are in contact with low-grade metamorphic units (lower grade biotite-chlorite schists, albite gneisses) of the Supragetic nappe [see also *Kräutner and Krstić*, 2003; *Kräutner and Bindea*, 2002]. Our field observations indicate a transitional area between the two units characterized by retromorphism of the high-grade Serbo-Macedonian rocks. This situation is very similar with other contact areas affecting Supragetic units in the South Carpathians that are retromorphosed during pre-Mesozoic times [*Săndulescu*, 1984]. Therefore, this contact was not mapped out as being part of the Cretaceous-Eocene nappe stack of either South Carpathians or Dinarides.

[36] More to the north, wells have penetrated Upper Cretaceous limestones and clastic rocks that overlie ophiolites and/or ophiolitic mélange (Figure 7). Thin Jurassic–early Lower Cretaceous basinal and deep-water sediments were found in few wells [*Čanović and Kemenci*, 1988]. These sediments are most probably part of an ophiolitic mélange that together with the overlying ophiolites are remnants of the

eastern Vardar ophiolitic unit, which was obducted eastward over the Serbo-Macedonian Massif during late Jurassic times. This is observed in our seismic lines by thrusting over non-metamorphic Middle Triassic sediments that unconformably overlie the Serbomacedonian basement (eastern edge of Figure 7).

[37] Northward, the footwall of the Szeged normal fault is made up by the high-grade metamorphic rocks of the Algyő High (Figure 6). These high-grade rocks are affected by a Permian age low-pressure amphibolite facies metamorphism that was later overprinted by a pressure-dominated eo-Alpine metamorphism. This metamorphic history was recorded in rocks drilled in Algyő High areas located immediately to the north in Hungary [*Lelkes-Felvári et al.*, 2005]. These rocks are correlated with the medium to high-grade Middle-Late Jurassic and Early Cretaceous metamorphic overprint of the Biharia nappe in the Apuseni Mountains (Figure 3) [*Dallmeyer et al.*, 1999; *Schmid et al.*, 2008]. The metamorphic rocks of this nappe are often overlain by thick sequences of Upper Cretaceous–lowermost Paleogene turbidites (Rimeti and Bozes flysch [*Schuller et al.*, 2009]). The absence of such sediments overlying the Algyő metamorphic basement suggests significant post-Cretaceous exhumation and erosion. However, we cannot completely exclude the presence of metamorphic rocks belonging to the Tisza unit in the Algyő High (Figure 6).

[38] The Biharia basement extends from the Algyő High south and westward (around Bački Brestovac and Srpski Miletić highs, Figure 3) in a zone of where a Cretaceous age basinal, carbonatic, pelagic, deep-water and turbiditic facies overlies directly the metamorphic basement. Following the tectonic contacts observed in the Apuseni Mountains, the metamorphosed Biharia basement should be thrusted northwestward over the Tisza unit, which in turn should contain a nonmetamorphic Triassic sequence (Figure 1b) [*Balintoni et al.*, 1996]. However, such a contact is not obvious in seismic lines and therefore is only speculatively suggested (Figures 8 and 9). More southward, the same Cretaceous sequence described above overlies the East Vardar ophiolites and ophiolitic melange (Figures 8 and 9) [see also *Čanović and Kemenci*, 1988].

[39] The pre-Miocene sequence in the hanging wall of the Szeged normal fault was drilled by numerous wells and is made up by nonmetamorphosed continental to shallow marine Lower Triassic sediments (Figure 6). These sediments are overlain westward by shallow marine Middle–Upper Triassic limestones and clastics (Velebit High, Figure 6). A similar Middle Triassic sequence overlies the hanging wall of the Szeged Depression immediately northward in Hungary [*Haas et al.*, 2010]. The same type of Triassic sediments is often drilled by wells in the NW part of the studied area [*Čanović and Kemenci*, 1999]. This shallow marine carbonatic facies is typical for the Tisza unit, as found cropping out in the Apuseni Mountains [e.g., *Balintoni et al.*, 1996]. The Triassic sequence was often removed by erosion in the footwall of normal faults, where wells have encountered metamorphic rocks with local migmatitic intrusions and rhyolitic volcanics directly beneath the Neogene sediments (Figures 6 and 8). In the same area, the Triassic sequence is duplicated by top-NW thrusts that truncate pre-Neogene sediments (e.g., in Čantavir Depression, Figure 8d). This is compatible with the kinematics of the intra-Turonian tectonic event of the Apuseni Mountains, which is responsible for the thrusting recorded by the Biharia and Tisza nappe stack [e.g., *Merten et al.*, 2011; *Schmid et al.*, 2008, and references therein]. The pre-Neogene deformation observed in the Čantavir Depression may represent the intra-Turonian thrusting of the Codru nappe over the Bihor unit [*Balintoni*, 1994]. This implies that the large-scale antiformal structure exposing beneath the Neogene sediments the metamorphic basement of the Bačka uplift (Bački Brestovac High, Telečka High, Bačka Topola Depression) and Triassic sediments along its flanks (Čantavir and Bački Monoštor Depressions, Figures 3, 6, 8, and 9) is the lateral prolongation of the large-scale Bihor dome that formed during Late Cretaceous times in the Apuseni Mountains (Figure 1) [*Merten et al.*, 2011].

4.2. Dinarides and Sava Suture Zone

[40] In the SW part of the studied area (Figures 8 and 10), the metamorphosed basement is overlain by Lower Triassic clastic-carbonatic and evaporitic sediments, Middle Triassic shallow water and partly hemipelagic deposits, Upper Triassic recrystallized and deep water limestones, slightly metamorphosed calc-schists, nodular, brecciated and silicified limestones. This succession is tectonically overlain by (serpentinized) ophiolites and/or ophiolitic mélange [see also *Čanović and Kemenci*, 1999]. This is a typical sequence of distal Adriatic margin obducted by West Vardar ophiolites in Late Jurassic–earliest Cretaceous times [*Dimitrijević*, 1997; *Schefer et al.*, 2010] that overlie the low-grade metamorphosed Paleozoic sediments of the Jadar unit. Therefore, this area has been assigned to the Dinaridic units.

[41] The pre-Neogene structure in and around the Fruška Gora Mountains is a rather complex one due to the proximity of the Sava suture zone (Figure 1). The overall structure is the one of a large antiform exposing in its core a metamorphosed Triassic sequence of Adriatic affinity that is overlain by metamorphosed Upper Cretaceous turbidites [*Toljić et al.*, 2012]. This metamorphic core is located in the footwall of a large-scale late Oligocene–early Miocene extensional detachment and is truncated by subsequent middle Miocene normal faults. Along the flanks of the antiform, the detachment hanging wall exposes a metamorphic basement that is covered by a highly deformed Triassic clastic-carbonatic sequence of Adriatic affinity, West Vardar ophiolites and ophiolitic mélange, uppermost Cretaceous shallow marine limestones and deep-water turbidites, locally intruded by Paleogene volcanics [*Toljić et al.*, 2012]. The metamorphosed and nonmetamorphosed Upper Cretaceous turbidites are relicts of the Sava suture zone as defined in neighboring Bosnia and Croatia [*Toljić et al.*, 2012; *Ustaszewski et al.*, 2010]. Such a structural complexity, involving metamorphosed and nonmetamorphosed rocks of the same age including sediments of Dinaridic affinity and relicts of the Sava suture zone, cannot be resolved by available seismic and well data. One interesting observation is the absence of Cretaceous sediments in the wells drilled in the area between the Fruška Gora Mountains and Dinarides (Figure 8f) [see also *Čanović and Kemenci*, 1999]. Therefore, the distribution of sediments of the Sava suture zone is probably exaggerated in this area of Figure 1b.

[42] The contact between the Sava suture zone and the European (Tisza and Dacia) margin is also difficult to map out because the uppermost Cretaceous turbidites, characteristic for the Sava suture zone [*Schmid et al.*, 2008; *Ustaszewski et al.*, 2010], were also deposited over the Dacia unit and its

overlying eastern Vardar ophiolites (Figure 7) [*Čanović and Kemenci*, 1988]. This contact must be located north of the Fruška Gora Mountains, whose basement, cover and ophiolites have a western Vardar affinity (Figure 3) [*Toljić et al.*, 2012]. We assume that the contact is located along a large reverse fault dipping northward north of the Slankamen High (Figure 8). Hence, ophiolites are drilled on both sides of the fault (probably eastern Vardar in contact with western Vardar), and therefore seismic lines cannot be fully diagnostic (Figure 8). More eastward, this contact is located near the western boundary of the Zrenjanin Depression (Figure 7), where drilled wells suggest a lateral transition from Lower Cretaceous clastics and shallow water carbonates in Urgonian facies in the east, assumed to be of European affinity, to western Vardar obducted ophiolites and ophiolitic mélange in the west. The group of Miocene normal faults located at the western end of the Zrenjanin Depression may have reactivated an earlier west vergent contact between Dacia (Serbo-Macedonian) and Dinarides (Jadar-Kopaonik) units (Figure 7).

5. Miocene–Quaternary Kinematics of the SE Part of the Pannonian Basin and Inferences for Its Pre-Neogene Geometry

[43] The analysis of deformation structures identified by seismic interpretations correlated with calibrating wells and regional inferences derived from surface mapping and kinematic studies enable a quantitative analysis of the evolution of the Pannonian Basin in its SE area.

5.1. Mechanics of Extension in the SE Part of the Pannonian Basin

[44] Our results demonstrate that the extension was fundamentally asymmetric in geometry, the deformation migrating in space and time across the basin. The synrift time span is substantially larger than previously assumed; that is, it covers the entire time period from early Miocene to early Pontian times, i.e., it lasted from 20 to 8–5.5 Ma. The moment when the extension ceased is fairly well constrained in seismic lines, but its absolute age (i.e., the 8–5.5 Ma) is rather uncertain, due to unresolved biostratigraphic correlations of the lower Pontian limit in Central Paratethys.

5.1.1. Extensional Asymmetry Versus Synrift Ages

[45] The presence of major detachments accommodating exhumation of core complexes has always been speculatively inferred in the subsurface of the Great Hungarian plain based on footwall geometries and low-angle attitude of normal faults [*Tari et al.*, 1999; *Tari and Horváth*, 2006]. Similarly, typical seismic geometries suggest the presence of major detachments at the transition between the Carpathians and Dinarides (Figures 4 and 5). These detachments have been recently documented in the Fruška Gora, Bukulja and Cer Mountains (Figure 3) to accommodate footwall uplift in the order of 10–15 km [*Stojadinović et al.*, 2012; *Toljić et al.*, 2012]. Near the Morava valley, the contact between Serbo-Macedonian and Jadar-Kopaonik dips westward in outcrops near Bukovac, being connected with a large detachment dipping eastward that crops out in the Bukulja Mountains (Figure 3) (L. Matenco et al., Superposed orogenic collision and core complex formation at the present contact between the Dinarides and the Pannonian Basin: The Bukulja and Cer Mountains in central and western Serbia, submitted to *Global Planetary Change*, 2012). This means that the Pančevo detachment has an antiformal geometry west of the seismic lines depicted in Figures 4 and 5 and connects with the detachment that crops out on the eastern flank of the Bukulja Mountains. The overall geometry is the one of a detachment folded by isostatic rebound during footwall exhumation [see *Lister and Davis*, 1989] of a Serbo-Macedonian dome that crops out in the center of the Morava valley (Matenco et al., submitted manuscript, 2012).

[46] Deformation patterns in an E-W oriented regional cross section that extends to the border with the Apuseni Mountains indicate asymmetric extensional patterns, the structures being younger eastward (Figure 11a). The deformation is dominated by low-angle normal faults, the most important ones dipping northeastward or eastward, associated with higher-angle antithetic normal faults (Figures 3 and 11a). Offsets along these listric faults are associated with antithetic block rotations and footwalls exhumation that created the regional asymmetry of the uppermost Miocene–Quaternary postrift basin fill (Figure 11a). These geometries are visible by antithetic rotations of basement or sedimentary cover in, for instance, the Bačka Topola Depression, Makó Trough or Pančevo Depressions (Figures 11a and 11c). Footwall uplift is evident by erosional removal of strata both in the case of large offset structures, such as the Algyő or Gaj Highs, and when faults display smaller offsets, such as the Telečka or Đurđin Highs (Figure 11a). This type of geometry is characteristic for series of low-angle detachments that form in simple shear extension. In this situation, the gradual isostatic uplift of footwalls creates asymmetric basins that are abandoned and successive younger detachments form in the transport direction [e.g., *Lister and Davis*, 1989]. This is compatible with observations in the studied area: relatively older basins are located southwestward and westward, and other basins are gradually younger toward the NE and east. For instance, the simple shear extension has created the early Miocene Bačka Topola Depression, the Badenian Čantavir Depression and Szeged Trough, and the deep Pannonian Makó Trough (Figure 11a). Similarly, in the southern part of the studied area, the extension is associated with a gradually younger extension that peaks in Badenian times in the Pančevo Depression and becomes gradually Sarmatian–early Pontian in the Drmno/Plandište/Zagajica Depressions (Figures 11a and 11c). The exception to this overall rule is the Badenian—early Sarmatian period of extension that has a larger areal extent. Compared with early or late Miocene normal faults, middle Miocene extensional (half) grabens formed also in areas that are located either more westward or southward than early Miocene normal faults, such as the Bački Monoštor Depression or the Bački Breg High (Figures 3 and 9) or more eastward than late Miocene structures, such as the Lugoj Depression (Figure 11c). In other words, the extension started during early Miocene times near the Dinarides, continued everywhere during middle Miocene and finished during late Miocene times close to the Apuseni Mountains and South Carpathians. Furthermore, the extensional age changes along the strike of the same structure: normal faulting in the Pančevo structure is early Miocene–early Sarmatian, while in its northern prolongation in the Makó Trough is essentially Pannonian (Figures 11a, c).

[47] The wider distribution of Badenian–early Sarmatian (half) grabens is correlated with a different extensional

geometry. Early and late Miocene structures are fundamentally asymmetric and formed in relationship with major NE and east dipping low-angle normal faults. This is also valid for middle Miocene structures that formed in the SE part of the studied area (e.g., Pančevo Depression, Figure 11c). While still controlled by low-angle listric faults, the asymmetry decreases in the case of middle Miocene structures located in the center or the SW part of the studied area (such as the Zrenjanin, Morović or Čantavir Depressions, Figures 7, 10, and 11a).

[48] The style of extension has a direct expression in sedimentological facies and biostratigraphical evolution. The onset of asymmetric extension in early Miocene times has resulted in the deposition of continental alluvial to lacustrine rift initiation sediments. Similar to other extensional detachments superposed over older orogenic structures, most notably in the Great Basins and Range province [e.g., *Eaton*, 1982; *Wernicke*, 1985], the asymmetric Miocene extension associated with block rotations and large footwall exhumation affected a Dinaridic crust thickened by predating Cretaceous–Eocene orogenic processes and created only comparatively thin basins filled with continental sediments that were situated at high elevations above sea level. A large number of such isolated, endemic lower–middle Miocene basins are still preserved over the Dinarides and their junction with Eastern Alps that form the so-called Dinaridic Lake System [*de Leeuw et al.*, 2010; *Harzhauser and Mandic*, 2008]. The largest expression of such an endemic continental system can be presently found along the Morava River in central and southern Serbia (Figures 1b and 3), where the asymmetric extension has resulted in thin continental sedimentation deposited in hanging walls during early Miocene times (Figure 11c), coarse alluvial conglomerates and sandstones being covered by lacustrine marls.

[49] The more symmetrical extension that took place during middle Miocene times has resulted in the localization of significant subsidence in the center of (half) grabens, which created the generalized marine transgression and deepening of the sedimentological facies during Badenian–Sarmatian times. Near the limit with the Pannonian, the rapid uplift of the Carpathians severed the connection with the eastern Paratethys and shed large amounts of sediments that resulted in a gradual regressive stage of basin fill. This stage was interrupted by the large-scale asymmetric Pannonian–early Pontian extension that took place near the South Carpathians and Apuseni Mountains and created deep extensional structures, such as the Makó Trough or the Drmno/Plandište/Zagajica system.

5.1.2. Extensional Structures in Map View

[50] In map view, the direction of extensional structures is highly variable (Figure 3) from NE-SW to N-S near the limit with South Carpathians and Apuseni Mountains, NW-SE to WSW-ENE in the north, NW and central part of the studied area, to W-E oriented in the area south of the Fruška Gora Mountains. No significant transcurrent deformation accompanying the Miocene extension could be identified by our study, although local strike-slip faults cannot be completely excluded. These apparently contrasting directions of extension can be better understood in the overall context of Pannonian back-arc deformation.

[51] The arcuate orogenic shape of the East and South Carpathians (Figure 1) was acquired during translations and 90° Paleogene–Miocene rotations around the Moesian corner (Figure 1a) [e.g., *Csontos*, 1995; *Ratschbacher et al.*, 1993]. These rotations are recorded in the Tisza-Dacia unit as far west as the Apuseni Mountains [*Pătraşcu et al.*, 1990, 1994]. In contrast, the Adriatic units have recorded 20° counterclockwise rotations since 35 Ma, generally driven by the northward push of Africa during collision with Europe [*Handy et al.*, 2010; *Márton et al.*, 2010; *Ustaszewski et al.*, 2008]. These observations imply that the Pannonian Basin area, located in between the Adria/Dinarides and Apuseni Mountains, should have accommodated these substantial differences in terms of opposite sense rotations. At a more local scale, paleomagnetic investigations in Fruška Gora have observed ∼80° counterclockwise rotations between the emplacement of Eocene volcanics and middle Miocene, being followed by ∼40° clockwise rotations since the end of Miocene times [*Lesic et al.*, 2007]. Although these latter values appear exaggerated, possibly due to local block rotations, these rotations imply that Fruška Gora underwent the Carpathians/Apuseni Mountains kinematics together with intervening areas during the early-middle Miocene extension.

[52] These constraints imply that the variability of extensional directions observed in the study area does not reflect a change of the tensional stress field with time. This is justified by the observation that structures with presently different strike were formed coevally. The mechanism must be the relative and gradual clockwise rotation of central and northern parts of the studied area during Miocene times. This mechanism implies different amounts of rotation in the two areas that presently have different Dinaridic strikes following the change in the present-day orientation of the Sava suture zone, E-W versus N-S (Figures 1b and 3). In the first area, the N-S oriented lineament near the Apuseni Mountains was initially parallel with the E-W strike of the Dinarides, being rotated clockwise during Miocene times (Figure 12). The rotation was accommodated by different amounts of extension decreasing toward a rotational pole located southeastward. Extensional structures that are closer to the Dinarides have a strike closer to E-W, while structures closer to the Apuseni Mountains have a strike closer to N-S. The few exceptions to this overall rotational mechanism (such as the Bački Monoštor or the Srobrobran Depressions) do not change this first-order pattern (Figures 3 and 12). Similarly, the second area shows a rotational change in strike during extension but less important (up to 45°). These structures are N-S to NNW-SSE near the Dinarides and change to N-S to NE-SW near the South Carpathians although kinematics across the border in Romania is less clear (Figure 3). This rotation is also accommodated by gradually decreasing the amount of extension toward the same pole of rotation (Figure 12). The rotational mechanism is in agreement with the decrease of fault offsets and size of early–middle Miocene basins southward in the "peri-Pannonian" domain along the Morava River (Figure 1c). The extension is still significant in the area of Jastrebac Mountains (Figure 1b) [*Marović et al.*, 2007b] but seems to disappear southward near the boundary with Republic of Macedonia/FYROM, where the pole of rotation should be located (Figure 12).

[53] The clockwise rotation of the South Carpathians and Apuseni Mountains in respect to the Dinarides accommodates the movement of the former into the external Miocene Carpathian embayment, presumably driven by the rollback of the external Carpathians slab [e.g., *Ustaszewski*

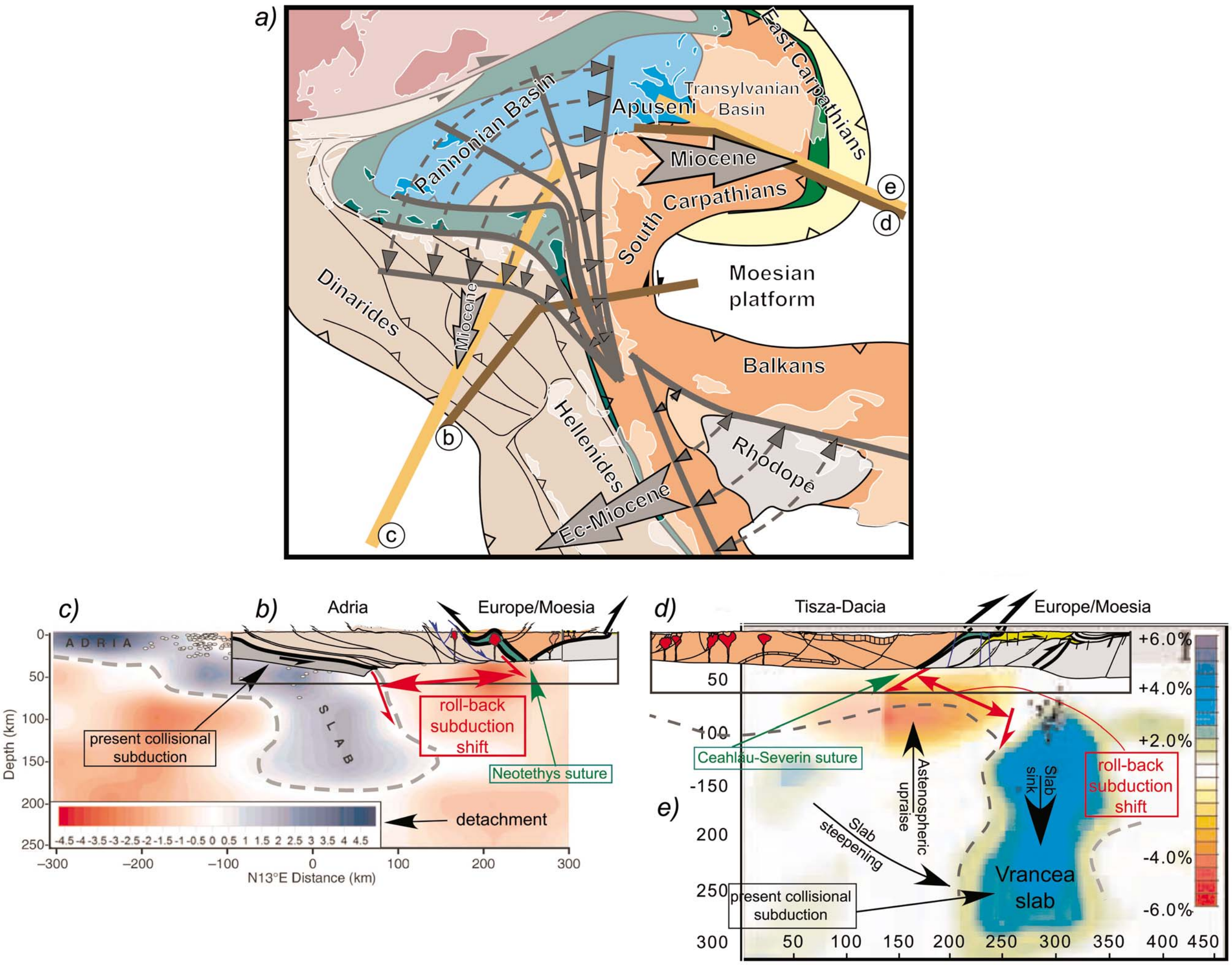

Figure 12. (a) Simplified map view sketch of the kinematic mechanism of extension in the Pannonian Basin illustrating the rotation of the Carpathians–Apuseni Mountains units in respect to the Dinarides (same legend as in Figure 1a). The presence of extension in the area adjacent to the Moesian platform cannot be explained by Tisza-Dacia rotation and must assume a component of rollback-driven extension in the Dinarides. (b–e) Illustration of the concept of shift between an oceanic suture zone and the present position of the slab driven by rollback subduction, by overlaying crustal-scale cross sections in Dinarides (Figure 12b, see Figure 1c) and Carpathians (Figure 12d, simplified and redrawn from *Matenco et al.* [2010]) over teleseismic tomography transects in Figures 12c [*Bennett et al.*, 2008; *Piromallo and Morelli*, 2003] and 12e [*Martin and Wenzel*, 2006]. The location of the main suture zones is taken from *Schmid et al.* [2008]. The detailed geometry of the upper crustal portion of profile in Figure 12d is displayed in Figure 13a.

et al., 2008, and references therein]. However, one piece of the puzzle does not fit the application of this rollback mechanism to the study area. The extensional structures located south of an approximated lineament that connects Fruška Gora with the Vršac/Vărădia Mountains (Figure 3) cannot be driven by the rollback of a slab situated at the exterior of the Carpathians. This extensional segment faces eastward the stable Moesian platform, across the locally N-S oriented Carpathian segment (Figures 1a, 1b, and 12). An eastward movement of this segment would create Miocene shortening, either internal in the South Carpathians or at their external contact with the Moesian platform (Figure 12). Such significant shortening able to accommodate large block rotations is not recorded. The N-S oriented contact of the Carpathians with the Moesian platform is a major transcurrent lineament accommodating an up to 100 km dextral offset during Oligocene–Miocene times (cumulated Cerna-Jiu and Timok faults offset, Figure 1b) [*Berza and Drăgănescu*, 1988; *Kräutner and Krstić*, 2003], but no significant Miocene shortening is recorded here [e.g., *Tărăpoancă et al.*, 2007]. Therefore, the Miocene extension of the Morava corridor and part of its northern prolongation can only be related to a southwestward to southward motion of the Dinarides (Figure 12). This observation can be combined with the N-S extension observed elsewhere in the northern or central part of the Dinarides [*Schefer*, 2010; *Ustaszewski et al.*, 2010]. The mechanism would imply that Dinarides moved toward their foreland during Miocene times, at least partly coeval with the clockwise rotation of Carpathians structures, which is in agreement with the paleomagnetic studies of Adria. Intuitively, we suggest that the middle Miocene period of enlargement of the area where the extensional structures are observed is the peak of such a Dinaridic southwestward translation and/or counterclockwise rotation. This movement of the Dinarides toward their foreland can be justified by the rollback of a Dinaridic slab that has retreated toward SW during Miocene times. This is in agreement with the subducted remnant of partly continental nature observed in the external part of the Dinarides [*Bennett et al.*, 2008], that is shifted with $\sim$100 km more to the foreland when compared with the oceanic suture zone (Sava zone) located between Europe and Adria (Figure 12). The oceanic part of the slab should have been initially continuous with the Aegean slab in the Hellenides sector of the chain and has detached subsequently by break-off and/or delamination in the Dinarides from its overlying continental segment that is presently visible beneath the exterior of the chain (Figure 12) (see also *Schefer et al.* [2011] for a similar interpretation).

[54] Independent of the driving mechanism and the intuitive geodynamic evolution described above, the overall patterns of extension detected in this study demonstrates a *relative* clockwise rotation of the Carpathians in respect to the Dinarides and a *relative* counterclockwise rotation and/or southwestward translation of the Dinarides in respect to the Carpathians during Miocene times.

5.2. Basin Sag Subsidence and Its Relationship With the Mechanics of Extension

[55] Similarly with the kinematics of normal faulting, the Miocene–Quaternary thermal subsidence is also asymmetric and is best observed along the N-S oriented extensional lineament located in the proximity of Apuseni Mountains and South Carpathians (Figures 11a and 11c). Outside this lineament, the early–middle Miocene extension is not followed by any significant deposition that can be ascribed to a postrift thermal relaxation. In all cases, the early Miocene or Badenian–early Sarmatian extension is followed by the deposition of thin Badenian and/or Sarmatian postrift strata that only fill the earlier created basin space by normal faults or are slightly extended over its margins (Figures 11a and 11b). Often, this fill is subsequently eroded by footwall uplift of structures located more to the east or NE. Sarmatian and locally Pannonian strata are either very thin or absent, Pannonian–lower Pontian deposits overlying directly Badenian sediments, such as in the Szeged, Makó structures or along their flanks (Figure 11a). Except the SE corner, this is regionally observed in the entire studied area, being a systematic rule for the post-early middle Miocene period of rifting. This feature is diachronous and follows the changes in timing of the early middle Miocene extension along low-angle listric normal faults. In other words, the erosion or thin deposition is not localized in time in just one stratigraphic interval, for instance by a regional uplift near the end of Sarmatian times, the erosion removing previously deposited strata. This is clearly demonstrated in the SE part of the studied area, where such uplift is not documented. Here, Badenian–lower Pontian deposits are gradually transgressing over the flanks of the Pančevo–Drmno–Zagajica structures, with no marked unconformity (either subaerial or by facies change) in between (Figures 4 and 5). This observation contrasts with the previously defined Sarmatian/Pannonian unconformity in the Pannonian Basin as being the result of regional uplift during the main moment(s) of Carpathians collision (i.e., the first phase of inversion of *Horváth* [1995]). Although the latter interpretation cannot be completely excluded, there are no supporting compressional structures near the Pannonian/Sarmatian boundary and deposition of middle Miocene–Pannonian strata is only controlled by the accommodation space created by earlier normal faults.

[56] Where is the thermal sag sedimentation associated with the early–middle Miocene period of extension? The only solution available is that the low-angle normal faults are connected to a lower crustal detachment that prolonged eastward [see also *Tari et al.*, 1999] beneath the Apuseni Mountains and affected the mantle lithosphere below the Transylvanian Basin (Figure 13). The Transylvanian Basin is a passive sag basin with middle–upper Miocene sediments that reached 3.5 km in its center (Figure 13a) [e.g., *Krézsek and Bally*, 2006]. The only extensional deformation visible is early Badenian normal faults that have small offsets up to a couple of hundred meters, which cannot explain the observed Badenian–Pannonian Basin subsidence. This sag subsidence postdates the early Miocene–(early) Sarmatian phase of extension observed by our study in the Pannonian Basin. In the Transylvania Basin, the Badenian–Sarmatian sag deposition was followed by subsidence and a gradual regressive stage of basin fill of Pannonian in age [*Krézsek et al.*, 2010; *Matenco et al.*, 2010]. This stage was interrupted by the exhumation of the Transylvania Basin toward the end of Pannonian times due to the collision that took place at the exterior of the Carpathians (Figure 13a). The coupling between the mechanical extension of the Pannonian Basin and its thermal effects recorded in the Transylvania Basin should have taken place in such a way that the intervening Apuseni Mountains did not suffered any significant Miocene vertical movements, whose exhumation and large-scale domal structure is mainly the effect of Cretaceous-Paleogene deformations (Figure 13) [*Merten et al.*, 2011]. We are aware that such a large-scale hypothesis connecting extensional deformation and postrift subsidence across mountain chains is fairly speculative at this stage of research and requires modeling, but it is the only one that matches observations in both basins.

[57] By contrast with earlier periods of extension, massive thermal sag sedimentation is observed in direct relationship with and postdating the Pannonian–lower Pontian detachments and/or normal faults (such as the Makó or Drmno/Plandište/Zagajica structures, Figures 11a, 11c, and 13). The main depocenters of the thermal sag sedimentation overlie these asymmetrical extensional structures. Furthermore, this thermal sag sedimentation has a far larger areal extent than the one of the half grabens, covering an area that corresponds to the asthenospheric upraise presently observed beneath the Pannonian Basin [*Horváth et al.*, 2006]. A significant amount of Pontian–Quaternary thermal subsidence is recorded (up to 3–4 km), sediments being gradually deposited over the entire basin by covering gradually the remaining structural highs (such as the Bačka or Gaj uplifts, Figures 11a, 11c, and 13). Starting with Pontian times, the basin was rapidly filled by a massive progradation from north and NW, and to a lesser extent from the east, SE and south. Once filled, thermal

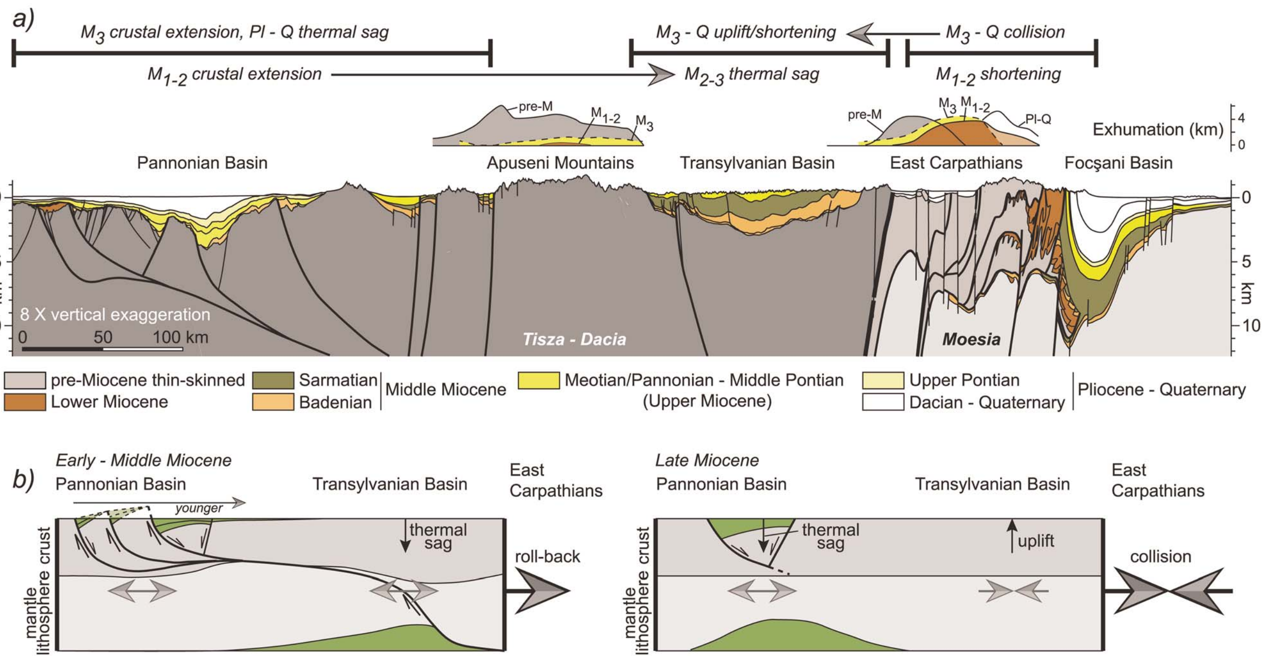

Figure 13. (a) Simplified geological cross section across the SE part of the Pannonian Basin, Apuseni Mountains, Transylvanian Basin and East Carpathians (simplified and modified from *Matenco et al.* [2010], *Schmid et al.* [2008], and the results of the present study) and amounts of exhumation over the Apuseni Mountains and East Carpathians derived from low-temperature thermochronology (simplified from *Merten* [2011] and *Merten et al.* [2010, 2011]). The geological cross section displays only Miocene-Quaternary sediments geometries and faults patterns. All pre-Miocene structures were ignored. The location of the cross section is displayed in Figure 1a. Note the striking contrast in sediments thickness and structural style between the Pannonian and Transylvanian basins. Lower–middle Miocene sediments in the central part of the Pannonian Basin are thin, were deposited strictly in the space created by the normal faults in their hanging wall and were largely removed by the subsequent erosion. This is in contrast with the thick middle Miocene sediments in the Transylvanian Basin, which were deposited continuously in the basin center with no apparent fault control. The late Miocene–Quaternary exhumation and low-offset thrusting recorded by the Transylvanian Basin is an effect of the coeval shortening and collision recorded in the East Carpathians (see *Matenco et al.* [2007, 2010] for further details). While the main part of the East Carpathians has been exhumed during the Miocene–Quaternary, the topography of the Apuseni Mountains and its domal structure is mainly the result of pre-Neogene (i.e., Cretaceous-Paleogene) deformations (see *Merten et al.* [2011] for further details). Abbreviations are pre-M, pre-Miocene; M_1, lower Miocene; M_2, middle Miocene; M_3, upper Miocene; Pl, Pliocene; Q, Quaternary. The crustal and lithospheric structure of the central and eastern part of the profile is displayed in Figure 12d. (b) Simplified sketch of the proposed Miocene–Quaternary mechanisms controlling the evolution of the East Carpathians, Pannonian Basin and Transylvanian Basin. The early–middle Miocene subduction retreat of the East Carpathians was accompanied by crustal stretching in the Pannonian Basin and lithospheric mantle stretching in the Transylvanian Basin. The extension is asymmetric and gradually migrates in time eastward, while the gradual exhumation of footwalls has eroded earlier deposited sediments westward. The late Miocene collision recorded by the East Carpathians has uplifted and slightly inverted the Transylvania Basin, while the Pannonian Basin still recorded coeval extension that took place in a symmetric way at lithospheric scale. Therefore, the thermal sag effects following the mechanical extension (not displayed in the sketch but visible in the cross section above) are spatially located in two different places for the early–middle Miocene and late Miocene moments of extension (i.e., in the Transylvanian and Pannonian Basins, respectively).

subsidence derived from the latest extensional event kept pace with sedimentation, the basin being continuously filled by continental alluvial deposits [*Juhász et al.*, 2007, and references therein].

[58] The exception to the postrift subsidence mechanism migrating in time and space is the SE part of the studied area, where the thermal sag sedimentation overlies the extensional detachments during the entire Miocene period of extension (Figure 11c). We interpret this geometry as an effect of the upper Carpathians plate geometry in this sector of the chain and the eastward presence of the Moesian indentor across the N-S oriented segment of the South Carpathians (Figure 12a). There is no Miocene subduction recorded in this transcurrent segment of the chain and the much narrower Carpathians unit did not had the required space to move or shift the stretching of mantle lithosphere elsewhere.

This can be viewed as an additional argument for a Dinaridic component of rollback-driven extension that changed the geometry of the extension when compared to the one driven by the Carpathian kinematics.

5.3. Early Pontian–Quaternary Inversion

[59] The inversion of the Pannonian Basin started in the studied area during early Pontian times as observed by synkinematic sedimentation along the flanks of antiformal structures and local erosion along their culminations (such as the Orahovo, Bački Breg, Srpski Miletić or Turija structures, Figures 8 and 9). This is in agreement with an earlier onset of the inversion recorded along the Dinaridic margin when compared with the typical Pliocene-Quaternary inversion that is observed in the main Pannonian depocenter located northward [*Bada et al.*, 2007; *Placer*, 1998; *Tomljenović and Csontos*, 2001; *Vrabec and Fodor*, 2005]. This earlier onset can be interpreted in terms of mechanical coupling between crustal and lithospheric layers, that take place faster in mechanically strong when compared to a weak lithosphere, a lateral variability that characterizes the Dinarides–Pannonian transition [*Jarosinski et al.*, 2011].

[60] Seismic geometries indicate E-W oriented contractional structures that are parallel with the present Dinarides strike and therefore are in agreement with studies suggesting that the Adriatic indentation is the mechanism responsible for this late stage inversion [e.g., *Pinter et al.*, 2005, and references therein]. The clearest expression of this inversion is the E-W oriented lineament formed by Fruška Gora Mountains and the Slankamen High. The vertical offset of this transpressional structure dies out rapidly eastward (Figure 3), while the wide open anticline itself makes just a minor vertical bump in the regional structure of the Pannonian Basin (Figure 11b). This uplifted area combined with coeval thrusting recorded at the southern margin of Bačka regional uplift overprinted the initial W-E to NW-SE oriented extensional subsidence. The overall inversional deformation recorded in the studied area is less important when compared with elsewhere, larger amplitudes of uplift and faults offsets being recorded in the central parts of the Pannonian Basin and Transdanubian Central Range in Hungary, Croatia and Slovenia [e.g., *Fodor et al.*, 2005; *Horváth and Cloetingh*, 1996; *Magyar and Sztanó*, 2008; *Sacchi et al.*, 1999; *Tomljenović and Csontos*, 2001].

5.4. Further Inferences for Pre-Neogene Adria–Europe Kinematics

[61] The pre-Neogene evolution of the area presently buried beneath the sediments of the SE Pannonian Basin has been a long time the concern of researchers not only in Serbia, but also in neighboring countries, driven in particular by petroleum exploration and potential fields geophysics studies [e.g., *Čanović and Kemenci*, 1988; 1999; *Dicea et al.*, 1984; *Haas et al.*, 2010]. Despite discrepancies, corrections and details beyond seismic resolution, we find that that our pre-Neogene data are in general agreement with the tectonic evolution of *Schmid et al.* [2008], among the few geodynamic scenarios available for the area [e.g., *Dimitrijević*, 1997; *Karamata*, 2006; *Robertson et al.*, 2009, and references therein].

[62] The Sava zone of the Dinarides (Figure 1) contains typical uppermost Cretaceous (Maastrictian, possibly extending into the Paleogene) mainly siliciclastic and locally carbonatic trench turbidites. In the study area, the deposition of this flysch started already during upper Turonian times, sediments being deposited over the European domain in slightly shallower water conditions [*Čanović and Kemenci*, 1988]. The long trace of the Sava zone in map view is characterized by a marked change in strike from E-W to N-S that takes place in the studied area (Figure 1). It is rather obvious that this change is controlled by Miocene extensional lineaments gradually changing strike from E-W to N-S in the area situated east of the Fruška Gora Mountains (Figure 3). The change takes place in the same area where the contact between Europe and Adria has been reactivated by Miocene normal faults or extensional detachments (Figures 3–5 and 7). Therefore, this change in strike must be related to the Miocene *relative* clockwise rotation of the Apuseni Mountains and South Carpathians in respect to the Dinarides.

[63] The Biharia unit can be prolonged from the Apuseni Mountains though the Algyő High to the roughly E-W oriented zone in central studied area (Figure 3). The contact between the Biharia and Serbo-Macedonian/Supragetic nappes (or their lateral equivalents) is not exposed anywhere in the Carpathians-Dinaridic system, being always covered by overlying ophiolitic sequences, Cretaceous sediments, or Neogene deposits of the Pannonian and Transylvanian Basins (Figure 1a). There is no significant structure that would separate these units in the studied area. The Middle–Late Jurassic and/or Early Cretaceous metamorphic overprint observed at the NNW to NW Biharia margin decreases southward where nonmetamorphosed to slightly metamorphosed Middle Triassic–Jurassic sediments were drilled (Figure 7). Furthermore, there is no contact visible in our seismic lines between Serbo-Macedonian and Supragetic units and the only area that exposes this contact (Vršac/Văradia Mountains) has a typical Paleozoic geometry. Therefore all these names (i.e., Supragetic, Serbo-Macedonian and Biharia) can be combined into the same tectonic unit for the Mesozoic-Tertiary Europe-Adria evolution.

[64] The bivergent shape in map view of the East Vardar ophiolites (Figure 1c) is the result of poly phase deformation. The late Jurassic obduction direction is the one recorded in the southern part of the studied area as top-east (i.e., over Serbo-Macedonian), subsequently rotated clockwise during Miocene times to top SE and top-south (Figures 1, 4, 5 and 7). The northern contact (e.g., Figure 8) is an erosional feature in map view (Figure 1), created by the subsequent exhumation during the intra-Turonian thrusting of Biharia over Tisza units.

[65] The Middle–Upper Triassic facies affinity makes possible the separation of Dinarides units in the south and SW part of the studied area. Although a reduced number of wells are available, the gradual transition from Lower–Middle Triassic continental to shallow water deposits to deeper water Middle–Upper Triassic carbonatic-clastic deposition [*Čanović and Kemenci*, 1988] testifies the same deepening of Adriatic facies that took place elsewhere on the southern continental rifting and passive continental margin of Neotethys during late Middle–Late Triassic times. South of Fruška Gora Mountains, the Triassic succession is locally complete (Figure 11b). The seismic interpretation and the few available wells are unable to distinguish the thin overlying deep water and basinal Lower-Middle Jurassic radiolarites and pelagic facies that is exposed in the Fruška Gora Mountains [*Toljić*

et al., 2012]. This sequence is overlain by obducted West Vardar ophiolites and associated ophiolitic mélange.

6. Conclusions

[66] Our interpretation of seismic lines corroborated with calibrating wells and correlated with the few available studies has generated significant new constraints for the evolution of the Pannonian Basin in the critical SE sector connecting the Dinarides with the South Carpathians and Apuseni Mountains. We demonstrate that the opening of this sector of the Pannonian Basin took place along a fundamentally asymmetric simple shear extensional mechanism. Previously inferred by indirect observations such as the low-angle geometries of normal faults, the presence of a series of large listric detachments that migrated in time and space has been demonstrated by their geometries in rotated hanging walls, exhumation of footwalls and correlation with recent outcrop studies. These detachments have variable offsets, from listric normal faults to large-scale exhumed footwalls, and accommodate the relative up to 90° clockwise movement of the South Carpathians and Apuseni Mountains in respect to the Dinarides. Given the roughly eastward dip of these detachments, one can say that extension has rotated the Carpathians and Apuseni Mountains in the hanging wall of the Dinarides (Figure 12a). The amount of extension decreases southward, a pole of rotation should be defined somewhere near the boundary between Serbia and Republic of Macedonia/FYROM. Such a rotational mechanism associated with detachments and exhumation of core complexes is not unique in the Dinarides-Hellenides system. Similar kinematics has been proposed more southeastward for the exhumation of the Eocene-Miocene Rhodope core complex and Aegean extension that gradually decrease displacements northeastward toward a pole of rotation located somewhere in the Republic of Macedonia/FYROM (Figure 12a) [e.g., *Brun and Sokoutis*, 2010; *Jolivet and Brun*, 2010, and references therein]. These combined rotational movements in the Pannonian and Aegean areas are strikingly similar and deserve further investigation.

[67] The large amounts of extension observed southward of the latitude of the Fruška Gora Mountains cannot be reconciled with a mechanism assuming only the rollback-driven rotation of Carpathian units into their embayment during Miocene times. We propose a Miocene Dinarides rollback mechanism to account for the structures observed, an inference that is in agreement with the present-day shifted position of an external Dinaridic slab that could have detached meanwhile. This may be a first demonstration that rollback extension driven by two different slabs is present in the same back-arc basin.

[68] The analysis of synkinematic reflectors demonstrates that normal faulting migrates in time and space, and took place on a wide Miocene time interval (roughly 20–5.5 Ma). The initial early middle Miocene period of extension was not followed by any significant postrift thermal subsidence in the Pannonian Basin, but by gradual isostatic rebound in the footwall of normal faults and detachments that are younger toward the Carpathians and Apuseni Mountains. This mechanism created a Badenian–early Pannonian period of uplift and erosion that is associated with the formation of a diachronous unconformity. This unconformity does not have a compressional genesis as previously suggested, but it is just an isostatic rebound accommodating asymmetric extension, at least in the studied area of the Pannonian Basin. A flat-lying lower crustal shear zone that truncates the lithosphere outside the Pannonian Basin is the only explanation of the absence of a significant Badenian–Pannonian postrift subsidence. We propose that the early–middle Miocene stage of mechanical extension in the studied area of the Pannonian Basin and northward is associated with postdating thermal relaxation in the Transylvanian Basin, an eastward located sag basin that has no genetically associated normal faults (Figure 13). The intervening Apuseni Mountains located in between did not recorded any significant coeval vertical movements. This mechanism has, potentially, key inferences for studying the mechanical coupling of basins situated across intervening mountain chains.

[69] The final moment of extension took place during Pannonian times and created deep and asymmetric (half) grabens located in the immediate vicinity of South Carpathians and Apuseni Mountains. These are associated with a subsequent Pontian–Quaternary thermal sag with a much larger areal distribution that is an effect of the large-scale asthenospheric upraise that is presently still observed beneath the Pannonian Basin. In this context, what has been defined as typical late Miocene thermal sag is mostly synrift and just the uppermost part can be defined as postrift. The Pliocene-Quaternary inversion of the Pannonian Basin is rather reduced in the studied area when compared with the much larger deformation recorded elsewhere in the center or margins of the Great Hungarian plain. This contraction cannot explain the geometry of the large Pliocene-Quaternary depocenter in the vicinity of the Makó depression (Figure 11a), which should have mainly a thermal sag origin.

[70] By connecting the seismic interpretation with a critical reevaluation of wells that have penetrated the pre-Neogene sequence of the Pannonian Basin, our study is in general agreement with previous interpretations derived from surface studies or wells [*Čanović and Kemenci*, 1988; *Schmid et al.*, 2008]. The three major continental blocks (Dinarides, Tisza and Dacia) were indeed observed in the subsurface of the studied area together with the sediments of the Sava suture zone. The major change in strike of the Sava suture zone from E-W to N-S taking place in the study area is clearly related to Miocene detachments accommodating the rotational extension of the Pannonian Basin.

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