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Architecture of the Focşani Depression: A 13 km deep basin in the Carpathians bend zone (Romania)

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[1] In front of the SE Carpathians Bend a very deep basin (Focşani Depression) developed in Miocene to Recent times. An important part of its subsidence occurred after the main stages of thrusting in the Carpathians. Apparently, the basin lies in the "wrong" place and evolved in the "wrong" time. In this study, we constrain its architecture and evolution by analyzing a large database consisting of more than 1000 km two-dimensional seismic lines and more than 60 wells. Around 13 km thick, Badenian-to-Quaternary (<16.5 Myr) sediments were deposited in the central part of the Focşani Depression. During the Badenian (16.5–13 Myr), the foreland (south of Trotuş fault) underwent NE-SW directed extension and NW trending basins opened in the eastern Moesian platform. A NW-SE oriented area of subsidence stretched from the Transylvania basin through the Focşani Depression to the SE of the Moesian platform while thrusting was going on in the East European/Scythian platform, East Carpathians, and Getic Depression. Starting with the Sarmatian (13–10 Myr), the Focşani Depression depocenter moved out of the Carpathian belt coeval with the exhumation of the south and the East Carpathians north of the Trotuş fault. The basin became wider and was tilted toward the belt. Tilting was accompanied by dextral shearing mainly along the Intramoesian and Peceneaga-Camena faults. After Sarmatian times, subsidence occurred practically only SSE of Trotuş fault. During Meotian-Pontian (10–5 Myr), subsidence slowed down. Stronger, Pliocene-Quaternary subsidence is coeval with normal faulting and shearing in Moesian platform. The western margin of the Focşani Depression was then tilted eastward, coeval with the exhumation of the bend zone and opening of the intramontane basins in the inner part of the belt. *INDEX TERMS:* 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 0905 Exploration Geophysics: Continental structures (8109, 8110); 9335 Information Related to Geographic Region: Europe; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* Carpathians foredeep, Focsani Depression, basin subsidence, extension, shearing, tilting. **Citation:** Tărăpoancă, M., G. Bertotti, L. Maţenco, C. Dinu, and S. A. P. L. Cloetingh, Architecture of the Focşani Depression: A 13 km deep basin in the Carpathians bend zone (Romania), *Tectonics*, *22*(6), 1074, doi:10.1029/2002TC001486, 2003.

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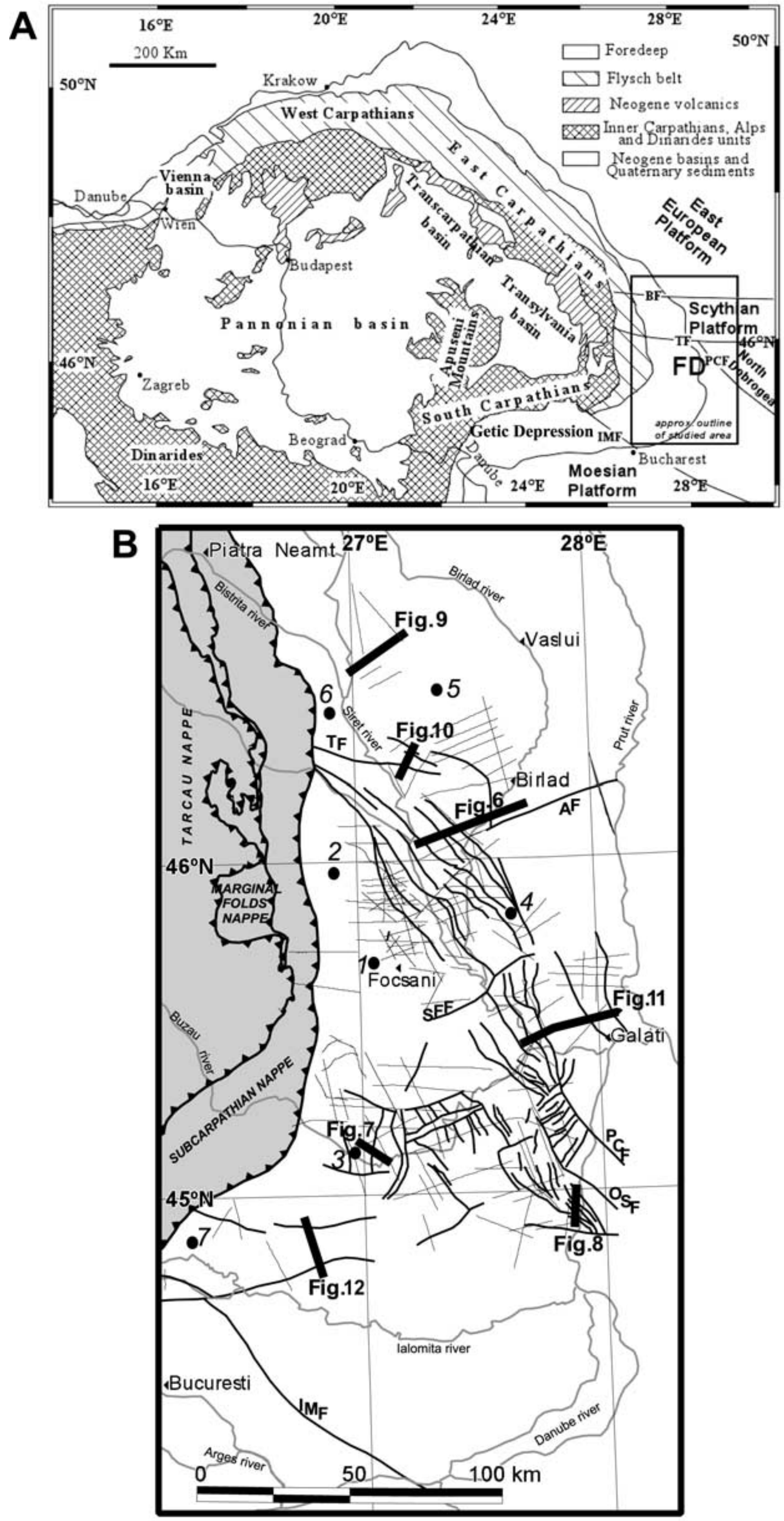
1. Introduction

[2] Foredeep basins develop on both sides of orogens mainly as a consequence of thrust loading. Timing and magnitude of subsidence in these basins should therefore directly relate to shortening kinematics in the orogen itself. After the cessation of convergence, the orogen and the foredeep might be uplifted as a consequence of isostatic rebound. Detailed analyses show that these "text book" models are sometimes different from real world basins. The SE Carpathians bend zone is one of such zones.

[3] The Carpathian Bend Zone is the area where the NNW-SSE trending East Carpathians meet the E-W striking South Carpathians (Figure 1a) [e.g., *Roure et al.*, 1993]. The Carpathians are associated with a >10 km thick foredeep basin, particularly well developed in the frontal part of the bend zone. This basin is known as the Focşani Depression [e.g., *Dicea*, 1995], and formed during and, more interestingly, following the main contractional stages (i.e., Miocene to Quaternary times). The special interest of the Carpathians bend zone and Focşani Depression is related to the fact that the area is site of the youngest deformations in the Carpathians domain [e.g., *Săndulescu*, 1984]. In addition, the region is contiguous with one of the largest seismogenic zone of Europe, the Vrancea area, with a cluster of seismicity distributed between 40 and 200 km depths [e.g., *Oncescu*, 1984]. The internal geometry of the Focşani Depression and its relationship with the Tertiary regional evolution are poorly constrained so far, only the base Tertiary map being available in the area [e.g., *Maţenco et al.*, 2003]. To understand the unusual thickness of the basin fill, the large postthrusting subsidence and the relationship with the Vrancea seismogenic zone, a detailed three-dimensional (3-D) basin geometry and structural evolution is required.

[4] Interpretations of the Carpathians foredeep (including Focşani Depression) [*Săndulescu*, 1984; *Săndulescu and Visarion*, 1988; *Rădulescu*, 1988; *Royden*, 1993; *Dicea*, 1995] did not pay much attention to the quantitative evolution of the basin. The anomalous character of subsi-


A
16°E
20°E
24°E
28°E
50°N
200 Km
Foredeep
Flysch belt
Neogene volcanics
Inner Carpathians, Alps and Dinarides units
Neogene basins and Quaternary sediments
Krakow
West Carpathians
East Carpathians
Vienna basin
Danube
Wien
Transcarpathian basin
East European Platform
Budapest
Transylvania basin
BF
Scythian Platform
Pannonian basin
Apuseni Mountains
TF
46°N
FD
PCF
North Dobrogea
Zagreb
South Carpathians
approx. outline of studied area
Getic Depression
IMF
Beograd
Dinarides
Danube
Bucharest
Moesian Platform
B
Piatra Neamt
27°E
28°E
Birlad river
Bistrita river
Fig.9
Vaslui
6
5
Siret river
Prut river
Fig.10
TF
TARCAU NAPPE
Birlad
Fig.6
AF
2
46°N
MARGINAL FOLDS NAPPE
4
1
Focsani
SFF
Fig.11
Galati
Buzau river
SUBCARPATHIAN NAPPE
Fig.7
3
PCF
45°N
OSF
7
Fig.8
Fig.12
Ialomita river
Bucuresti
IMF
Danube river
Arges river
0
50
100 km

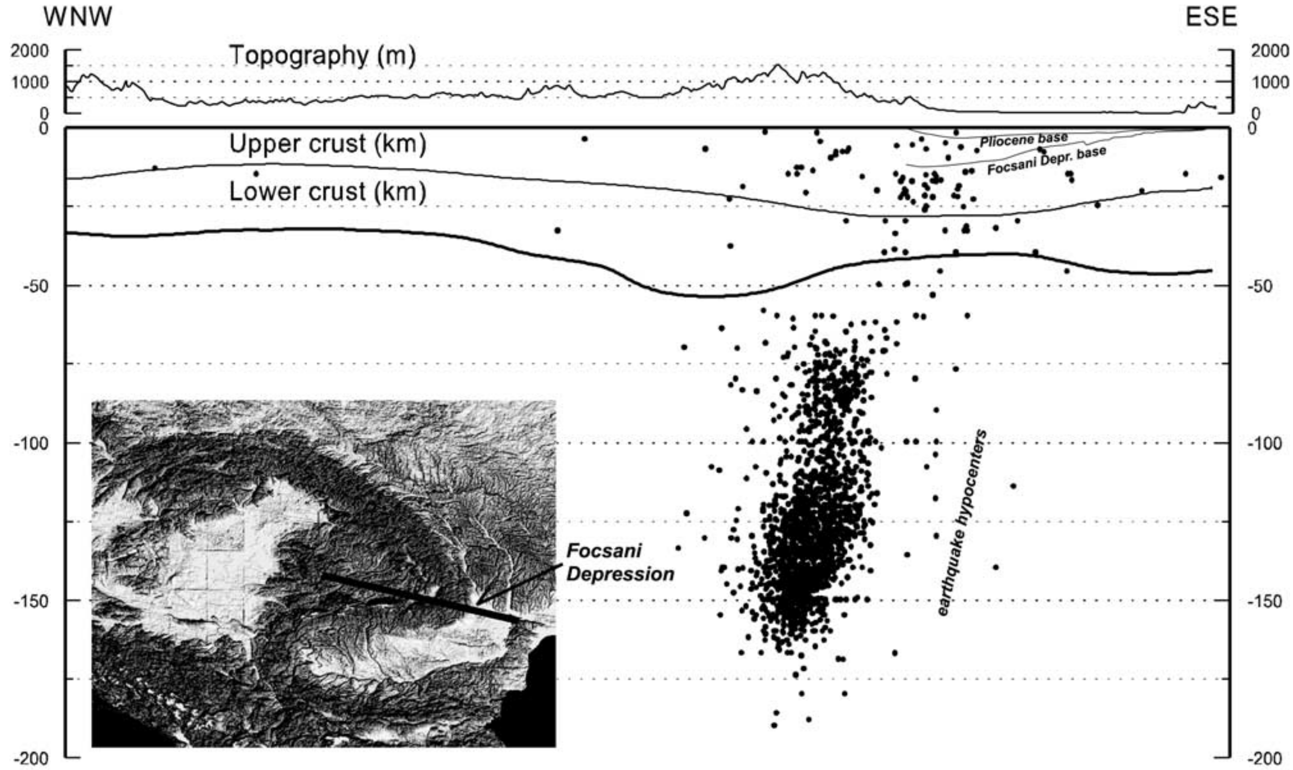


Figure 1. (continued)

dence became clear in eighties the when flexural modeling studies [*Royden and Karner*, 1984; *Royden*, 1988] demonstrated that the present-day topographic load could not explain the very large thickness of the foredeep and "hidden loads", possibly associated with an oceanic slab remnant, were required. Models requiring this slab remnant [*Royden*, 1988, 1993; *Linzer*, 1996; *Wortel and Spakman*, 2000] suggest that the East Carpathians evolution is dominated by an eastward rollback of the subducting plate.

[5] Various ideas have been proposed to explain the anomalous timing of subsidence in the Focşani Depression and in particular, its essentially posttectonic character. The currently most popular theory envisages a progressive detachment of the hanging slab [*Wortel and Spakman*, 2000; *Gvirtzman*, 2002]. Accordingly, slab detachment would have occurred in Badenian in the West Carpathians, migrated southward and reached the bend zone in the Quaternary [*Wortel and Spakman*, 2000]. The intense intermediate mantle seismicity between 70 and ~200 km depth [e.g., *Oncescu*, 1984] would be the testimony of the sinking slab [*Wortel and Spakman*, 2000]. A pattern of laterally migrating foredeep depocenters based on stratigraphic columns has been proposed to support these ideas [*Meulenkamp et al.*, 1996], but these are not confirmed by more recent studies that incorporated a large well database covering the Carpathians foreland [*Maţenco et al.*, 2003]. Other authors have pointed to the anomalous timing of subsidence in the Focşani Depression and ascribed it to deep-seated phase changes [*Artyushkov et al.*, 1996].

[6] One of the peculiarities of the area is that the Carpathian bend zone and the adjacent western sectors of the Focşani Depression have experienced recent exhumation associated with the erosion of a rock column of >4 km since 5 Myr [*Sanders et al.*, 1999]. Shallow marine and

Figure 1. (opposite) (a) Tectonic map of the Carpathians region and the location of the studied area (partly compiled after *Maţenco and Bertotti* [2000]). FD represents the approximate location of the Focşani Depression. (b) Studied area. The thin lines represent the seismic survey used. The thick lines represent the foreland structural pattern this paper is referring to (bold names for major faults). The location of seismic lines presented in this paper is shown in very thick labeled lines. The numbered dots are pseudowells where the total subsidence curves are shown in Figure 5. AF, Adjud fault; IMF, Intramoesian fault; OSF, Ostrov-Sinoe fault; PCF, Peceneaga-Camena fault; SFF, south Focşani fault; TF, Trotuş fault. (c) Topography, crustal thicknesses (modified from *Rădulescu et al.* [1976]), earthquake hypocenters distribution (black dots) [after *Oncescu*, 1984; *Oncescu et al.*, 1998] and position of Focsani Depression (the basin and Pliocene base horizons from this study). Location of the cross section is shown in the inset representing the topography of the Carpathians/ Panonnian region.

Ma	GEOLOGICAL TIME SCALE		
	QUATERNARY		
	NEOGENE	PLIOCENE	ROMANIAN
5			DACIAN
		MIOCENE	PONTIAN
10			MEOTIAN
			SARMATIAN
15			BADENIAN
20			BURDIGALIAN

Figure 2. Geological timescale used in this paper [after *Maţenco*, 1997].

brackish beds of the Focşani Depression steeply dip to the east [*Dumitrescu et al.*, 1970] and form at present elevations up to 1000 m.

[7] The purpose of this study is to provide new data on the internal architecture and history of the Focşani Depression. As long as the detailed foredeep architecture and development of the Focşani Depression have not been established, the link among Carpathians deformations, Focşani Depression subsidence and Vrancea seismicity cannot be constrained. We discuss then the subsidence evolution in Focşani Depression and the bend zone foreland. Subsequently, observations made in the Focşani Depression are correlated with deformations taking place at the scale of the Carpathian belt.

2. Tectonic Setting

2.1. Main East Carpathians Deformations

[8] The evolution of the Carpathians arcuate belt (Figure 1a) [e.g., *Săndulescu*, 1984, 1988] started with Triassic-Early Cretaceous extension followed by Middle Cretaceous-Pleistocene contraction. The contraction period is usually subdivided into Cretaceous deformations (Dacides) affecting the basement and the innermost thin-skinned nappes and the Neogene stage (Moldavides), producing the external thin-skinned nappes (timescale in Figure 2).

[9] The Focşani Depression is bounded to the west by the southern part of the East Carpathians. Here, Moldavides deformations started with late Burdigalian-Badenian ~E-W shortening affecting the Tarcau and Marginal Folds nappes (Figure 1b) [*Maţenco and Bertotti*, 2000]. Further foreland propagating shortening continued during Sarmatian times leading to emplacement of those nappes onto the most external one (Subcarpathian). In addition, the Subcarpathian nappe was thrust over the foreland.

[10] The next deformation stage (latest Sarmatian-early Meotian) was characterized by a strike-slip regime with NNE-SSW to N-S compression direction. North of the Trotuş fault, strike-slip deformation was accommodated by ~E-W sinistral faults whereas NW-SE dextral faults formed in the southwesternmost East Carpathians. In between, the bend zone advanced toward ESE by roughly 40–50 km [*Maţenco and Bertotti*, 2000]. Strong exhumation took place in the northern East Carpathians since late Badenian-early Sarmatian (13–11 Myr) when >5 km of rocks have been eroded [*Sanders et al.*, 1999].

[11] In the bend zone, Pliocene-Pleistocene NNW-SSE directed shortening induced small-scale, less than 15 km, out-of-sequence thrusting [*Maţenco and Bertotti*, 2000]. Exhumation in the bend zone began 5–6 Ma and is thus is younger than in the north [*Sanders et al.*, 1999]. Exhumation was associated with eastward tilting of the most internal parts of the foredeep and with the development of substantial morphology as documented by the presence of marine to brackish sediments at elevations of several hundred meters above sea level [*Dumitrescu et al.*, 1970].

2.2. Carpathians Foreland and Foredeep

[12] The Carpathian foreland is composed of an assemblage of three basement blocks, known as platforms in the East European literature, overlain by a slightly deformed sedimentary cover [*Săndulescu*, 1984; *Ionesi*, 1994] (Figure 1a): From north to south, the East European, Scythian and Moesian platforms. To the northeast, the Moesian platform is separated from the North Dobrogea orogen (known as the North Dobrogea promontory west of the Danube) by the NW-SE trending Peceneaga-Camena fault (Figures 1a and 1b). Deep seismic profiles across this fault reveal a thinning of the crust from 46–47 km in the NE to 30–31 km in the SW [*Rădulescu et al.*, 1976; *Rădulescu*, 1988]. The boundary between North Dobrogea promontory and Scythian platform is generally associated with the Trotuş fault, but their structural relations are not yet clearly established. The Scythian platform is separated from the East European craton by the Bistriţa fault. The latter is characterized by a 170–200 km thick lithosphere and a 35–40 km thick crust [e.g., *Nemcok et al.*, 1998].

[13] Foreland sediments are organized in four major cycles the last of which represents the Carpathians foredeep basin fill [e.g., *Ionesi*, 1994]. The basin presents significant variations in thickness and width moving from one basement block to the other. The greatest depth of the foredeep (around 13 km, filled with Badenian to Quaternary deposits) is recorded in the Focşani Depression developed on top of the NE part of the Moesian platform (Figures 1a and 1b). The early sedimentation in the Carpathians foredeep is formed by Badenian evaporites, clastics, tuffs, and limestones. Sarmatian deposits consist of various siliciclastics rocks and locally limestones. Post-Sarmatian sedimentary

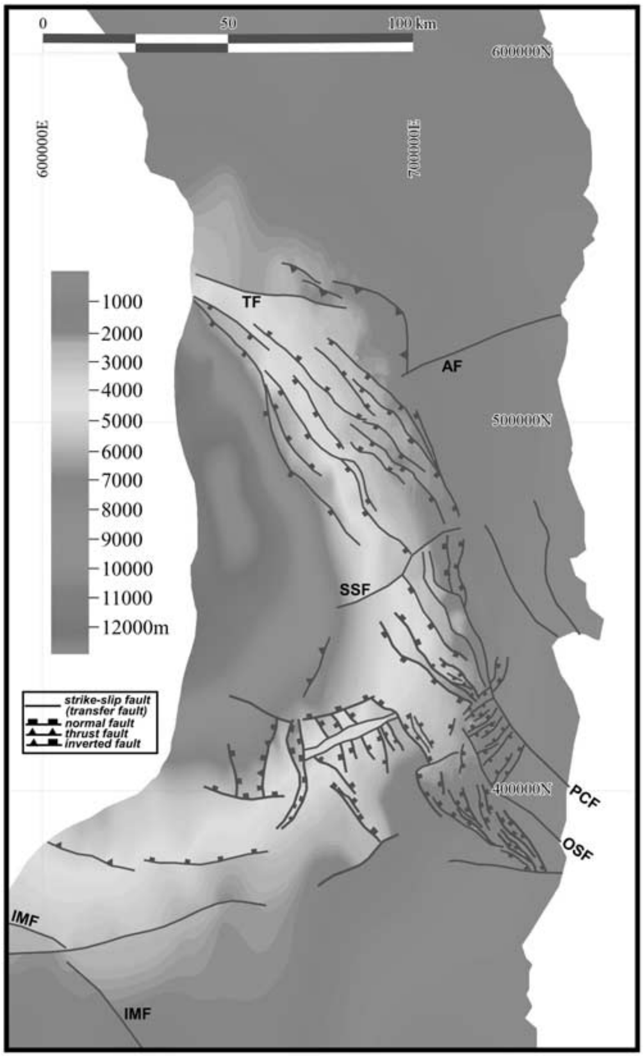


Figure 3. Structural map of the base Tertiary. The reference datum is 100 m above sea level. AF, Adjud fault; IMF, Intramoesian fault; OSF, Ostrov-Sinoe fault; PCF, Peceneaga-Camena fault; SFF, south Focşani fault; TF, Trotuş fault. See color version of this figure at back of this issue.

sequences are represented by siliciclastic rocks, which are mainly pelitic-siltitic during the Pontian and become subsequently progressively coarser grained [e.g., *Paraschiv*, 1979; *Ionesi*, 1994].

2.3. Carpathians Bend Seismicity (Vrancea Region)

[14] The epicenters of Vrancea earthquakes are clustered in a surface area of 30 km × 70 km and describe a nearly vertical column [e.g., *Oncescu*, 1984; *Oncescu et al.*, 1998] (Figure 1c). Most focal mechanisms show NW-SE or NE-SW oriented contraction, but some strike-slip and even normal fault solutions have been derived as well [e.g., *Enescu and Enescu*, 2000]. Preliminary results of the recent tomography studies [e.g., *Sperner et al.*, 1999; *CALIXTO "99 Research Group*, 1999] reveal a high velocity subvertical body containing the earthquakes hypocenters and surrounded by low velocity zones. Horizontal sections across this body have two different elongations: NE-SW at depths up to 120–130 km and N-S at larger depths.

3. Focşani Depression

3.1. Database

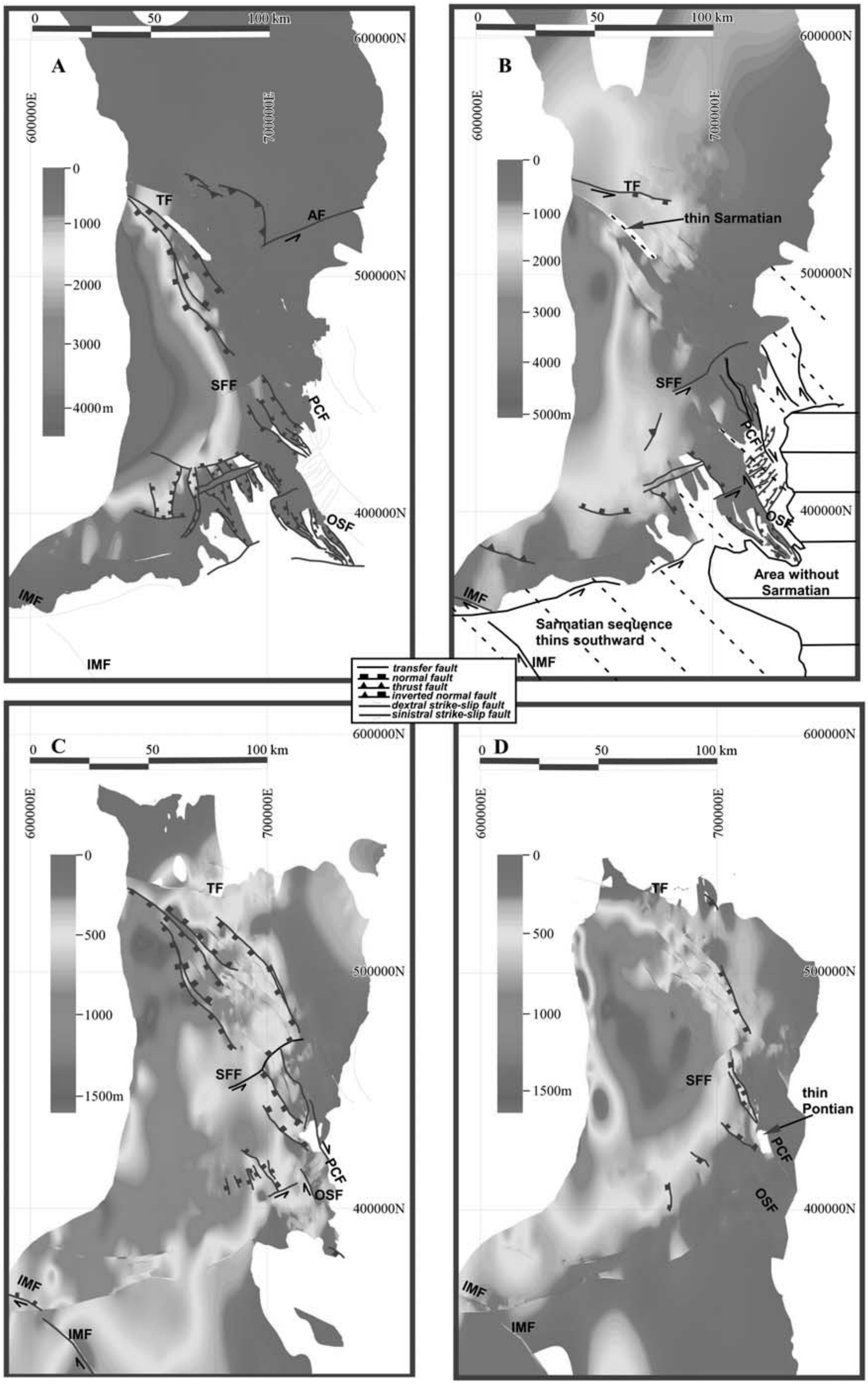
[15] We have used over 1000 km of 2-D seismic lines (Figure 1b) to establish the 3-D geometry of the SE Carpathians Bend foreland and its Neogene-to-Quaternary tectonic evolution. Seismic lines were acquired and processed by Prospectiuni S.A. Romania and their interpretation was correlated with more than 60 wells to date seismic horizons and derive information on seismic velocities. Five seismic horizons were interpreted and mapped: Tertiary Base, Top Badenian, Top Sarmatian, Top Meotian and Top Pontian. Each time-structural map of the horizons has been depth converted using average velocity maps instead of interval velocities. This approach is appropriate because not all sequences cover the entire studied region and because of the large dimensions of the area (>20,000 km^2). Finally, isopach maps have been obtained by extracting the depth-structural map of each sequence base from the map of its top.

[16] The western limit of the maps produced corresponds to the Pliocene-Pleistocene Casin-Bisoca reverse fault, which is conventionally taken as the western border of the Focşani Depression. However, layers in the vicinity of and to the west of the fault are tilted toward the east and partly eroded. This not only makes it difficult to provide accurate thickness estimates, but also leaves open the question of the original western termination of the basin. Geometries at the eastern margin of the Focsani Depression are well constrained because of the shallower basin floor and the existence of numerous industry wells.

3.2. Present-Day Geometry of the Bend Zone Foreland and Structural Relations With the Carpathians

[17] The overall shape of the Focşani Depression is shown in Figure 3. The largest sediments thickness of roughly 13 km is reached in a NW-SE oriented area slightly to the north of the bend zone. Thickness of the Focşani Depression infill gradually decreases both toward the ENE and to the SSE. This gradual trend is locally interrupted by faults. The western continuation of the Depression is deformed and partly buried under the Carpathians thrusts and thus more difficult to constrain.

[18] Toward the north, sediments of the Focşani Depression decrease in thickness across the WNW-ESE trending Trotuş fault. Despite the observed thinning of >2 km, sediments continue also to the north of the Trotuş fault, which, therefore, does not form the boundary of the basin. In contrast to the published maps of this area [e.g., *Săndulescu*, 1984; *Săndulescu and Visarion*, 1988], our interpretation shows the Trotuş fault ends toward the east and its position lies 25–30 km more northward than previously considered.


A
0
50
100 km
600000N
500000N
400000N
600000E
700000E
0
1000
2000
3000
4000m
TF
AF
SFF
PCF
OSF
IMF
IMF
B
0
50
100 km
600000N
500000N
400000N
600000E
700000E
0
1000
2000
3000
4000
5000m
TF
thin Sarmatian
SFF
PCF
OSF
Area without Sarmatian
IMF
Sarmatian sequence thins southward
IMF
transfer fault
normal fault
thrust fault
inverted normal fault
dextral strike-slip fault
sinistral strike-slip fault
C
0
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100 km
600000N
500000N
400000N
600000E
700000E
0
500
1000
1500m
TF
SFF
PCF
OSF
IMF
IMF
D
0
50
100 km
600000N
500000N
400000N
600000E
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thin Pontian
PCF
OSF
IMF
IMF

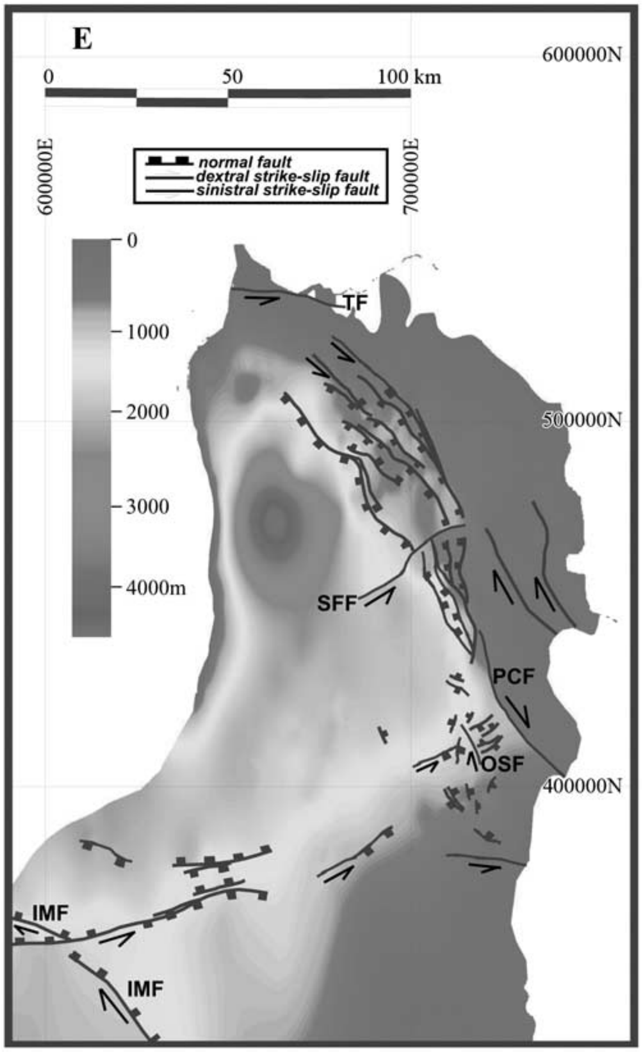

Figure 4. (continued)

[19] The transition from the Focşani Depression to its east and NE margin (i.e., North Dobrogea promontory) is affected by a NW-SE trending fault system stretching south of the Trotuş fault (Figure 3). To the south of the south Focşani fault, the North Dobrogea promontory is uplifted 1 km or more relative to the Moesian platform along the Peceneaga-Camena fault. On the whole, the ENE margin of the Focşani Depression has a distinct NNW-SSE trend, parallel to one of Europe's most important regional tectonic features, the Tornquist-Teisseyre Zone (Trans-European Suture Zone).

[20] The southern margin of the Focşani Depression is more gradual than the eastern one. N-S to NW-SE trending basins are observed in the eastern sectors (Figure 3) and will be described in more detail below. The western portions of the southern border are affected by the Intramoesian fault which displays a vertical offset of >1 km in the NW decreasing toward the foreland.

[21] The western border of Focşani Depression is conventionally identified with the Pliocene-Pleistocene Casin-Bisoca reverse fault [e.g., *Dicea*, 1995]. However, the issue of the western continuation of the Focşani Depression is largely unconstrained mainly because Sarmatian, Meotian and Pontian deposits of the western parts of the Depression are steep to subvertical [*Dumitrescu et al.*, 1970].

[22] The contact between the Carpathians thrust belt and the foredeep is variable along strike. North of the Trotuş River and west of the Intramoesian fault (Figure 1b) the Subcarpathian nappe is clearly thrust over the foreland [e.g., *Dicea*, 1995; *Maţenco*, 1997]. Between Trotuş and Buzau rivers (Figure 1b), the front of the Subcarpathian nappe is buried beneath the deposits younger than middle Sarmatian. The contact between the nappe frontal zone and the upper Sarmatian deposits is considered either stratigraphic [e.g., *Săndulescu*, 1984] or as a backthrust [*Maţenco and Bertotti*, 2000]. Between Buzau valley and Intramoesian fault (Figure 1b) the Subcarpathian nappe is interpreted as being sealed by the upper Sarmatian deposits [e.g., *Maţenco*, 1997].

4. Basin Architecture, Active Structures, and Basin Evolution

4.1. Badenian (16.5–13 Myr)

4.1.1. Thickness and Subsidence Patterns

[23] The Badenian marks the onset of subsidence in the Focşani Depression. The general pattern is one of increasing thicknesses and subsidence toward the west. Isopachs have a distinct NNW-SSE trend in the east and NE-SW in the south. Very high thicknesses up to >4 km and subsidence rates of >1 km/Myr are recorded in the western part of the investigated area.

[24] Although with much lower thicknesses, Badenian sediments are also found on the East European platform. Their presence demonstrates that subsidence affected vast areas, inclusive of large parts of the strong and competent East European platform. Badenian deposits are 0.2–0.4 km thick north of Trotuş fault and 0.5–0.6 km in front of the thrust system bounded by the Adjud fault (Figure 4a). To the ENE of Focşani Depression (toward the North Dobrogea promontory) thickness decreases rapidly to values as small as 0.1–0.2 km. Subsidence rates are correspondingly very low and are typically 10 times lower than in the central domains (Figure 5). Farther eastward the Badenian sequence pinches out.

Figure 4. (opposite) Isopach maps for (a) Badenian, (b) Sarmatian, (c) Meotian, and (d) Pontian. No decompaction correction is used. Note that the scale of color coding is different in Figures 4a–4d. (e) Top Pontian structural map. The reference datum is 100 m above sea level. The map also represents an estimation of the thickness of Dacian-Quaternary sequence. AF Adjud fault; IMF Intramoesian fault; OSF Ostrov-Sinoe fault; PCF Peceneaga-Camena fault; SFF south Focşani fault; TF Trotuş fault. For all maps, the highlighted structures are those active at the specified time interval (in Figure 4e the faults have been active after Pontian). See color version of this figure at back of this issue.

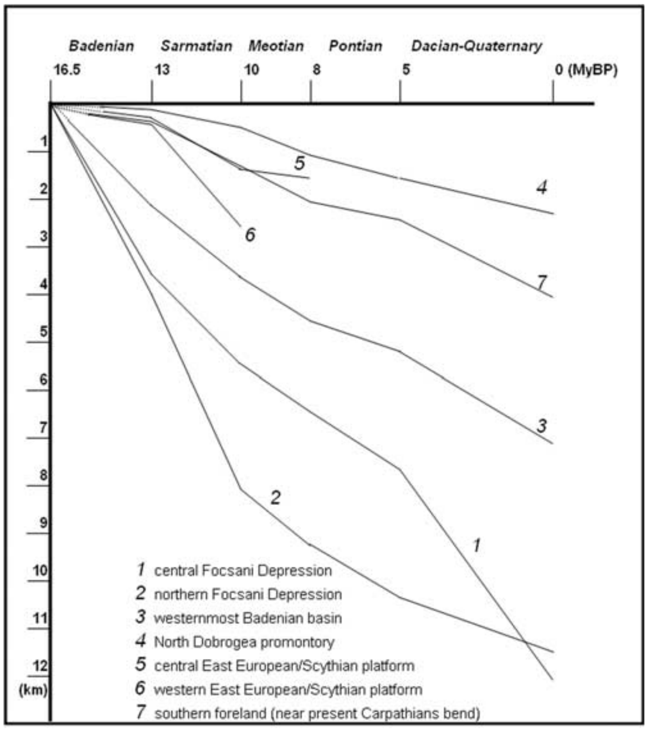

Figure 5. Total subsidence curves. For location, see Figure 1. Since the sediment deposition produced in generally in a shallow water basin, the paleobathimetry has been taken as 0 m. No decompaction has been performed because detailed lithological maps are not yet available.

[25] To the SE of Focşani Depression, fault-bounded basins control the distribution of Badenian deposits. Thicknesses range between 1.2 and 2.5 km in the northern fault-bounded basins and gradually decrease southeastward (Figure 4a). Some of the rift shoulders of these basins were emerged during Badenian. Subsidence curves from these domains are shown in Figure 5 (curve 7). Toward the SW, Badenian sediments are roughly 0.1–0.2 km near the Intramoesian fault and pinch out to the south (Figure 4a).

4.1.2. Active Structures

[26] The most apparent structures active during Badenian times are N-S to NW trending normal faults detected mainly in the SE termination of the Depression (Figure 4a). These faults are steep, often SW dipping and define N-S and NW-SE trending grabens and half grabens. A narrow and deep graben marks the transition from N-S trending basins in the west to those trending NW-SE (Figure 4a). Their width and depth decrease toward SE. Extensional faulting propagated from NW to SE as the Badenian synrift sequence becomes younger in the same direction (M. Tărăpoancă et al., Neogene kinematics of the northeastern sector of the Moesian platform (Romania), submitted to *AAPG Bulletin*, 2003, hereinafter referred to as Tărăpoancă et al., submitted manuscript, 2003). The basins are bounded by ENE-to-east trending transfer faults (Figure 4a). During middle-late Badenian, inversion started in the westernmost extensional basin and lasted until the beginning of Sarmatian when an erosional unconformity of regional extent developed.

[27] A possible prolongation of these normal faults toward the NW can be demonstrated only for the eastern parts of the Focşani Depression where Badenian sediments are quite shallow. NW-SE trending, mainly SW dipping normal faults follow, for instance, the margin of the depression north of the Buzau River. Offsets are in the range of tens to a few hundreds of meters (e.g., Figure 4a). Areas to the NE of the normal faults were part of their footwall and partly were emerged during the Badenian (note the narrow NW trending area with no sediments in Figure 4a).

[28] In the East European/Scythian foreland a NW-SE trending thrust fault system formed coeval with the Badenian foreland extension and with the contraction recorded within the orogenic wedge (Figures 4a and 6). The system is made up of three thrust faults, the longest one having a curved shape (Figure 4a). The dip of the faults increases progressively to the NW where the offset decreases. Piggyback and flexure-associated basins developed (Figure 6) related to thrusting. The thrust fault system is bounded to the south by the Adjud fault (interpreted as sinistral strike-slip fault), which extends beyond the eastern border of studied area (Figure 4a).

4.1.3. Basin Tectonics

[29] The overall Badenian subsidence pattern reflects a systematic increase in accommodation space and thus sediment thickness toward the west. Unfortunately, seismic data do not image very clearly Badenian sediments in the deeper parts of the Focsani Depression and it is, therefore, difficult to be more specific about how the westward thickening occurs.

[30] Active structures are observed in the marginal parts of the basin and mainly consist of NNW-SSE trending normal faults found in the SE corner of the Depression and along its NE margin. The first group of faults defines several extensional basins (e.g., Figure 7) and accommodates significant horizontal extension in the order of 10–20 km. How much of the observed subsidence can be ascribed to the associated NE-SW directed extension needs to be tested quantitatively. Faults along the NE margin are quite apparent but the vertical offset is in the order of hundreds of meters, and there is no doubt that these faults cannot explain the bulk of the observed subsidence. This is compatible with the observation that this fault system leaves the Focşani Depression and enters the North Dobrogea foreland moving toward the SE.

4.2. Sarmatian (13–10 Myr)

4.2.1. Thickness and Subsidence Patterns

[31] Sarmatian sediments are widespread over large areas. They are found not only in the Focşani Depression but also farther to the east and south on the East European and Moesian platforms. On the whole they are much less deformed than the Badenian (Figures 6–9).

[32] The area with the highest thicknesses of Sarmatian deposits is located in the western part of the Focşani Depression where it forms a N-S trending basin, with thicknesses >5 km in its northern part (Figure 4b). Sarmatian subsidence rates are here ~1.3 km/Myr and decrease toward the south to 0.6 km/Myr in the central part and to

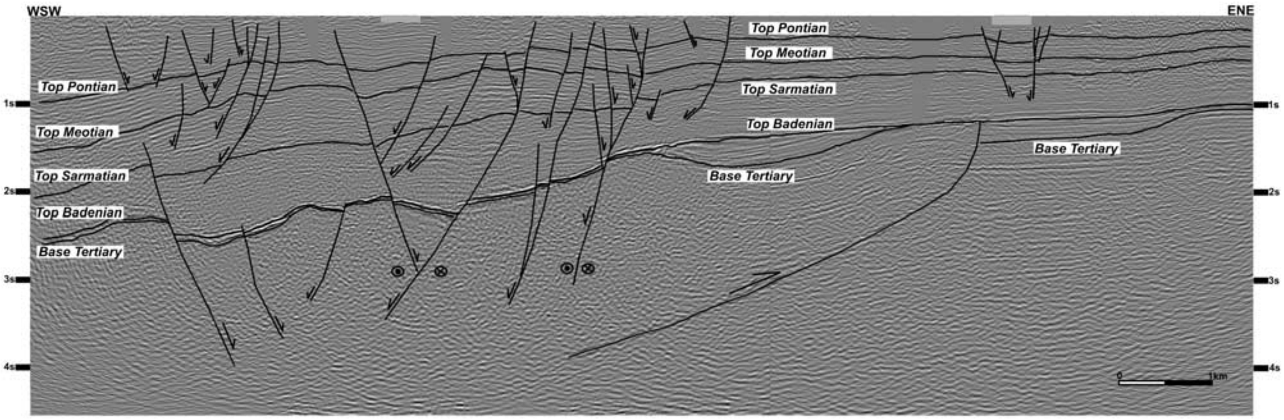

Figure 6. Interpreted seismic line from the northern foreland (for location, see Figure 1). A thrust fault is clearly revealed in the eastern part of the line. Piggyback and flexural basins developed during Badenian. The other structural features are mainly formed after Pontian. These faults are interpreted as normal faults, but some negative flower structures could also be observed. We suggest that these negative flower structures represent sinistral strike-slip faults associated with displacements along the major Trotuş fault, which had similar character according to *Maţenco* [1997] and *Maţenco and Bertotti* [2000]. The Pliocene sedimentary sequence is folded. The vertical scale is two-way travel time.

0.5 km/Myr farther south (Figure 5). Toward the west, the base of the basin becomes somewhat shallower possibly indicating its termination in the vicinity of the map boundary.

[33] Sarmatian deposits up to several hundred meters thick are found also outside the main depositional domains, over most of the East European/Scythian platform (Figure 4b) and only very gently thin eastward. Subsidence rates vary from 0.35 to 0.13 km/Myr (North Dobrogea promontory) (Figure 5). Sarmatian sediments are found also in front of the Carpathians bend zone where they show subsidence rates of around 0.3 km/Myr (Figure 5, curve 7) and decrease toward the SE. To the south of Focşani Depression, Sarmatian sediments are 1–1.2 km thick and progressively thin southward (Figure 4b). The first Sarmatian reflectors onlap the erosional unconformity that marks the end of the Badenian deposition (Figure 7). Also, note that the Sarmatian sequence extends farther south than the Badenian pinch-out limit.

[34] The middle to late Sarmatian basin fill is formed by thick prograding bodies having transport direction from north to south [*Negulescu*, 2001]. These prograding bodies were not confined to the vicinity of the Carpathians thrust front, but extended also over a much larger area to the east. This progradation correlates with the onset of the exhumation of the Carpathians North of the Trotuş fault (late Badenian-early Sarmatian in age) [*Sanders et al.*, 1999].

4.2.2. Active Structures

[35] The Sarmatian was a time of limited deformation in the Focşani Depression and only few active structures have been identified (Figure 4b). At a larger scale, tilting and major subsidence was going on (Figure 9).

[36] In the northern part of the East European foreland the major active structure during Sarmatian was the Trotuş fault (Figure 4b), which accommodated the subsidence of the southern block. It is imaged as a negative flower structure (Figure 10) with a sinistral sense of movement [*Maţenco*, 1997; *Maţenco and Bertotti*, 2000]. No faulting was recorded to the east of the Focşani Depression (Figure 4b).

[37] To the south, NE-SW striking normal faults separated by transfer zones are found mainly between the Peceneaga-Camena shear zone (Figure 11) and the Ostrov-Sinoe fault (Figure 4b) Tărăpoancă et al., submitted manuscript, 2003). The narrow NE-SW oriented basins are interpreted as pull-apart related to a dextral movement along the two main faults (Figure 4b). Other dextral faults with associated flower structures are observed east of Peceneaga-Camena shear zone (Figure 11). Neither the Peceneaga-Camena shear zone nor these other faults can be followed along their strikes to the north of south Focşani fault (Figure 4b). Farther to the south of these basins some of the Badenian structures were reactivated (Figures 4b and 8).

[38] In the southwestern part of studied area, dextral movements took place along the Intramoesian fault [*Tărăpoancă*, 1996; Tărăpoancă et al., submitted manuscript, 2003]. Transpression is recorded along its WNW-ESE trending segment whereas transtension occurred along the NW-SE trending one. A SE trending reverse fault formed near the Carpathians Bend, its western edge being covered by the Carpathians structures (Figure 4b).

4.2.3. Basin Tectonics

[39] The Badenian/Sarmatian transition is a time of major changes in the evolution of the Focşani Depression. The geographic distribution of sediment thicknesses changed. The main depocentral area became narrower and elongated in N-S direction (Figure 4b). Sarmatian subsidence rates in this central domain are slightly lower than the Badenian ones. The area is also characterized by a decrease in thicknesses toward the west, pointing to a synclinal shape of the basin floor at that time.

[40] At the same time, the basin widened to the east and sediments were deposited over previously stable areas even hundred kilometers to the east of the Carpathian front. This is the case, for instance, of the entire region north of the

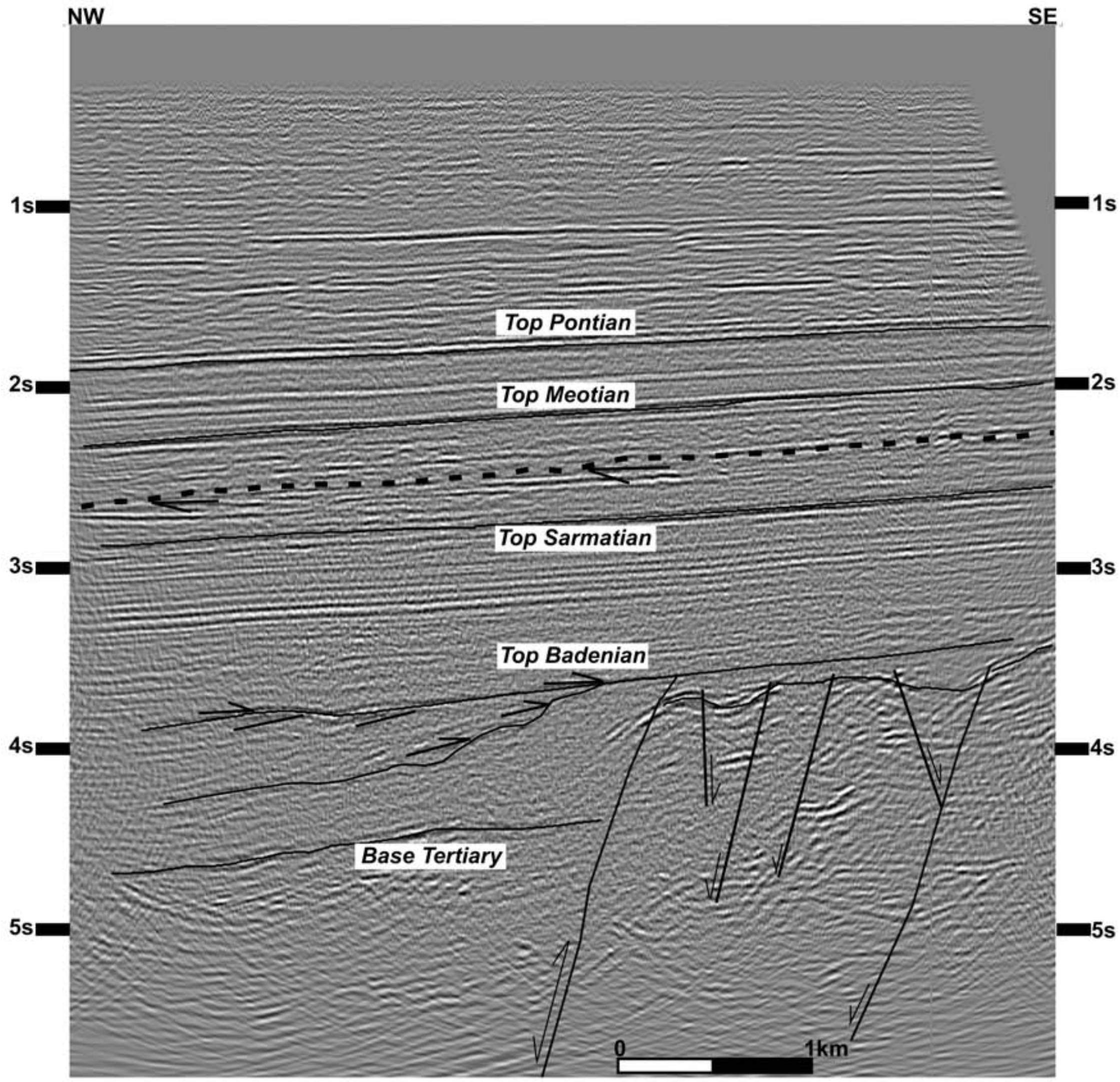

Figure 7. Interpreted seismic line across the westernmost Badenian fault-bounding basin from the southern foreland (for location, see Figure 1). Note the inversion occurred during Badenian and the erosional unconformity at the Sarmatian base (thicker black arrows denote on-lap terminations and black bars denote erosional truncations). The dashed line within Meotian sequence represents a top lap surface and the thicker arrows beneath it mean top lap stratal terminations (the same top lap surface correlates with that from Figure 12). Conventions are as in Figure 6.

Trotuş fault (e.g., Figure 9) and, farther to the south, the region of the Intramoesian fault. In these areas, thickness changes are very gradual (e.g., Figures 9 and 12) indicating a very large-scale control on subsidence. Subsidence curves outside the depocentral areas clearly describe this trend showing a significant increase in the rate of creation of accommodation space.

4.3. Meotian (10–8 Myr)

4.3.1. Thickness and Subsidence Patterns

[41] Meotian deposits (Figure 4c) are widespread over the entire area of the Focşani Depression. Two depocenters are identified south of the Trotuş fault (roughly coinciding with the Sarmatian ones) and, farther to the south, in front of the Carpathian bend zone. Thicknesses reached 1.5–1.6 km (Figure 4c). Isopachs contouring these depocenters trend roughly N-S. Meotian subsidence rates in the Focşani Depression are around 0.6 km/Myr in the northern part and 0.5 km/Myr in the central part (Figure 5).

[42] Outside the main deposition centers, Meotian sediments are found over most of the investigated area with very gently changing thicknesses. On the East European/Scythian platform they are typically 0.7–0.9 km thick and reduce to 0 km southeastward. Subsidence rates are correspondingly low, maximum being 0.1 km/Myr (Figure 5, curves 5 and 6). Since some Meotian deposits were subsequently removed by erosion the actual subsidence rate might have been slightly higher.

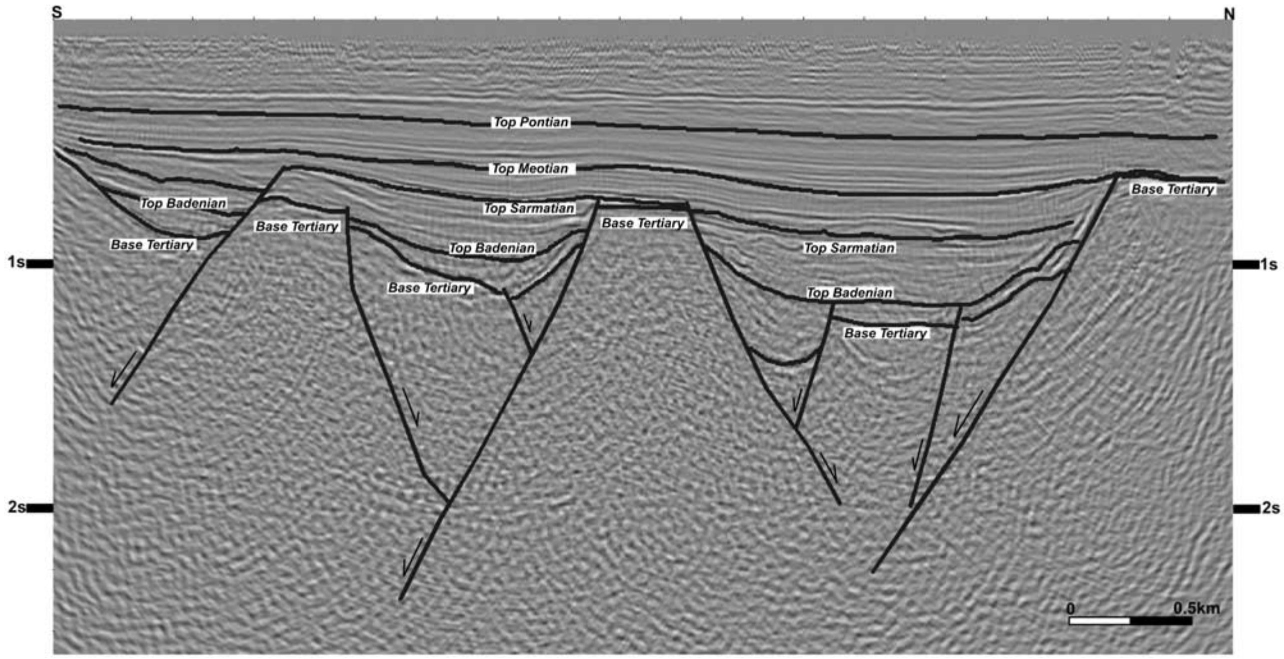

Figure 8. Interpreted seismic line across the Badenian basins from the southern foreland near the southeastern edge of the extended region (for location, see Figure 1). Extensional basins are imaged in this line with wedge-shaped sinrift Badenian deposits. In the southern basins the displacements along the bounding faults continued until Sarmatian. A general northward tilting occurred after Pontian (note the wedge shape of the post-Pontian sedimentary sequence). Conventions are as in Figure 6.

[43] Between the Focşani Depression and the North Dobrogea promontory, the Meotian sedimentation rate is around 0.27 km/Myr (curve 4 in Figure 5). Similar values of few hundred meters per million years are derived for the southern regions.

[44] The Sarmatian north to south progradation of the sediments continued during the early Meotian over almost the entire foreland south of the Focşani Depression and the end of this sedimentation pattern is marked by an extensive top lap surface (Figures 7 and 12). The western border of the basin supplied by the north to south prograding sediments is represented by Intramoesian fault.

4.3.2. Active Structures

[45] Little localized deformation took place in the Meotian mainly consisting in the reactivation of SW dipping Badenian normal faults along the NE margin of the Focşani Depression (Figures 4c and 6). Farther east, new NW trending normal faults formed. Vertical offsets increase toward the SE reaching few hundred meters. During the same time span, the south Focşani fault acted as a transfer fault. The Peceneaga-Camena and some of the associated faults were reactivated either as strike-slip or normal (Figures 4c and 8). In the southwestern part of studied area, the Intramoesian fault experienced dextral strike-slip movements (Figure 4c) (see also Tărăpoancă et al., submitted manuscript, 2003) with a component of normal displacement increasing toward the north.

4.3.3. Basin Tectonics

[46] The Meotian subsidence pattern partly resembles the one reconstructed for the Sarmatian. The main depocentral area still forms a N-S elongated stripe in front of the already structured Carpathian belt and is flanked to the east by a wide domain with persistent sedimentation and fairly regular thicknesses (Figure 4c). Continuing the existing trend, subsidence rates in the depocentral areas are lower than the Sarmatian ones (curves 1 and 2 in Figure 5). In contrast, a slight increase in subsidence rate is observed in the eastern regions (curve 4 in Figure 5).

[47] The most obvious changes with respect to the Sarmatian pattern are the cessation of subsidence north of the Trotuş Fault (Figure 9 and curve 5 in Figure 5) and the development of an elevated area (slightly subsiding or even stable) in the western sectors of the Focşani Depression (Figure 4c). Similarly to the Sarmatian, Meotian sediments are basically undeformed and the creation of accommodation space is controlled by larger-scale tilting (e.g., Figure 6).

4.4. Pontian (8–5 Myr)

4.4.1. Thickness and Subsidence Patterns

[48] During the Pontian, the older depocenters immediately south of the Trotuş fault and in front of the Carpathian bend zone are abandoned and the maximum accommodation space is created in the central part of the investigated area, that is, in the central parts of the Focşani Depression (Figure 4d) where thicknesses of 1.5–1.6 km are attained and isopachs are mainly directed NW-SE. Sediments thicknesses decrease toward the west. Pontian subsidence rate in the Focşani Depression is around 0.4–0.45 km/Myr in the central domains

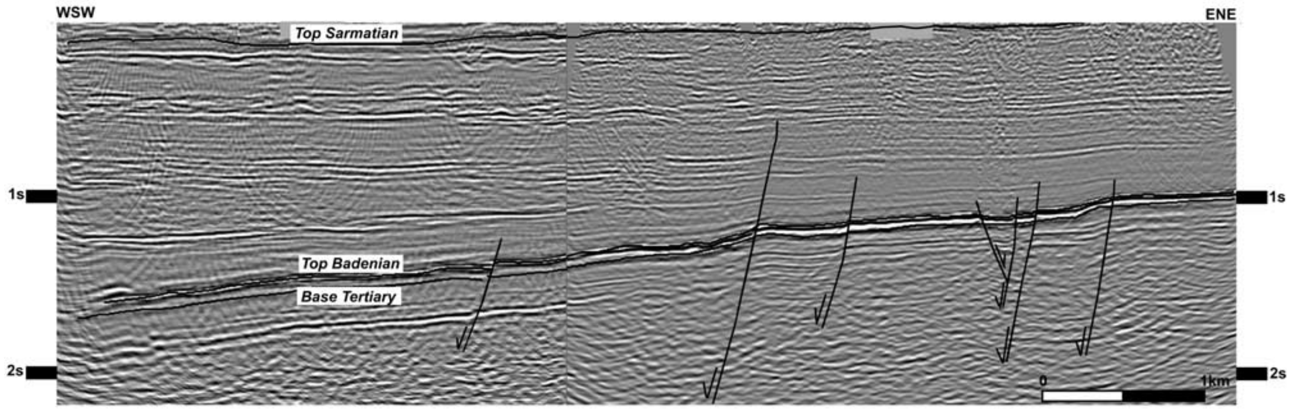

Figure 9. Interpreted seismic line from the northern foreland (for location, see Figure 1). The Sarmatian deposits have a wedge shape and dip to the west revealing a typical foredeep basin infill. The intervals with wavy/hummocky configurations represent north to south prograding deltaic lobes. Small west dipping faults formed during Sarmatian and are interpreted as a result of the flexure of the foreland due to the Carpathians nappes loading. Conventions are as in Figure 6.

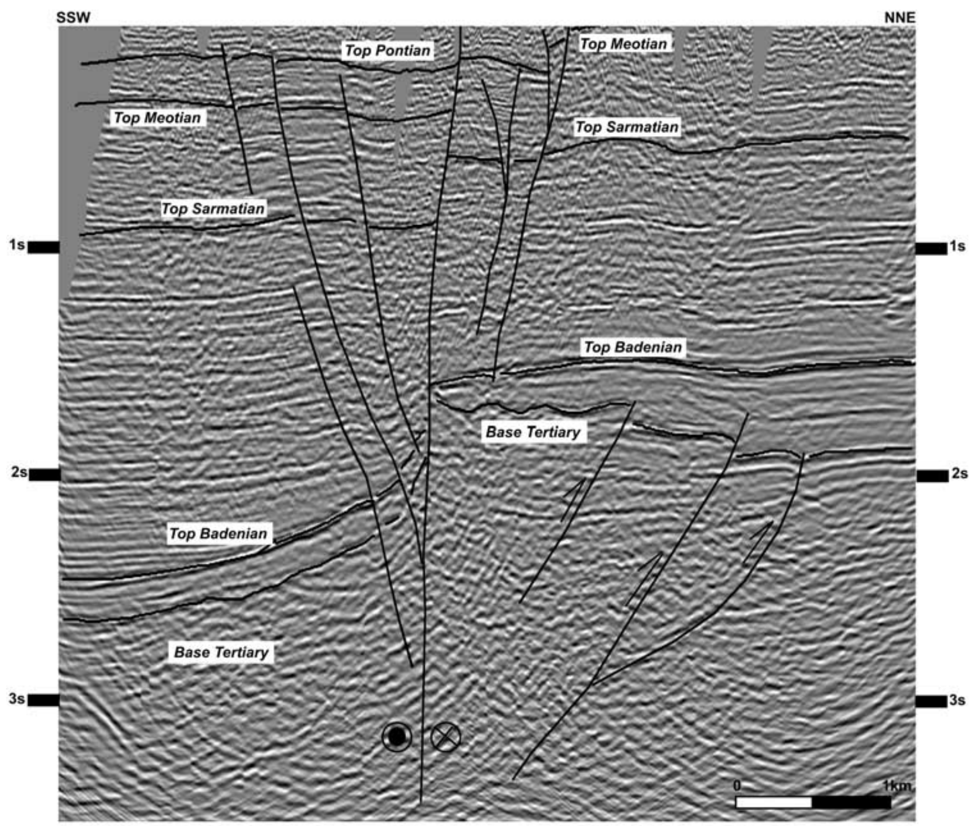

Figure 10. Interpreted seismic line across the Trotuş fault (for location, see Figure 1). Trotuş fault is interpreted as a negative flower structure associated with sinistral strike-slip faulting. This sense of displacement was inferred by *Maţenco* [1997] and *Maţenco and Bertotti* [2000] based mainly on kinematic indicators from outcrops close to its prolongation in the East Carpathians belt. Note the important vertical offset produced during Sarmatian. Young deformations (post-Pontian) can be noticed as well. In the uplifted block several inverse faults produced during Badenian are observed and belong to the same thrust system identified in Figure 6. Conventions are as in Figure 6.

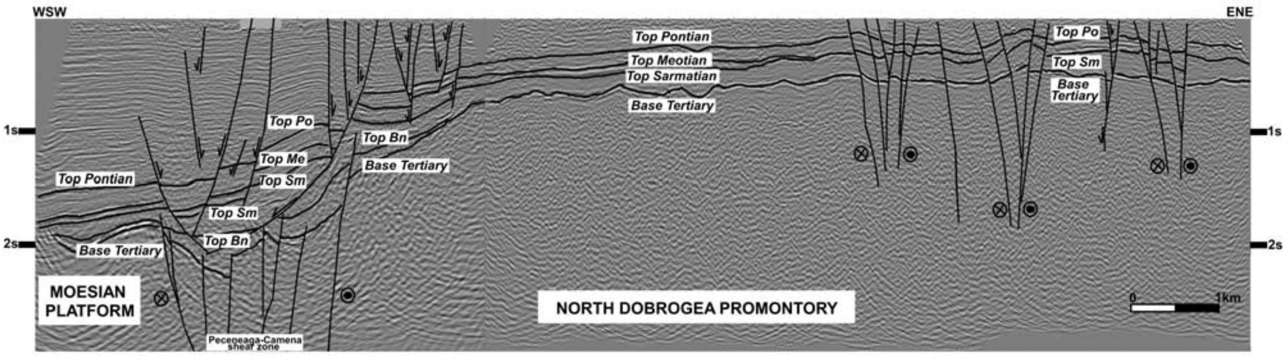

Figure 11. Interpreted seismic line across the boundary between the Moesian platform and North Dobrogea promontory (for location, see Figure 1). The boundary is represented by Peceneaga-Camena fault interpreted as a dextral shear zone. This sense of movement is inferred from the associated ENE-WSW oriented basins, which are probably pull-apart in origin (Figure 4b) (also Tărăpoancă et al., submitted manuscript, 2003). However, taking into account the dimension of these basins, the magnitude of dextral displacement is probably small, in order of few kilometers. Very young displacements along Peceneaga-Camena shear zone determined the listric normal fault system and associated structures above it as well as the drop of the Moesian platform relative to North Dobrogea promontory and the rapid westward thickening of the post-Pontian sedimentary sequence. To the western part of the line the Pontian deposits show a gently thickening as well. Inside North Dobrogea promontory negative and positive flower structures could be noticed and are interpreted as dextral strike-slip faults because they trend parallel with Peceneaga-Camena fault (see Figures 4b and 4e). Conventions are as in Figure 6.

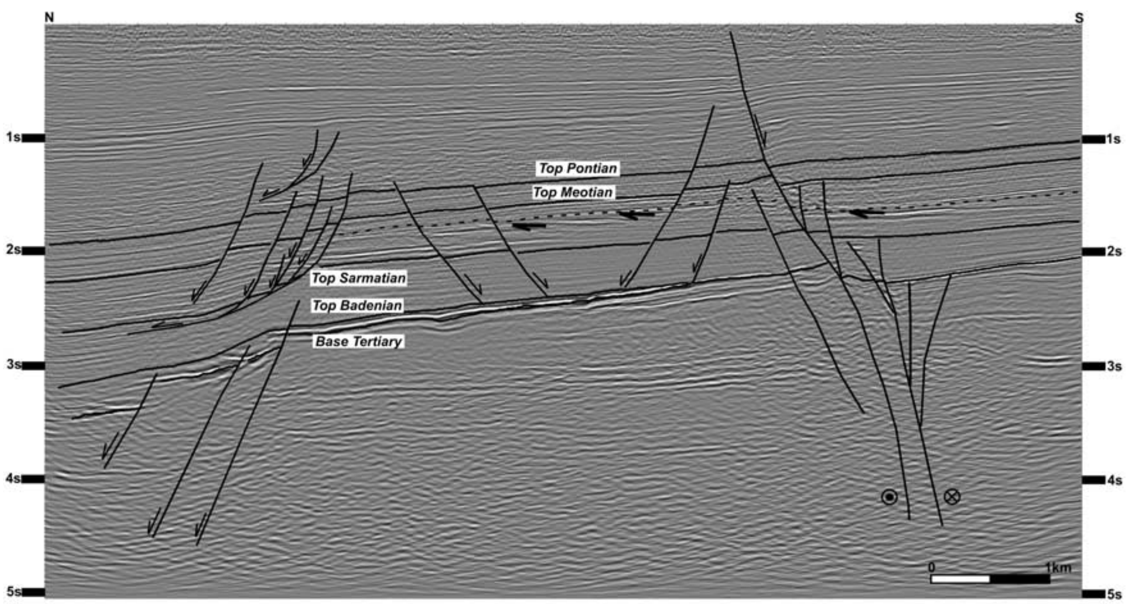

Figure 12. Interpreted seismic line from the southern foreland (for location, see Figure 1). In the southern part of the line a flower structure can be noticed and is interpreted as a sinistral strike-slip fault (note the occurrence of both normal and inverse offsets and the change in thickness revealed by the pre-Tertiary reflectors). This sense of displacement is supposed since farther to the south, faults with the same orientation and age were documented to be sinistral based on the offset of old Mesozoic rift structures [*Răbăgia and Tărăpoancă*, 1999]. Very young reactivation of this structure could be observed as normal or transtensional fault. Post-Pontian normal faults (planar and listric) are observed to the north. The dashed black line within Meotian sedimentary sequence represents a top lap surface and the thicker black arrows correspond to top lap stratal terminations implying a progradation from north to south (see also Figure 7). A northward tilting started in Pontian and accentuated after Pontian (note the thickening of these sedimentary sequences to the north). Conventions are as in Figure 6.

(curve 1 in Figure 5) decreasing toward the north (curve 2 in Figure 5).

[49] Pontian sediments are missing north of the Trotuş fault. Thicknesses regularly decrease from the main depocentral area toward the east, toward the North Dobrogea promontory and even the pinch out limit of the Pontian deposits moved farther east than the Meotian one (Figure 11). Subsidence rates in the area are in the order of 0.1–0.2 km/Myr (curve 4 in Figure 5). In the southern foreland, thicknesses decrease quite rapidly from the depocentral areas toward the south (Figures 7, 8, and 12) and very few Pontian sediments are observed in the region of the Intramoesian fault. Subsidence rates are again in the order of 0.1–0.2 km/Myr (Figure 5, curves 3 and 7).

4.4.2. Active Structures

[50] The Pontian is the time span with the lowest tectonic activity. Despite ongoing vertical movements no important structures formed. Only few normal faults continued to be active in the ESE part of the Focşani Depression (Figure 4d).

4.4.3. Basin Tectonics

[51] The Pontian is a time of significant changes in the subsidence pattern of the Focşani Depression and marks the transition to the presently active pattern of vertical movements. The main depocentral areas moved few tens of kilometers to the SE with respect to the position they had in Meotian times (Figure 4d). Consequently, (1) the neighborhood of the Trotuş fault ends its subsidence and (2) the Focşani Depression becomes clearly detached from the Carpathians Belt, meaning that maximum foredeep subsidence occurs away from the orogenic load. Subsidence rates in the subsiding areas continue to decrease with respect to previous periods. At the same time, little sediments are deposited in the southern reaches of the basin, especially south of the Intramoesian fault. The elevated NNW-SSE trending area in the western portion of the Focşani Depression continues to exist and Pontian sediments are very thin to missing. This zone is parallel to the main depocenter but slightly oblique with respect to the Carpathian trend.

4.5. Dacian-Quaternary (5–0 Myr)

4.5.1. Thickness and Subsidence Patterns

[52] The Dacian-Quaternary time interval is characterized by very strong subsidence in the central sectors of the Focşani Depression. Dacian-Quaternary deposits reach their maximum thicknesses of almost 4.5 km in the middle of Focşani Depression in a subcircular depocentral area (Figure 4e). Outside this area, isopachs between 2500 and 1000 meters have a distinct linear trend NW-SE in the east and NE-SW in the south. High subsidence rates up to 0.86 km/Myr are obtained for the central parts of the Focşani Depression (curve 1 in Figure 5). The Dacian to Quaternary depocenter is flanked to the west by an area of reduced to absent sedimentation (Figure 4e).

[53] Moving away from the main depocenter, Dacian to Quaternary sediments thin toward the north to 0 km near the Trotuş fault (Figure 4e). Subsidence rates are of few hundred metres per million years (e.g., curve 2 in Figure 5). Toward the east, coeval sediments are spread over the entire area up to the Pecenaga-Camena Fault. They are 1 km thick on the North Dobrogea promontory and around 2 km in the domain between Intramoesian and Peceneaga-Camena faults (Figures 4e and 11). Subsidence rates on the North Dobrogea promontory are around 0.15 km/Myr (curve 4 in Figure 5). The thickness pattern reveals the roughly uniform northwestward tilting of the southern foreland (Figures 4e, 7, 8, and 12). To the SSE of Focşani Depression the thickness gently reduces (Figure 4e). An abrupt decrease in thickness is observed across the Intramoesian fault.

4.5.2. Active Structures

[54] Widespread faulting took place during Dacian to Quaternary times compatible with the strong vertical movements recorded in the sedimentary succession. The NW-SE trending system of normal faults at the NE of the Focşani Depression was reactivated (Figures 4e and 6) in some cases with negative flower structures associated with sinistral strike-slip movements (Figures 4e and 6). Vertical offsets decrease from NW to SE. Dacian to Quaternary folding affects post-Sarmatian beds with intensities increasing to the west (Figure 6). Sinistral movements occurred also along the Trotuş (Figures 4e and 10) and south Focşani faults (Figure 4e).

[55] In the southern domains, the basin experienced further northward tilting partly related to movements along the Intramoesian and Peceneaga-Camena faults (Figures 4e and 11). Both faults have a dextral transtensional component of movement. The strike-slip faults from the North Dobrogea orogen underwent dextral reactivations as well (Figure 11). In the south, new ENE-WSW trending normal faults formed (e.g., Figure 12) and older faults with similar trend were reactivated either as sinistral strike-slip faults or as normal faults having in generally the northern block uplifted (Figures 4e and 12).

4.5.3. Basin Tectonics

[56] The northern part of the Focşani Depression, which had become strongly subsiding in the Pontian, keeps on doing so also during Dacian to Quaternary times. More than 4000 m of sediments have been deposited in the area associated with large wavelength vertical movements (e.g., Figure 11). Sedimentation rates increase in the central part of Focşani Depression with respect to previous time frames (Figure 5). Isopachs on the NE side of the basin have a distinct NW-SE trend parallel to the major faults of the area. In the internal side of the Focşani Depression, the uplifting area which began to be defined in Pontian times develops further and is associated with steepening and tilting of pre-Dacian beds. At a larger scale this corresponds to the uplift of Carpathians bend zone [*Sanders et al.*, 1999]. In the southern reaches of the investigated zone, subsidence affected previously stable areas involving large domains north of the Intramoesian fault.

5. Neogene Regional Evolution of the Focşani Depression

[57] A complete understanding of the dynamics of basin formation of the Focşani Depression can only be reached integrating it in a regional frame. Consequently, the progressive development of the major structures from the

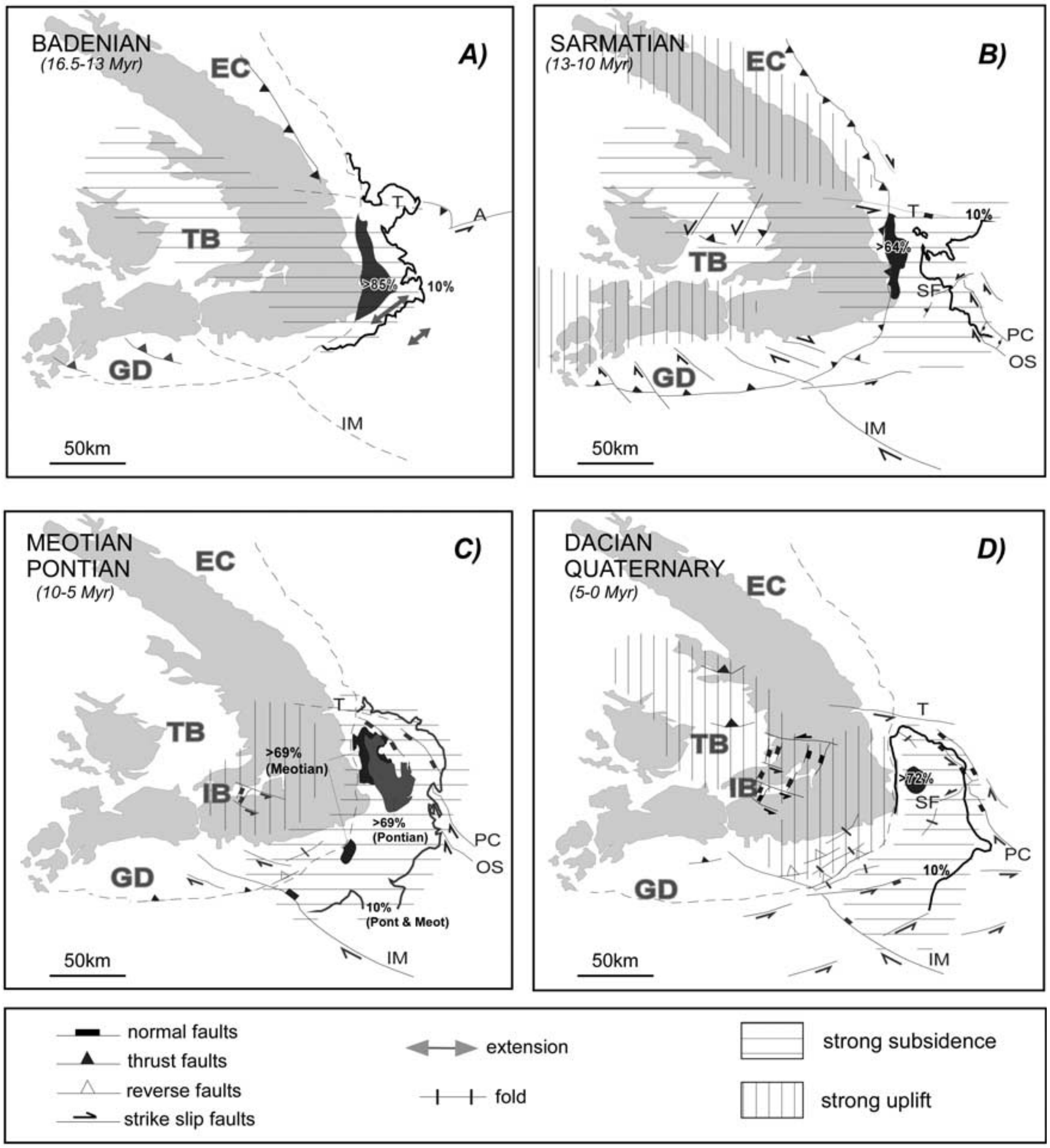

Figure 13. Tectonic model for Neogene evolution of the Carpathians region and subsidence patterns in Focsani Depression for four time spans: (a) Badenian, (b) Sarmatian, (c) Meotian-Pontian, and (d) Dacian-Quaternary. The dark grey areas indicate occurrence of major subsidence in Focsani Depression. The percentages refer to the subsidence rates relative to the their maximum value for each time frame. The present-day isoline of + 500 m elevation is shown in background for each time frame. AF, Adjud fault; IMF, Intramoesian fault; OSF, Ostrov-Sinoe fault; PCF, Peceneaga-Camena fault; SFF, south Focşani fault; TF, Trotuş fault. EC, East Carpathians; IB, Intramountain basins; GD, Getic Depression; TB, Transylvanian basin.

Carpathians/foreland/Transylvanian basin is shown together with the changes in the subsidence in the Focsani basin (Figures 13a–13d).

5.1. Badenian (16.5–13 Myr)

[58] During Badenian times, thrusting took place in the East Carpathians and inside the Getic Depression in the frame of regional NE-SW contraction (Figure 13a). On the basis of restored geological cross sections, the East Carpathians thrust front is inferred to have been at least 26 km farther to the west than the present position before the final displacement during Sarmatian [*Maţenco*, 1997; *Maţenco and Bertotti*, 2000]. The northern part of the Carpathians foreland, between the Trotuş and the south Focşani faults experienced NE-SW directed compression causing limited

thrusting and sinistral shearing along the Adjud fault itself (Figures 4a, 6, and 10) possibly as a far-field expression of Carpathian convergence [e.g., *Ziegler et al.*, 1998]. There is no evidence of contraction south of the south Focşani fault where NW-SE trending normal faults are found (Figure 4a). They lie on the continuation of the similarly trending faults running along the eastern margin of the Focşani Depression.

[59] In terms of vertical movements, the Badenian time span was characterized by strong subsidence in the Transylvanian basin [e.g., *Ciulavu et al.*, 2000] and the Focşani Depression. A continuous NW-SE oriented subsiding area is inferred connecting the two domains. This broad subsiding band was flanked by the stable areas of the East and South Carpathians that began being uplifted at the end of Badenian.

5.2. Sarmatian (13–10 Myr)

[60] Major contractional deformation occurred in the middle Sarmatian in the East Carpathians when the Subcarpathian nappe was thrust onto the foreland [e.g., *Săndulescu*, 1984, 1988] (Figure 13b). Shortening ended in the middle Sarmatian north of the Trotuş fault and in the late Sarmatian between the Trotuş and Intramoesian faults [*Maţenco and Bertotti*, 2000]. At the same time, dextral shearing was taking place in front of the South Carpathians and the Getic Depression was thrust over the Moesian platform to the west of the Intramoesian fault [*Maţenco*, 1997; *Răbăgia and Maţenco*, 1999]. Sarmatian sinistral shearing and transpressional structures were found in Transylvanian basin while the subsidence was diminishing [*Ciulavu et al.*, 2000]. The southern foreland underwent northwestward tilting and dextral movements along both major faults: Intramoesian and Peceneaga-Camena.

[61] Sarmatian vertical movements are characterized by a NW-SE oriented zone of subsidence ranging from the Transylvanian basin to the Focşani Depression. In the intervening Carpathians bend zone, basin floor subsidence was compensated by shortening and thrusting. As a result, little connection existed between the two marine basins. The subsiding zone was flanked to the NE and SW by areas of strong exhumation and uplift. Fission track data indicate that the uplift of East Carpathians north to the Trotus fault and of South Carpathians began to the end of Badenian and continued during Sarmatian [*Sanders et al.*, 1999].

5.3. Meotian-Pontian (10–5 Myr)

[62] At the end of the Sarmatian, the Carpathian belt was already structured and no major movements occured during Meotian-Pontian time span (Figure 13c). Inside the bend zone of the orogenic wedge, NW-SE dextral shearing and thrusting took place in response to the ongoing compression and the transpression exerted by the deformation along Intramoesian fault (paleostress data of *Hyppolite and Săndulescu* [1996] and *Maţenco and Bertotti* [2000]). These movements contribute in accommodating the northward flexure of the southern foreland. Toward the end of the Pontian, the ESE movement of the orogenic wedge from the bend zone diminished. Inside the Getic Depression dextral shearing and minor thrusting are recorded [*Maţenco*, 1997; *Răbăgia and Maţenco*, 1999] which correlate with movements along Intramoesian fault [*Tărăpoancă*, 1996; Tărăpoancă et al., submitted manuscript, 2003]. To the inner part of the East Carpathians, the opening of the intramontane basins began in Pontian [*Ciulavu*, 1999] behind the southeast moving orogenic wedge. To the eastern part of the southern foreland dextral reactivations of Peceneaga-Camena and Ostrov-Sinoe faults were documented. The eastern edge of the Focşani Depression experienced normal faulting.

[63] Meotian to Pontian subsidence was mainly localized in the Focşani Depression. Subsidence rates in Focşani Depression were somewhat lower than the older ones. Also, the Transylvanian basin still underwent subsidence [*Ciulavu et al.*, 2000]. The Carpathians bend zone started being uplifted [*Sanders et al.*, 1999] separating these two basins previously part of the same subsiding area. Uplift was not associated with major deformation. In the East and South Carpathians only erosion took place [*Sanders et al.*, 1999].

5.4. Dacian-Quaternary (5–0 Myr)

[64] After the Pontian, the contractional deformations resumed in the Bend area [e.g., *Hyppolite and Săndulescu*, 1996] (Figure 13d). The wedge-shaped orogenic block confined between Intramoesian and Trotuş faults moved ESE. Behind the moving block, the opening of the intramontane basins continued [*Ciulavu*, 1999]. Contractional deformations were documented in the eastern part of Getic Depression [*Maţenco*, 1997] and within the Transylvanian basin [*Ciulavu*, 1999], where sedimentation ceased and which was progressively uplifted. Downward movements along Intramoesian and Peceneaga-Camena faults accommodated the roughly uniform tilting of the southern foreland. Dextral displacements along these and other strike-slip faults from North Dobrogea orogen have been recorded. Very young ENE-WSW sinistral strike-slip faults were reported on a large area of the Moesian platform [*Răbăgia and Tărăpoancă*, 1999; *Răbăgia et al.*, 2000; Tărăpoancă et al., submitted manuscript, 2003] and they could be considered as conjugates of the Intramoesian and Peceneaga-Camena faults. The eastern margin of the Focşani Depression underwent normal faulting and sinistral shearing (Figures 4d and 6).

[65] During the Dacian-Quaternary time span the area of maximum subsidence became almost circular and localized in the central part of Focşani Depression. Here and to the south of it, subsidence rates increased significantly (Figure 5). The subsidence in Focsani Depression is coeval with the exhumation of the entire bend zone [*Sanders et al.*, 1999].

6. Conclusions

[66] The SE Carpathians foreland and in particular the Focşani Depression is characterized by a Tertiary polystage evolution, being affected by extension, contraction, shearing and tilting during various time periods. On the basis of a large 2-D seismic survey and an extensive well database we have constrained the 3-D architecture of the basin and the

Neogene to Quaternary tectonic and subsidence evolution of this area covering >20,000 km^2. These events have been integrated with deformations taking place at the larger regional scale, providing the first step toward quantitative modeling focused on basin formation processes and dynamics of the Carpathians Bend region.

[67] The present-day Focşani Depression is NW-SE oriented and is filled with ~13 km thick Badenian-Quaternary sediments. The overall shape and dimensions of the continuously subsiding domain have significant changes in space and time.

[68] Subsidence started in Badenian. Subsidence rates during this time span were ~1.1 km/Myr in the center of the present-day depression and increased westward, beneath the present-day Carpathians structures. Toward the NW, the subsiding area eventually connected with the equally subsiding Transylvania Basin. A local extensional regime is inferred in the SE corner of the Focsani Depression, documented by NW-SE to N-S trending normal faults. Coeval thrusting takes place in the foreland of the East Carpathians north of the Focsani basin and into the orogen itself.

[69] Following an almost regional unconformity at the Badenian/Sarmatian boundary, the Sarmatian depocenter acquired a N-S orientation and started to move away from the belt accompanied by important broadening of the subsiding basin. Sarmatian subsidence was larger close to the Carpathians and progressively diminished toward the foreland, as a result of the overall tilting of the foreland toward the belt due to thrust loading. Strong exhumation was taking place laterally in the South and East Carpathians. After Sarmatian times, subsidence ceased in the foreland of the East Carpathians, taking place only south of the Trotus fault.

[70] Subsidence decreased during Meotian to Pontian times. Normal faulting along the eastern margin of the Focsani Depression took place again, the tectonic activity decreasing toward the end of this period.

[71] During Pliocene-Quaternary times, the subsidence increased in the central part of Focşani Depression. Coeval uplift and exhumation taking place on the neighboring Carpathians bend zone has tilted the western flank of the basin and reduced its areal size.

[72] The Tertiary tectonic evolution of the Focsani basin is proving that in some cases foredeep subsidence does not follow the thrust load timing succession and typical wedge-type geometry. Horizontal loads affecting prestructured lithospheric and crustal blocks can significantly influence vertical movements in these areas [e.g., *Bertotti et al.*, 2003].

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References

Artyushkov, E. V., M. A. Baer, and N.-A. Mörner, The East Carpathians: Indications of phase transitions, lithospheric failure and decoupled evolution of thrust belt and its foreland, *Tectonophysics*, *262*, 101–132, 1996.

Bertotti, G., L. Maţenco, and S. Cloetingh, Vertical movements in and around the SE Carpathians foredeep: Lithospheric memory and stress field control, *Terra Nova*, *15*, 299–305, 2003.

CALIXTO "99 Research Group, Final stage of a plate detachment? Tomographic investigation to snapshot this process at the Carpathian bending zone, in *Dobrogea: The Interface Between the Carpathians and the Trans-European Suture Zone, Europrobe TESZ/PANCARDI/GeoRift, Abstr. Vol.*, edited by L. Maţenco, D. Ioane, and A. Seghedi, *Rom. J. Tect. Reg. Geol.*, *77*, *Suppl. 1*, 17–18, 1999.

Ciulavu, D., Tertiary tectonics of the Transylvanian basin, Ph.D. thesis, 154 pp., Vrije Univ., Amsterdam, Netherlands, 1999.

Ciulavu, D., C. Dinu, A. Szakacs, and D. Dordea, Late Miocene to Pliocene kinematics of the Transylvanian basin (Romania), *AAPG Bull.*, *84*, 1589–1615, 2000.

Dicea, O., The structure and hydrocarbon geology of the Romanian East Carpathians border from seismic data, *Pet. Geosci.*, *1*, 135–143, 1995.

Dumitrescu, I., M. Săndulescu, and T. Bandrabur, Geological map, scale 1:200,000, sheet 29 Covasna, Inst. Geol. Rom., Romania, 1970.

Enescu, D., and B. Enescu, Seismotectonic model regarding the genesis and the occurrence of Vrancea (Romania) earthquakes, in *SEG/EAGE/RSG Bucharest Internantional Geophysics Conference and Exhibition, Conference Volume*, edited by R. G. Dimitriu and D. Ioane, *Rom. Geophys.*, *7*, *Suppl. 1*, 496–497, 2000.

Gvirtzman, Z., Partial detachment of a lithospheric root under the southeast Carpathians: Toward a better definition of the detachment concept, *Geology*, *30*, 51–54, 2002.

Hyppolite, J. C., and M. Săndulescu, Paleostress characterization of the "Walachian phase in its type area, southeastern Carpathians, Romania, *Tectonophysics*, *263*, 235–249, 1996.

Ionesi, L., *Geologia unitatilor de platforma si a Orogenului Nord Dobrogean*, 280 pp., Ed. Tehnica, Bucharest, Romania, 1994.

Linzer, H. G., Kinematics of retreating subduction along the Carpathian arc, Romania, *Geology*, *24*, 167–170, 1996.

Maţenco, L., Tectonic evolution of the outer Romanian Carpathians: Constraints from kinematic analysis and flexural modeling, 160 pp., Ph.D. thesis, Vrije Univ., Amsterdam, Netherlands, 1997.

Maţenco, L., and G. Bertotti, Tertiary tectonic evolution of the external East Carpathians (Romania), *Tectonophysics*, *316*, 255–286, 2000.

Maţenco, L., G. Bertotti, S. Cloetingh, and C. Dinu, Subsidence analysis and tectonic evolution of the external Carpathian-Moesian platform during Neogene times, *Sediment. Geol.*, *156*, 71–94, 2003.

Meulenkamp, G. E., M. Kovacs, and I. Cicha, On late Oligocene to Pliocene depocentre migrations and the evolution of the Carpathian-Pannonian system, *Tectonophysics*, *266*, 301–317, 1996.

Negulescu, R., Studiul geologic complex al formatiunilor neogene din zona de trecere de la Platforma Moldoveneasca la Avanfosa Carpatilor Orientali cu privire speciala asupra conditiilor de formare a acumularilor de hidrocarburi, Ph.D. thesis, 183 pp., Univ. of Bucharest, Bucharest, Romania, 2001.

Nemcok, M., L. Pospisil, J. Lexa, and R. A. Donelick, Tertiary subduction and slab break-off model of the Carpathian-Pannonian region, *Tectonophysics*, *295*, 307–340, 1998.

Oncescu, M. C., Deep structure of the Vrancea region, Romania, inferred from simultaneous inversion for hypocenters and 3-D velocity structure, *Ann. Geophys.*, *2*, 23–28, 1984.

Oncescu, M. C., K.-P. Bonjer, and M. Rizescu, Weak and strong ground motion of intermediate depth earthquakes from the Vrancea region, in *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation*, edited by F. Wenzel, D. Lungu, and O. Nowak, pp. 27–42, Kluwer Acad., Norwell, Mass., 1998.

Paraschiv, D., *Romanian Oil and Gas Fields*, 212 pp., Stud. Tehn. si Econ., Inst. Geol. Rom., Bucharest, Romania, 1979.

Răbăgia, T., and L. Maţenco, Tertiary tectonic and sedimentological evolution of the South Carpathians foredeep: Tectonic versus eustatic control, *Mar. Pet. Geol.*, *16*, 719–740, 1999.

Răbăgia, T., and M. Tărăpoancă, Tectonic evolution of the Romanian part of the Moesian platform:

An integrated model, in *Dobrogea: The Interface Between the Carpathians and the Trans-European Suture Zone, Europrobe TESZ/PANCARDI/GeoRift, Abstr. Vol*., edited by L. Maţenco, D. Ioane, and A. Seghedi, *Rom. J. Tect. Reg. Geol.*, *77*, *Suppl. 1*, 58, 1999.

Răbăgia, T., M. Tărăpoancă, C. Dinu, and R. Smith, Neotectonics of the Moesian platform: Seismic implications, in *SEG/EAGE/RSG Bucharest International Geophysics Conference and Exhibition, Conference Volume*, edited by R. G. Dimitriu and D. Ioane, *Rom. Geophys.*, *7*, *Suppl. 1*, 284 – 285, 2000.

Rădulescu, F., Seismic models of the crustal structure in Romania, *Rev. Roum. Geol. Geopys. Geogr., Ser. Geophys.*, *32*, 13 – 17, 1988.

Rădulescu, D. P., I. Cornea, M. Săndulescu, P. Constantinescu, F. Rădulescu, and A. Pompilian, Structure de la croûte terrestre en Roumanie. Essai d'interprétation des études séismique profondes, *Ann. Inst. Geol. Geofiz.*, *50*, 5 – 36, 1976.

Roure, F., E. Roca, and W. Sassi, The Neogene evolution of the outer Carpathians flysch units (Poland, Ukraine and Romania): Kinematics of a foreland/fold-and-thrust belt system, *Sediment. Geol.*, *86*, 177 – 201, 1993.

Royden, L. H., Late Cenozoic tectonics of the Pannonian basin system, in *The Pannonian Basin: A Study in Basin Evolution*, edited by L. H. Royden and F. Horvath, *AAPG Mem.*, *45*, 27 – 48, 1988.

Royden, L. H., The tectonic expression of the slab pull at continental convergent boundaries, *Tectonics*, *12*, 303 – 325, 1993.

Royden, L. H., and G. D. Karner, Flexure of the lithosphere beneath Apennine and Carpathian foredeep basins: Evidence for an insufficient topographic load, *AAPG Bull.*, *68*, 704 – 712, 1984.

Sanders, C. A. E., P. A. M. Andriessen, and S. A. P. L. Cloetingh, Life cycle of the East Carpathian orogen; Erosion history of a doubly vergent critical wedge assessed by fission track thermochronology, *J. Geophys. Res.*, *104*, 29,095 – 29,112, 1999.

Săndulescu, M., *Geotectonica Romaniei*, 450 pp., Ed. Tehnica, Bucharest, Romania, 1984.

Săndulescu, M., Cenozoic tectonic history of the Carpathians, in *The Pannonian Basin: A Study in Basin Evolution*, edited by L. H. Royden and F. Horvath, *AAPG Mem.*, *45*, 17 – 25, 1988.

Săndulescu, M., and M. Visarion, La structure des plates-formes situees dans l'avant-pays et au-dessous des nappes du flysch des Carpates orientales, *St. Tehn. Econ. Geofiz.*, *15*, 62 – 67, 1988.

Sperner, B., F. Lorentz, S. Hettel, B. Mueller, and F. Wenzel, Geodynamics of the Eastern Carpathians, in *Dobrogea: The Interface Between the Carpathians and the Trans-European Suture Zone, Europrobe TESZ/PANCARDI/GeoRift, Abstr. Vol*., edited by L. Maţenco, D. Ioane, and A. Seghedi, *Rom. J. Tect. Reg. Geol.*, *77*, *Suppl. 1*, 46, 1999.

Tărăpoancă, M., Tectonica faliei Intramoesice, Ms. thesis, 90 pp., Univ. of Bucharest, Bucharest, Romania, 1996.

Wortel, R., and W. Spakman, Subduction and slab detachment in the Mediterranean-Carpathian region, *Science*, *290*, 1910 – 1917, 2000.

Ziegler, P. A., J.-D. van Wees, and S. Cloetingh, Mechanical controls on collision-related compressional intraplate deformation, *Tectonophysics*, *300*, 103 – 129, 1998.

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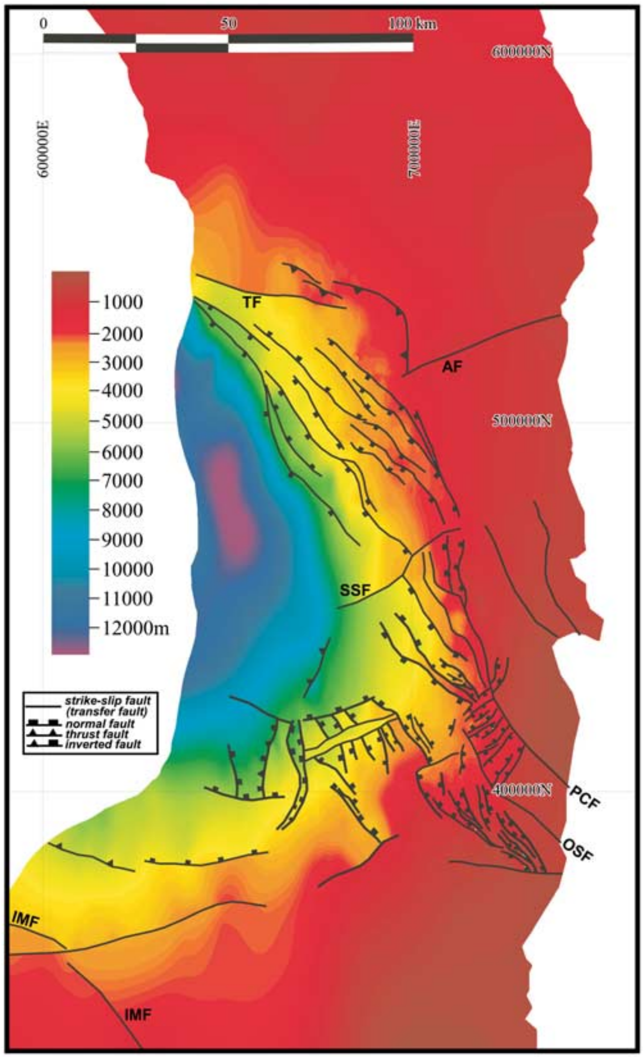
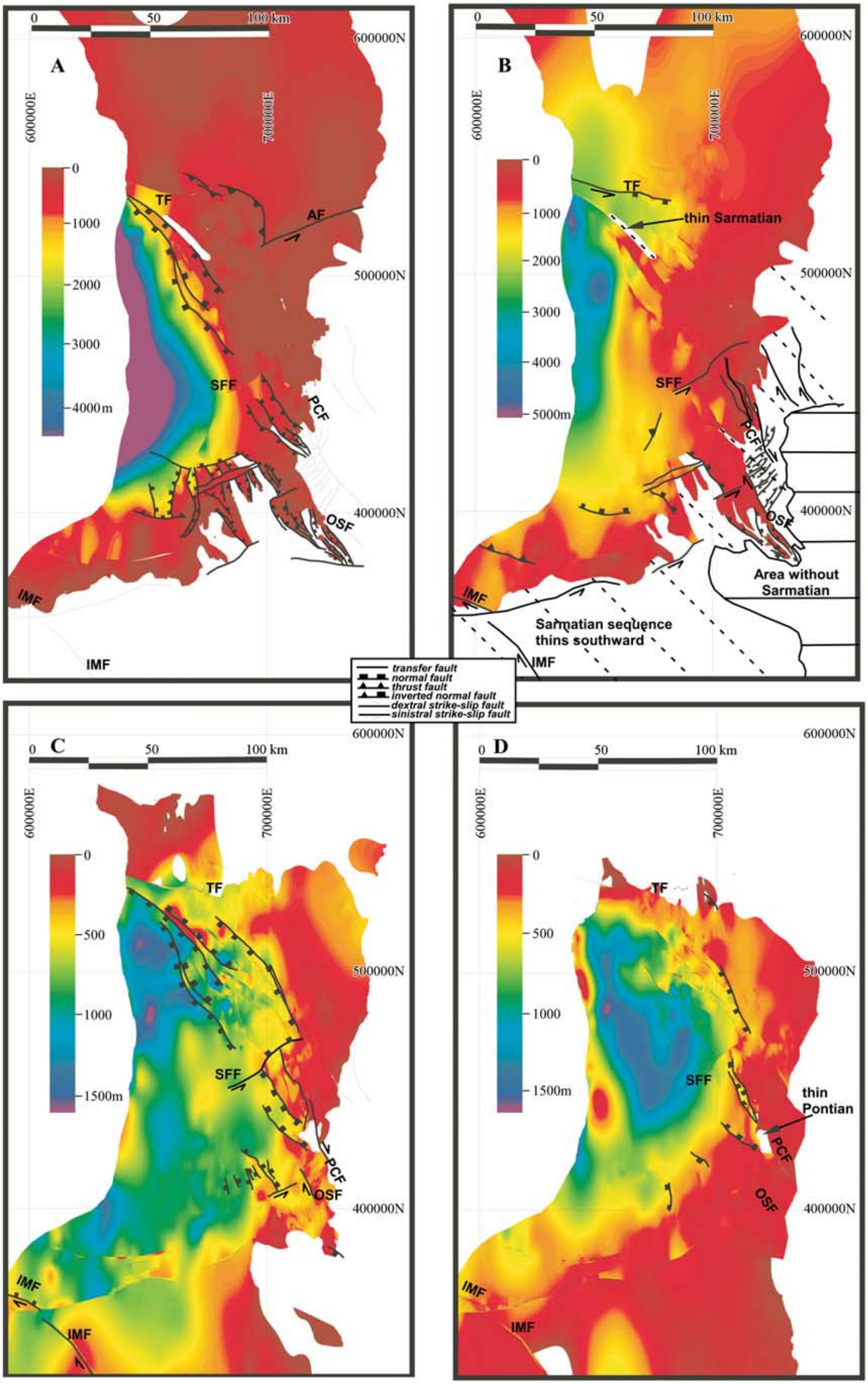


Figure 3. Structural map of the base Tertiary. The reference datum is 100 m above sea level. AF, Adjud fault; IMF, Intramoesian fault; OSF, Ostrov-Sinoe fault; PCF, Peceneaga-Camena fault; SFF, south Focşani fault; TF, Trotuş fault.



A
0
50
100 km
600000N
600000E
700000E
500000N
400000N
0
1000
2000
3000
4000m
TF
AF
SFF
PCF
OSF
IMF
IMF
B
0
50
100 km
600000N
600000E
700000E
500000N
400000N
0
1000
2000
3000
4000
5000m
TF
thin Sarmatian
SFF
PCF
OSF
Area without Sarmatian
IMF
Sarmatian sequence thins southward
IMF
transfer fault
normal fault
thrust fault
inverted normal fault
dextral strike-slip fault
sinistral strike-slip fault
C
0
50
100 km
600000N
600000E
700000E
500000N
400000N
0
500
1000
1500m
TF
SFF
PCF
OSF
IMF
IMF
D
0
50
100 km
600000N
600000E
700000E
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thin Pontian
PCF
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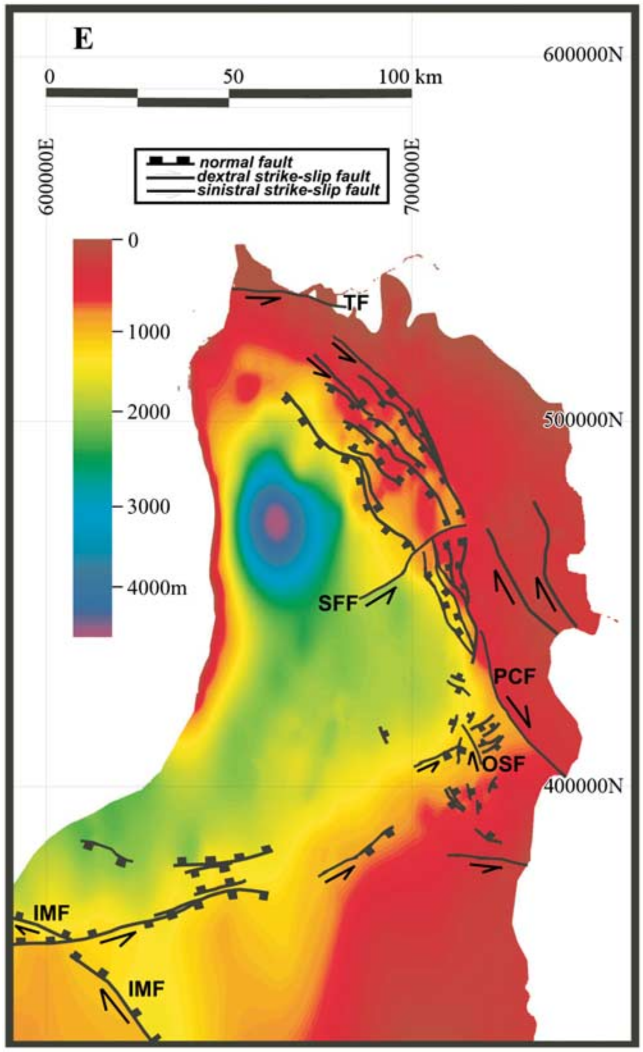

Figure 4. (continued)

Figure 4. (opposite) Isopach maps for (a) Badenian, (b) Sarmatian, (c) Meotian, and (d) Pontian. No decompaction correction is used. Note that the scale of color coding is different in Figures 4a–4d. (e) Top Pontian structural map. The reference datum is 100 m above sea level. The map also represents an estimation of the thickness of Dacian-Quaternary sequence. AF Adjud fault; IMF Intramoesian fault; OSF Ostrov-Sinoe fault; PCF Peceneaga-Camena fault; SFF south Focşani fault; TF Trotuş fault. For all maps, the highlighted structures are those active at the specified time interval (in Figure 4e the faults have been active after Pontian).