Neogene kinematics of the Transylvanian basin (Romania)

Daniel Ciulavu, Corneliu Dinu, Alexandru Szakács, and Dorin Dordea

ABSTRACT

The Transylvanian basin is a major sedimentary basin located in the eastern part of the European Alpine orogenic system. It has a sedimentary fill more than 5 km (up to 8 km in some small areas) thick of Upper Cretaceous to upper Miocene deposits. It represents the main gas-producing province in Romania and central, eastern Europe.

In this article we analyze seismic lines and structural data from the basin as well as from its northern, eastern, and southeastern borders. These data indicate a tectonic origin for the Neogene structures from the Transylvanian basin. These structures include (1) northeast- and southwest-dipping thrust faults, and (2) east-northeast– and west-northwest–striking strike-slip faults having normal or reverse slip. Secondary structures such as salt diapirs and folds are related to these faults.

Structural data from the basin and its border indicate a Neogene overall compressional/transpressional regime having maximum principal stress oriented north to northeast.

INTRODUCTION

The Transylvanian basin is a major sedimentary basin located in the eastern part of the European Alpine orogenic system, adjacent to the Pannonian basin (Figure 1). Its sedimentary fill (5 to 8 km thick) is comprised of Upper Cretaceous to upper Miocene deposits. The basin has a roughly circular shape and covers an area of around 20,000 km^2 (Figure 2). The Transylvanian basin is the main gas-producing province in Romania and in central, eastern Europe, having more than 34 tcf reserve in place (Popescu, 1995). Gas is produced from the middle to the upper Miocene sedimentary sequence.

The term "Transylvanian basin" is used stratigraphically in two different ways: (1) for the Upper Cretaceous to upper Miocene

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sediments (Păucă, 1969; Ciupagea et al., 1970; Ciulavu and Bertotti, 1994; Huismans et al., 1997), and (2) for the Badenian to uppermost Miocene sediments (e.g., Săndulescu, 1984). In this article, the term "Transylvanian basin" will be used for the entire Upper Cretaceous to upper Miocene sedimentary sequence.

Many workers (e.g., Horváth and Royden, 1981; Royden, 1988) have observed that the structural development of the Transylvanian basin is poorly understood. This lack of understanding has been due in large part to the lack of publicly available seismic data. However, since 1994 seismic data have been released by industry and/or published in several papers. Seismic lines published by de Broucker et al. (1998) summarized the pre-Badenian tectonic evolution of the northern sector of the Transylvanian basin. Structural work performed in the last decade along the basin borders has helped put constraints on the tectonic evolution of the Transylvanian basin (e.g., Ciulavu and Bertotti, 1994; Huismans et al., 1997; Ciulavu et al., 1998). However, no seismic data on the Neogene tectonics of the Transylvanian basin have been published to date.

In this article, we interpret six reflection seismic lines acquired by Prospectiuni SA and by Shell Romania Exploration BV (Figure 2). We also prepare a regional cross section that summarizes available data (Figure 2). Surface structural data have been acquired in the basin and its northern, eastern, and southeastern borders (Figure 2).

The Neogene kinematics of the Transylvanian basin is important because it puts new constraints on the tectonic evolution of this basin, as well as of the entire Pannonian-Carpathian area. We interpret a Neogene compression/transpression in the Transylvanian basin. Neogene faults in the Transylvanian basin are much more abundant than has been presented until now. These faults are (1) east-northeast– and west-northwest–striking strike-slip faults, and (2) northeast- and southwest-dipping thrust faults. Secondary structures such as folds and salt diapirs are related to these faults. These structures are the most important components in gas accumulation in the Transylvanian basin. Structures within the basin and at the borders are developed in a north to northeast–oriented stress field. Structures and paleostress data from and around the Transylvanian basin indicate the same Neogene tectonics, which is controlled by basement faults or inherited discontinuities.

REGIONAL GEOLOGICAL SETTING

The arcuate Carpathian mountain belt connects southward to the Bulgarian Balkan chain (Figure 1). Westward, the Carpathians are linked to the Eastern Alps, which are separated from the Southern-Dinaric Alps by the peri-Adriatic line (Figure 1).

The Carpathians are the result of the Cretaceous closure of an oceanic lithosphere, the Mures-Vardar unit (Figure 1), formed during Middle Triassic and Middle Jurassic phases of rifting (e.g., Săndulescu, 1984). Two continental blocks are separated by the

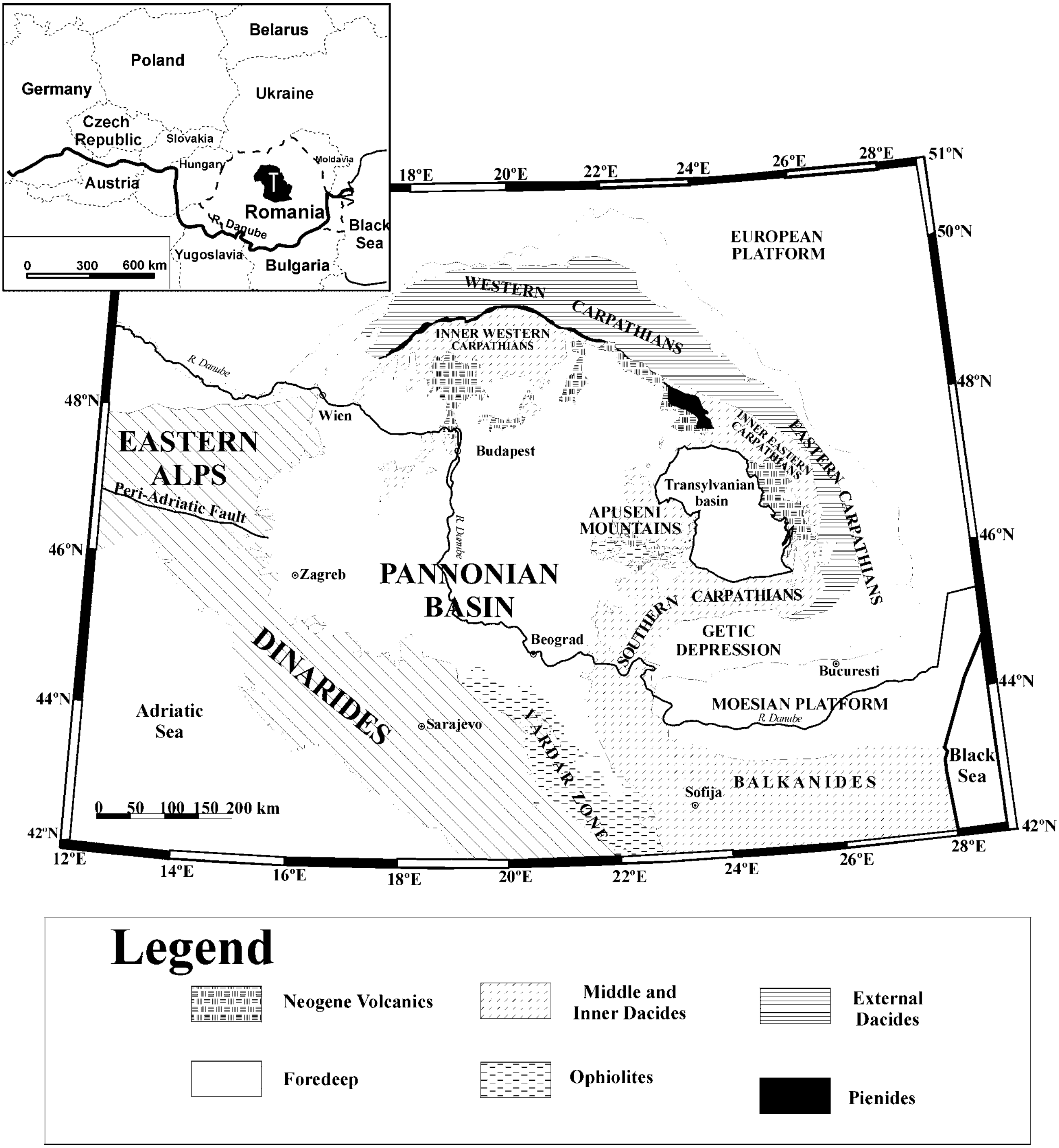


Figure 1. Main tectonic units of the Carpathian-Pannonian area. The inset represents political boundaries from eastern, central Europe and position of the Transylvanian basin (T).

Vardar-Mures unit: (1) a block belonging to Europe (Middle Dacides) to the east (Săndulescu, 1984), and (2) a block belonging to the Austro-Alpine fragment (Inner Dacides) to the west (Burchfiel, 1976; Săndulescu, 1984).

The Carpathians consist of two radially directed fold and thrust belts: (1) an inner belt formed by Cretaceous to early Paleogene thrusting, and (2) an outer belt that is the result of Neogene thrusting. Pienides represent the only tectonic unit that recorded both

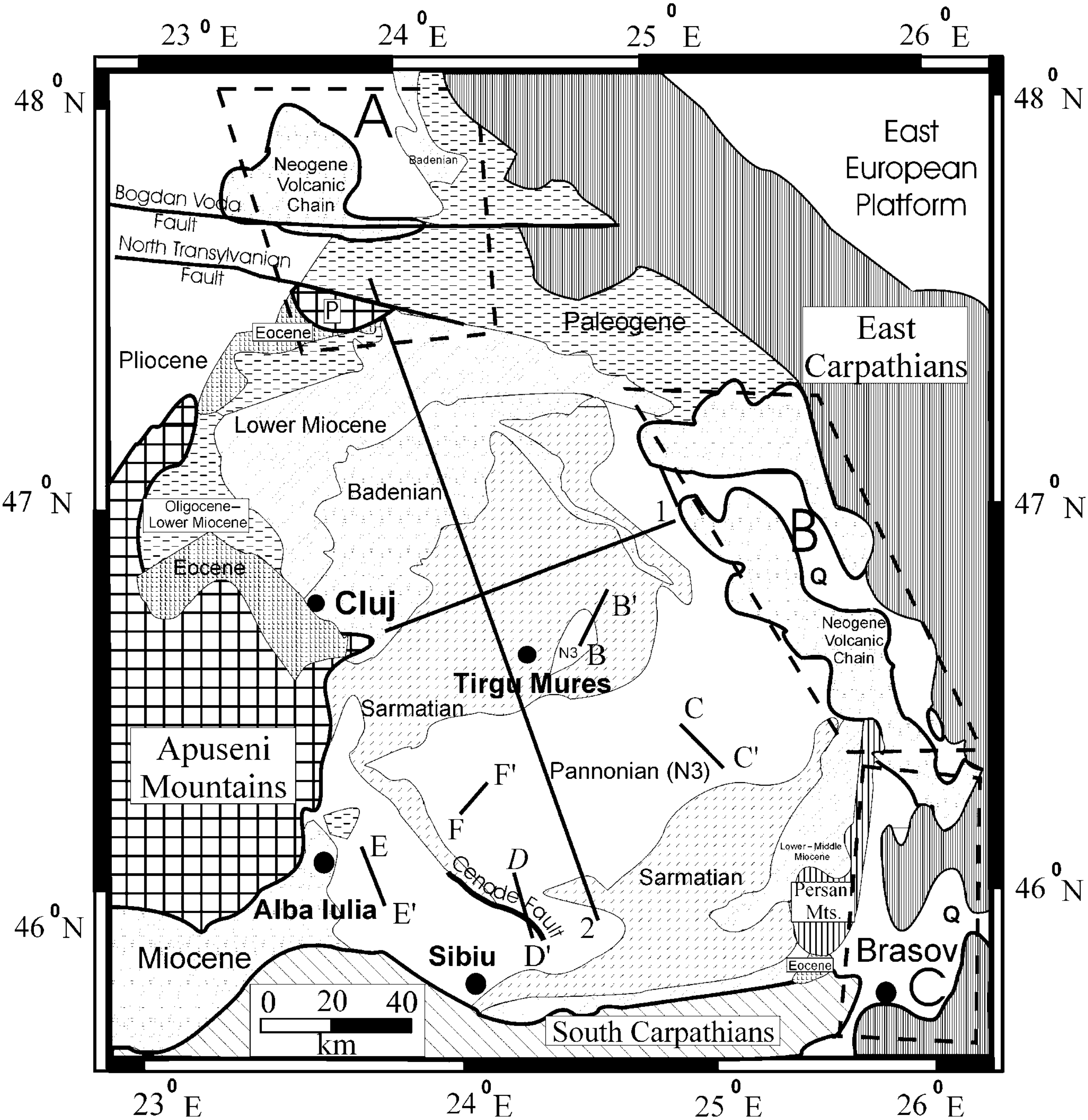


Figure 2. Geological sketch map of the Transylvanian basin (simplified after Giușca et al., 1967a; Răileanu et al., 1967, 1968a, b; Codarcea et al., 1968; Dessila-Codarcea et al., 1968; Ianovici et al., 1968; Patrulius et al., 1968;). The designations BB′ to EE′ represent the location of the seismic lines acquired by Prospectiuni SA and line 1 represents the location of the seismic line acquired by Shell Romania Exploration BV used in this article. Line 2 is drawn compiling available data. The symbols A, B, and C represent areas along the basin borders where structural work has been undertaken. Q = Quaternary, P = Preluca Mountains.

Cretaceous and early Neogene thrusting (Figure 1). The inner belt can be further subdivided into West, East, and South Carpathians (Figure 1).

Tertiary thin-skinned deformation is documented in the Outer Carpathians, where about 180 km of shortening took place (e.g., Roure et al., 1993). The thin-skinned deformation progressively migrated eastward (Săndulescu, 1988). This migration is related, in all models regarding the tectonic evolution of this area, to the eastward movement of the Transylvanian basin as a rigid block (e.g., Csóntós, 1995). This block was gradually pushed in a space surrounded to the north, east, and south by the East European and Moesian platforms (Figure 1) (e.g., Săndulescu, 1984). Deformation associated with this movement is developed in the Outer Carpathians (e.g., Dumitrescu and Săndulescu, 1970). Miocene extension took place in the Pannonian basin, a basin superposed on the inner zone of the Carpathians (e.g., Royden, 1988). This extension is related to the eastward retreat of the European margin (Royden, 1993). The age of the last nappe emplacement in the Carpathians is intra-Sarmatian (Stefănescu, 1986; Săndulescu, 1988). That nappe emplacement was followed by Pliocene compression and inversion of major structures (Horváth and Cloetingh, 1996).

The youngest geological features of the Carpathians are (1) the folded Pliocene–Pleistocene deposits in the external part of the bend zone of the East Carpathians, and (2) the late Miocene to Quaternary basins developing in the inner part of the bend zone of the East Carpathians (Figure 2) (Dumitrescu and Săndulescu, 1970; Săndulescu, 1988). The bend zone of the East Carpathians is the most seismically active area in Romania, having magnitude of the earthquakes up to 7.2 (e.g., Cornea and Lăzărescu, 1980). Intermediate earthquake foci occur in a small, quasi-vertical, north-northeast–striking, confined area, down to about 200 km (Roman, 1970; Fuchs et al., 1979; Oncescu and Bonjer, 1997).

Magmatic activity followed, or was coeval, to the nappe emplacement. In the following, we present only the magmatic activity from Romania. Latest Cretaceous–Paleocene magmatism occurs in the Apuseni Mountains and in the western part of the South Carpathians (Soroiu et al., 1986; Strutinski et al., 1986). Neogene calk-alkaline magmatism, interpreted as subduction-related, occurs along the northern and eastern borders of the Transylvanian basin (Figure 2) (Rădulescu, 1973). K-Ar dating indicates 13.4–0.2 Ma and a decrease of the age of volcanism from north to south (Lang et al., 1994; Pecskay et al., 1995). Neogene (15–7 Ma) calk-alkaline magmatism, without any coherent geodynamical explanation so far, occurs in the Apuseni Mountains (e.g., Borcos, 1994; Rosu et al., 1997). Alkaline basaltic volcanism took place during Pliocene–Pleistocene times in the southeastern part of the basin, close to the Persani Mountains and in the southern part of the Apuseni Mountains.

BASIN EVOLUTION

Development of the Transylvanian basin began in the Late Cretaceous after the main phases of deformation in the Carpathians (Figure 3). Upper Cretaceous sediments were deposited in two north-northeast–striking basins. These were interpreted as either graben structures (Ciupagea et al., 1970; Stefănescu, 1986; Ciulavu and Bertotti, 1994) or sag basins (de Broucker et al., 1998). The basin superposed on the Inner Dacides is filled with Senonian shallow-water sediments (Gosau type), whereas the basin superposed on the Middle Dacides is filled with Cenomanian deep-water sediments (Figure 4) (Săndulescu and Visarion, 1976).

Thrusting took place during the Late Cretaceous–Paleocene in the northern sector of the basin. During the Paleocene, the northern sector of the basin was above the sea level; the Paleocene deposits are missing in the Transylvanian basin (Ciupagea et al., 1970). Two sedimentary cycles have been recognized in the Eocene(?)–middle Oligocene interval in the northern part of the Transylvanian basin (Figure 3) (Popescu, 1984). Each cycle consists of red-bed deposits followed by gypsum evaporites, capped by shallow marine sediments. The lower Eocene sediments were deposited in north-northeast–striking piggyback basins and are involved in thrusting (Figure 4). The lowest red-bed continental deposits are known as the Jibou Formation (Figure 3). The second sedimentary cycle has been interpreted as the result of the reactivation of the late Cretaceous–Paleocene structures (Proust and Hossu, 1996; de Broucker et al., 1998). The thrusts are sealed by the Oligocene to lower Miocene sediments, which were deposited in west-east–trending basins (Figure 4) (de Broucker et al., 1998).

Upper Burdigalian conglomerates, having a wedge-shape thinning southward, are developed in the northern sector of the basin (Figures 2, 4). The Badenian represents the beginning of a new sedimentary cycle that covers the entire area of the Transylvanian basin. The Badenian strata are similar to the Badenian strata from the East Carpathians and South Carpathians. The mechanism of this regional subsidence is still unknown. An extensional mechanism is not suitable because of the lack of Badenian extensional features of regional importance (Ciulavu et al., 1998; de Broucker et al.,

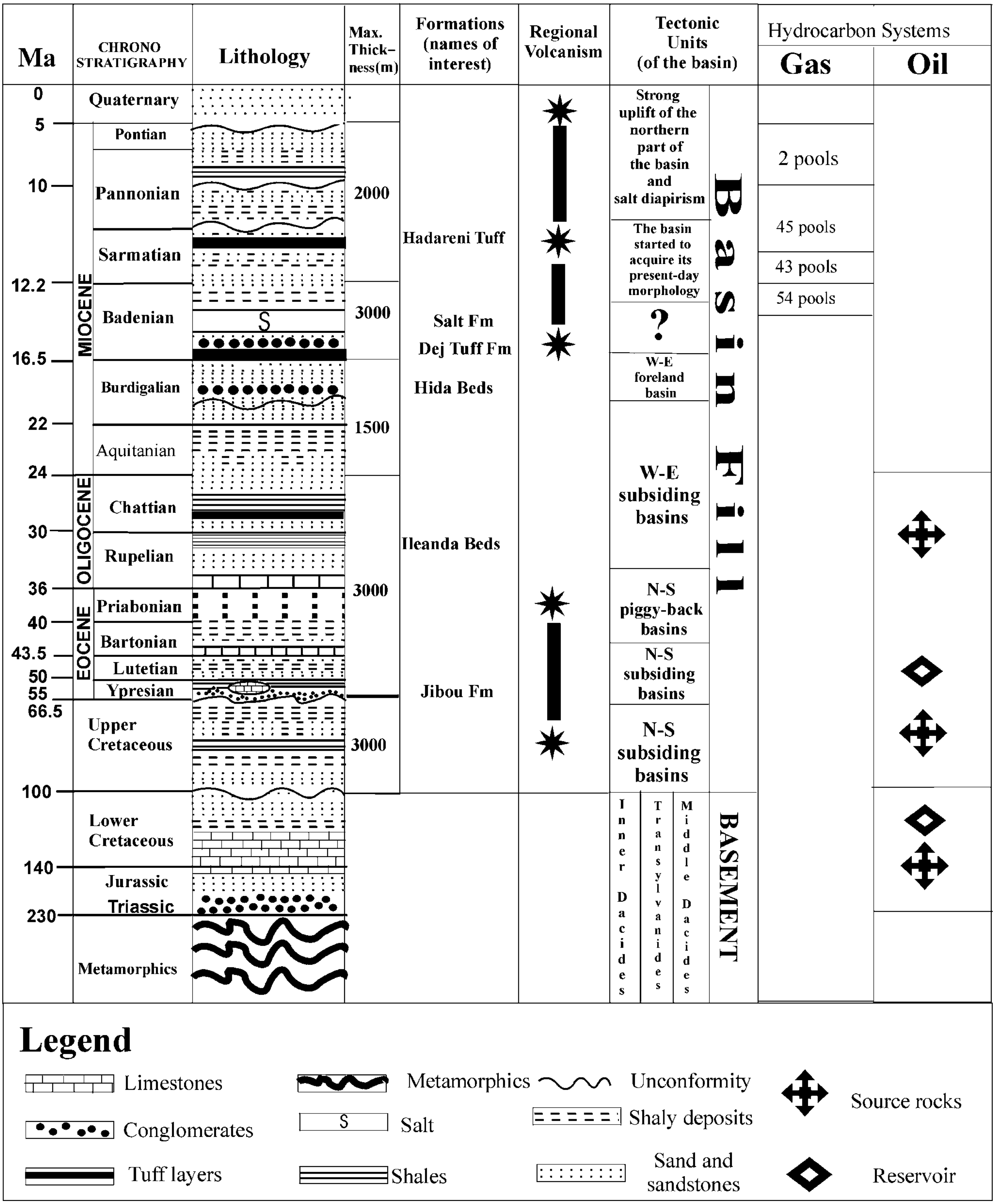


Figure 3. Lithostratigraphic column of the Transylvanian basin. Data compiled after Ciupagea et al. (1970), Gheorghian et al. (1970), Bombiță et al. (1971), Popescu (1984), and de Broucker et al. (1998). Ages are given in million of years (after Rögl, 1996). Petroleum systems are also drawn. In the Transylvanian basin (Central Parathetys), the lower Sarmatian is used as Sarmatian sensu stricto and the upper Sarmatian and the Maeotian as the Pannonian sensu stricto, referred to in this article as Pannonian (e.g., Nicorici and Mészáros, 1994).

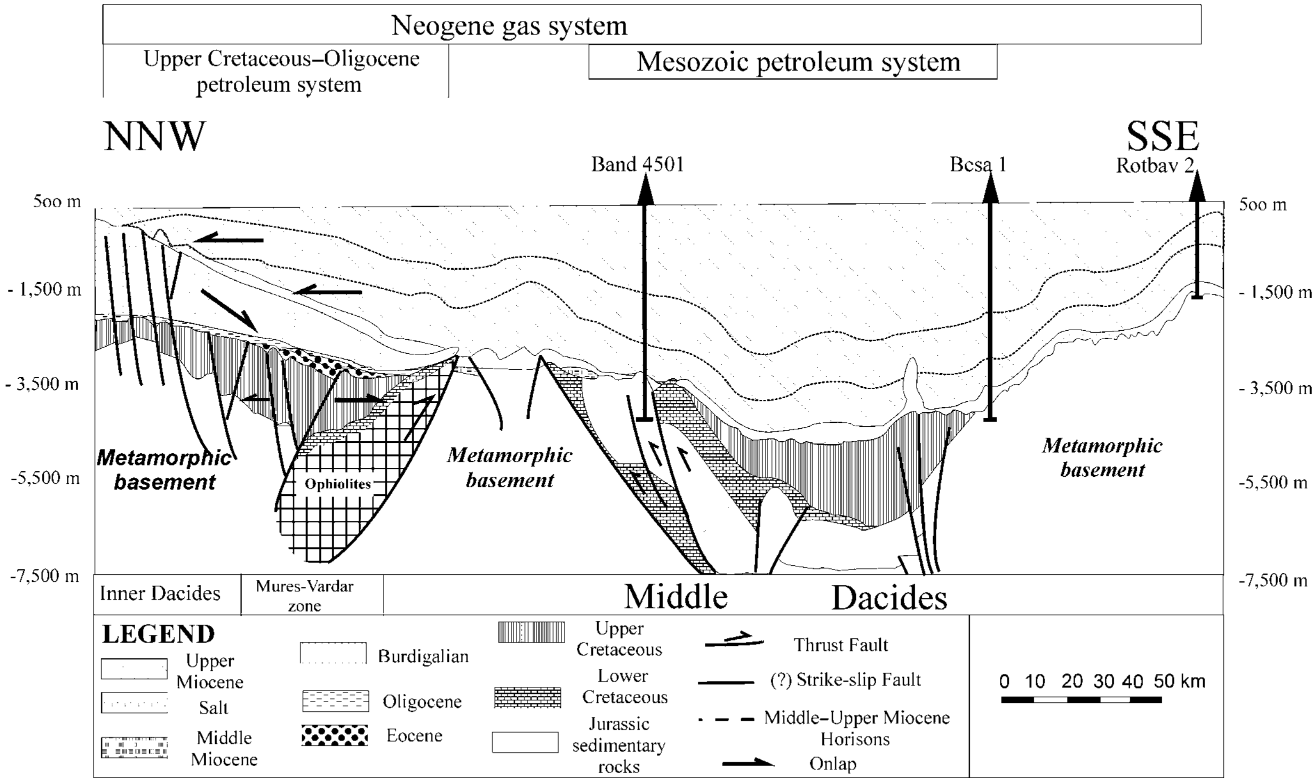


Figure 4. Regional cross section 2 compiling the seismic and well data (see Figures 2, 5 for approximate location). Thrusting took place in the northern part during the Late Cretaceous–Eocene. A Burdigalian clastic wedge is developed in the same part of the basin. The Badenian deposits cover the whole basin. During the middle Badenian, the northern part of the basin was tilted and the middle–upper Miocene deposits onlap the older ones. During the late Miocene, strike-slip movement took place, mainly along inherited faults.

1998). The Badenian sedimentation starts with the Dej Tuff Formation, made of acidic tuff horizons and numerous interbedded conglomerates (Figure 3). The Dej Tuff Formation is overlain by the Salt Formation, which locally forms diapirs (Figure 4) (Mrazec, 1907; Visarion et al., 1976). The Badenian sedimentation ends with sands and marls.

An intra-Badenian tectonically induced unconformity is documented in the northern sector of the basin as elsewhere in the Carpathians (de Broucker et al., 1998). Tilting of the early Badenian deposits and onlaps of the middle–upper Badenian sedimentary deposits onto early Miocene–Paleogene deposits indicate an uplift of the northern sector and/or border of the basin (Figure 4). Tectonic evolution of the northern border of the Transylvanian basin is controlled by the North Transylvanian and Bogdan Voda faults (Figure 2) (Săndulescu, 1984). Blocks of metamorphic basement, as the Preluca Mountains, are uplifted along the North Transylvanian fault (Figure 2). The North Transylvanian and Bogdan Voda faults are seismically active sinistral strike-slip faults (Cornea and Lăzărescu, 1980; Polonic, 1980). The North Transylvanian fault stopped its main movement in the Burdigalian (Săndulescu et al., 1993). It was reactivated as a normal fault having a downfaulting of its northern block during the late Miocene. The Bogdan Voda fault is interpreted to control the mineralized veins, west- and northeast-striking, from this area (e.g., Cornea and Lăzărescu, 1980). The age of movements along the Bogdan Voda fault is constrained by the age of the hydrothermal events; K-Ar dating indicates ages between 9.3 $\pm$ 0.2 and 8.7 $\pm$ 0.2 Ma, and Ar-Ar dating indicates an age of 7.9 $\pm$ 0.2 Ma for the hydrothermal events (Lang et al., 1994).

Since the middle–late Badenian, the basin started to acquire its present shape (Ciupagea et al., 1970; de Broucker et al., 1998; Sanders, 1998). The Sarmatian deposits are made of sands and marls (Figure 3), with the exception of some conglomerates from the eastern part of the basin. Several basic tuff horizons have been found in the Sarmatian deposits (e.g., the Hadareni Tuff). A gap was found between the Sarmatian and the Pannonian deposits similar to the gap in sedimentation found in the same stratigraphical interval in the Carpathians (Ciupagea et al., 1970).

The Badenian and the Sarmatian deposits crop out along northwest-striking lineaments in the northeastern and central sectors, respectively, of the basin (Figure 2).

The Pannonian and Pontian deposits, comprising sands and marls, end the sedimentation in the Transylvanian basin. These deposits onlap onto older sedimentary deposits in the northern border and/or sector of the basin (Ciupagea et al., 1970). Since the Pliocene, the whole basin has been in uplift, because the difference in the elevation of the upper Miocene deposits from the Transylvanian basin and the Pannonian basin is more than 1000 m. The present mean elevation of the Transylvanian basin is around 600 m above sea level (Ciupagea et al., 1970). Currently, geodetic data indicate zero vertical motions of the Transylvanian basin (Popescu and Dragoescu, 1986). The heat-flow of the basin is low, about 60 mW/m^2 in the northern sector of the basin, decreasing to 40 mW/m^2 in its southern sector (Demetrescu and Veliciu, 1991; S. Veliciu, 1998, personal communication). The crust of the Transylvanian basin is thick, about 42–47 km, having a large transition zone between about 27 km and about 42–47 km (Răileanu and Diaconescu, 1998).

PETROLEUM SYSTEMS

Data from 2369 wells, drilled since first discovery in 1909, have been used to define the petroleum systems of the Transylvanian basin (Popescu, 1995; Morariu, 1998). Two main petroleum systems occur in the Transylvanian basin: (1) a Miocene gas system, and (2) a Mesozoic petroleum system. Popescu (1995) indicates a third petroleum system, that is, an Upper Cretaceous–Oligocene system (Figure 3). Petroleum systems by Popescu (1995) will be used in the following (Figures 3, 4).

(1) A Miocene gas system covers an area of about 12,000 km^2. Source rocks are Badenian to upper Miocene in age, having $C_{org} = 0.5\%$ on average and total organic carbon (TOC) $> 1.2\%$. Kerogen is type II and type III (Morariu, 1998). Rock-Eval pyrolysis analyses of 10 well samples between 950 and 2250 m show low source potential and thermal immaturity; TOC $= 0.21–0.85\%$, $S_2 = 0.14–0.48$ mg HC/g, and $T_{max.} = 423–436°C$ (Popescu, 1995). No crude oil has been generated. Time of gas generation is interpreted to be either 7–9 Ma (Morariu, 1998) or 13–5 Ma and to occur at depths ranging from 440 to 8800 m (Cringanu and Deming, 1996). Most of the gas is biogenic and is commonly 98% methane, having negligible amounts of CH_4+, O_2, CO_2, and N_2 (Ciupagea et al., 1970). A mixture of biogenic and thermogenic gas was found in a few places in the central and eastern sectors of the basin. This thermogenic gas is interpreted as being generated in either the Mesozoic sedimentary sequence of the Middle Dacides (Morariu, 1998) or the Miocene gas system, due in part to a higher geothermal gradient induced by the thermal conductivity of salt (Popescu, 1995). Reservoirs are Badenian to upper Miocene sands, sandstones, and marly sands, having up to 22 gas sands on a field (Figure 3). Average physical characteristics of the reservoirs are (1) porosity about 12–30%, (2) saturated thickness 30–150 m, and (3) permeability about 5–100 md (Ciupagea et al., 1970). The traps are structural and stratigraphic (Ciupagea et al., 1970; Ionescu, 1994). Proven gas reserves are 34 tcf but estimated to be about 44 tcf (Popescu, 1995). The gas is exploited from 88 gas fields having 144 pools (Figure 3). The average size of structures is about 10 km^2 (Morariu, 1998).

(2) The Upper Cretaceous–Oligocene oil system has been known since the 19th century, when about 700,000 barrels of oil were recovered from hand dug pits. The oil system covers an area about 5000 km^2 and is superposed on the Inner Dacides (Figure 4). We interpret the Ileanda Formation to be the main source rock, although the Upper Cretaceous clays could also represent a good candidate (Figure 3). An outcrop sample from the Ileanda beds shows TOC = 1.07%, $T_{max} = 420°C$, hydrogen index = 347 mg HC/g TOC, $S_2 = 3.72$ mg HC/g (Popescu, 1995). Reservoirs are developed in the red beds of the Jibou Formation. Three wells drilled by Romgaz after the Second World War, in the presalt sequence of this area, were abandoned dry (Popescu, 1995). In 1996, Shell Romania Exploration drilled three wells in the same area. No data have been released about the results of these wells. After this drilling program, Shell Romania Exploration abandoned exploration in the Transylvanian basin.

(3) The Mesozoic petroleum system is only speculative. It covers an area of about 2500 km^2 in the Mesozoic rocks of the Middle Dacides (Figure 4). Crude oil shows were found between 4600 and 4800 m in Jurassic carbonate sequences drilled by Wildcat Deleni 6042 (Popescu, 1995). Oil may have been generated from Mesozoic pelitic rocks (Morariu, 1998). No data have been released about the characteristics

of this oil. Exploration of this petroleum system is in progress. Only 90 wells penetrated the Salt Formation, and only 4 of them are deeper then 4000 m.

NEOGENE STRUCTURES WITHIN THE TRANSYLVANIAN BASIN

Salt diapirs and folds represent the main Neogene structures in the basin (Figure 5). Faults offsetting the postsalt sedimentary sequence are poorly reported (e.g., Ciupagea et al., 1970). Mrazec (1907) assumed that the folds and salt diapirs in the Transylvanian basin are related to the ongoing deformation from the Carpathians. He speculated that the lineaments of salt diapirs are controlled by inherited fractures.

Salt diapirs occur along north-northwest–striking lineaments in the northeastern part of the basin (Figure 5). Salt walls and southwest-verging salt diapirs crosscut by vertical faults are interpreted in this sector (Visarion et al., 1976). Faults crosscutting the salt are probably old faults reactivated during an east-northeast–directed latest Miocene–Pliocene compression (Visarion et al., 1976). Elliptical salt domes having the long axis oriented east-west occur in the central part of the basin (Figure 5). Salt diapirs on north-northeast–oriented lineaments are developed in the central-southeastern part of the basin (Figure 5).

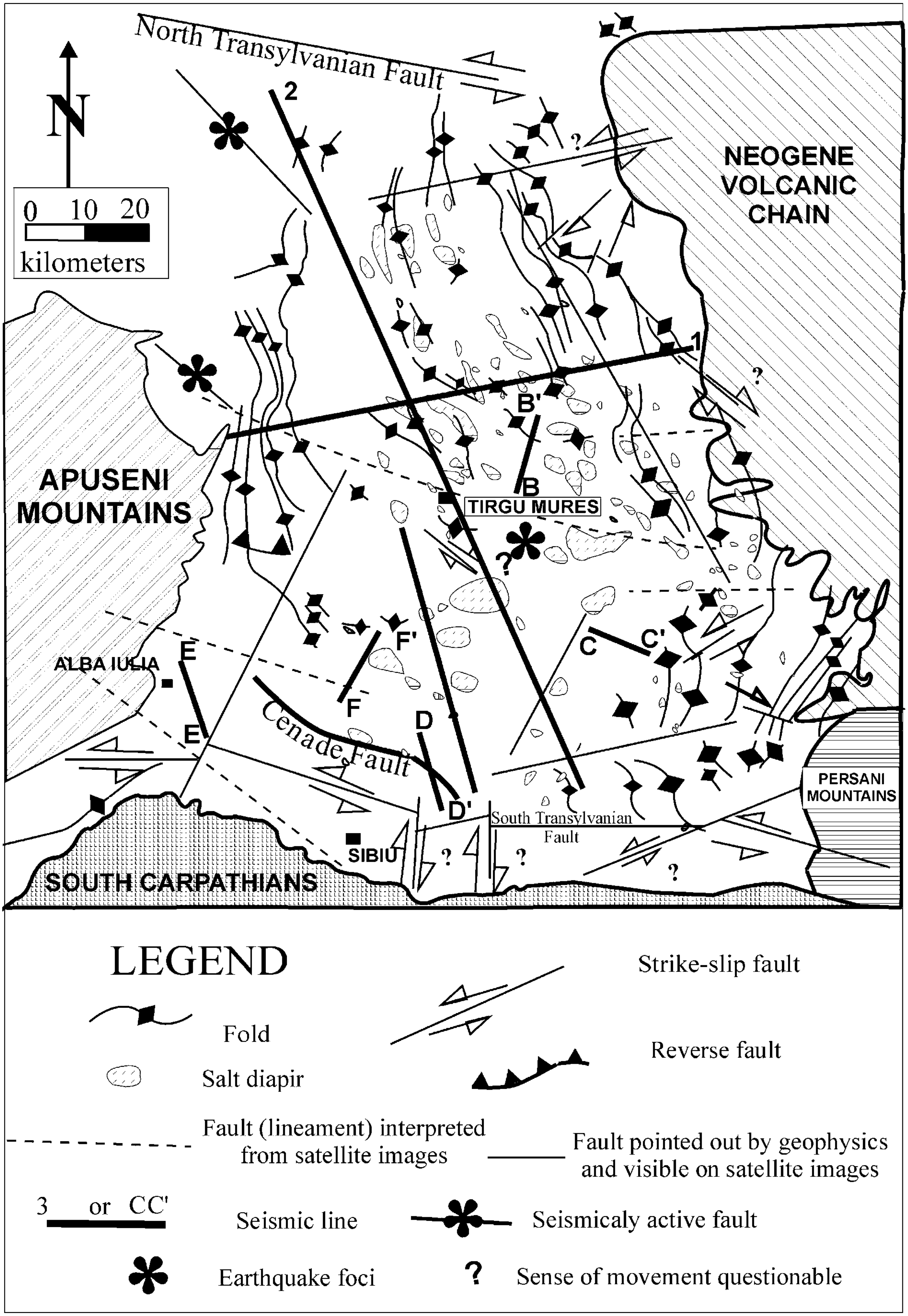
Fold axes from the northern and central sectors of the basin have a north-northwest direction, whereas the fold axes from the southeastern sector have a northeast direction (Figure 5). The folds from the southern part of the basin are en echelon and are developed between east-northeast–oriented faults. Conjugate dextral north northeast to northeast–striking and sinistral northeast-striking strike-slip faults, offsetting the fold axes, are mapped in the northeastern part of the basin (Figure 5).

Several crustal faults have been interpreted to influence the Tertiary tectonic evolution of the Transylvanian basin (e.g., Ciupagea et al., 1970). The west-striking South Transylvanian fault is interpreted as a normal fault having a downfaulting of its northern block since the Pliocene (Figure 5) (Săndulescu, 1988). The South Transylvanian fault is used in all the models of the Tertiary tectonic evolution of the Carpathian region (e.g., Csóntós, 1995). A right-lateral movement is supposed along it, although the left-lateral movement is the only one proven (Dumitrescu and Săndulescu, 1970). A dextral west-northwest–trending crustal fault and a sinistral east-northeast–trending crustal fault offset the South Transylvanian fault (Figure 5). A curve southwest-verging Pliocene fault, the Cenade fault, is mapped in the southwestern part of the basin (Ciupagea et al., 1970) (Figure 5).

Two northwest-trending seismically active faults are known in the northwestern part of the Transylvanian basin (e.g., Cornea and Lăzărescu, 1980). Several zones of discontinuities are also highlighted by the seismic activity from the Transylvanian basin area. Earthquakes having magnitude up to 3.3 and focal depths up to 10 km are recorded beneath the Transylvanian basin (Cornea and Lăzărescu, 1980). The earthquake foci are located in the Tirgu Mures area (Figure 5). The strongest earthquakes have been recorded along northwest-trending structures; lesser intensity was recorded along northeast-trending features.

Several other Neogene structures can be recognized in the seismic lines published before this article: (1) a late Sarmatian, northeast-trending, negative flower structure (Harding, 1990) is imaged in the middle of the basin (Ionescu, 1994); (2) Pliocene west-northwest–trending strike-slip faults having a reverse component are imaged in the eastern part of the Transylvanian basin, and these faults also crosscut the Neogene volcanic rocks (Bucur and Zirnovan, 1980); (3) west-striking faults, without a clear sense of movement but crosscutting the middle–uppermost Miocene deposits of the Transylvanian basin and its border, are evidenced by gravity measurements in the southeastern part of the basin (Proca and Lungu, 1970); and (4) north-northeast–striking transpressional strike-slip faults are localized at the boundary of the Eocene and the metamorphic basement in the western sector of the basin (de Broucker at al., 1998). However, the grid density of the seismic lines is not sufficient to precisely determine the motion and offset of these strike-slip faults.

Previous structural works undertaken at the borders of the Transylvanian basin indicate (1) late Miocene to Pliocene northeast-southwest–oriented shortening along meter- to decameter-scale fault-propagation folds in the southwestern corner of the basin (Ciulavu et al., 1998). This shortening was accommodated by north-northeast–striking dextral tear faults. Small-scale, west-northwest–striking normal faults, offsetting the older structures, have been interpreted as the result of the gravitational gliding during the South Carpathians uplift. The youngest structures found in this area are small-scale conjugate northwest-trending sinistral and east-northeast–trending dextral strike-slip faults; (2) early Miocene northeast-oriented


North Transylvanian Fault
NEOGENE
VOLCANIC
CHAIN
0 10 20
kilometers
APUSENI
MOUNTAINS
TIRGU MURES
ALBA IULIA
Cenade Fault
SIBIU
South Transylvanian
Fault
SOUTH CARPATHIANS
PERSANI
MOUNTAINS
LEGEND
Fold
Salt diapir
Strike-slip fault
Reverse fault
Fault (lineament) interpreted
from satellite images
Fault pointed out by geophysics
and visible on satellite images
3 or CC'
Seismic line
Seismicaly active fault
Earthquake foci
Sense of movement questionable

contraction in the northern sector of the basin (Huismans et al., 1997); (3) late Miocene west-east–oriented tension and Pliocene east-west–oriented contraction in the northern and southeastern margins of the basin (Huismans et al., 1997); (4) Miocene north-south–oriented contraction and subsequent northeast–oriented tension at the border between the Apuseni Mountains and the Transylvanian basin (Huismans et al., 1997); (5) late Miocene strike-slip deformation along conjugate northwest-trending dextral and northeast-trending sinistral strike-slip faults having a north-south to north-northeast direction of maximum principal stress in the southern part of the Apuseni Mountains (Ciulavu et al., 1998).

Indication of the tectonic regime has been also highlighted by the study of the Pliocene–Pleistocene basalts from the southeastern part of the basin and the southern end of the Apuseni Mountains. East-west directed transtension was assumed in both cases (e.g., Seghedi et al., 1998).

SUBSURFACE DATA

For this study, we selected only seismic lines perpendicular to known or supposed Neogene structures to obtain a better structural image (Figures 2, 5). We undertook the interpretation of the seismic lines mainly for the Neogene structures. Older structures have been also highlighted, where possible. The most prominent seismic horizons in the middle–uppermost Miocene deposits are the Hadareni and Dej tuffs, as well as the Salt Formation.

Differences in structural style between the western and eastern sectors of the basin are visible in the regional seismic line 1 (Figure 6). Thrust faults, east-northeast–dipping and having salt acting as a decollement level, and a salt wall have been identified in the eastern part of the line. The thrust faults are Pliocene in age, because they affect the upper Miocene sedimentary deposits. The Neogene deformation is localized in the eastern sector of the basin. This seismic line is shot across the northwest-striking Badenian outcrops from the northeastern sector of the basin (see also Figure 2).

A reverse fault is imaged in the seismic line BB′, shot perpendicular to the northwest-striking Pliocene structures (Figure 7). This fault continuously offsets the Upper Cretaceous to upper Miocene deposits. Therefore, fault movement occurred during the Pliocene.

A Pliocene northwest-dipping reverse fault is observed in the southeastern part of the line CC′ (Figure 8). Upward diverging splays are developed in the upper Miocene deposits. A near vertical fault having reverse offset is imaged in the northwestern part of the line. The age of these faults is Badenian, because the Hadareni Tuff is not affected by them.

A negative flower structure (Harding, 1990) and three vertical faults display normal and reverse offsets, respectively, in the seismic line EE′ (Figure 9). They account for changes in dipping attitude of the upper Miocene soft sediments. We interpret the three vertical faults as strike-slip faults. Both negative flower structure and vertical faults are coeval, that is, Pliocene, as they affect the upper Miocene deposits.

Control of Pliocene structures by inherited discontinuities is visible in the central sector of line FF′ (Figure 10). The salt diapir and the thrust fault are located above a high-angle inherited fault. The salt acted as the decollement horizon. Other near-vertical faults having a reverse component occur also in the southwestern part of the line. The age of the faults is Pliocene, because they offset the upper Miocene deposits. The seismic line FF′ is perpendicular and located north of the Cenade fault. Therefore, a northwest trend and a northeast dip are assumed for the faults.

A typical Pliocene structure is visible in the seismic line DD′ shot above and oblique to the Cenade fault (Figure 11). In this area, this fault was previously interpreted as a single fault, which crosscut the metamorphic basement to upper Miocene deposits as well (e.g., Răileanu et al., 1968b). From gravity-magnetic data, the Cenade fault clearly relates to a fault crosscutting the basement, but this fault does not crosscut the upper Miocene deposits. The uplifted basement block forced the overlying Miocene deposits to ramp upward during thrusting. A clear direction of

Figure 5. Pattern of the folds, salt diapirs, and main faults within the Transylvanian basin, compiled after Ciupagea et al. (1970), the Cosmo-tectonic map of the Eastern and Central Europe (1970), Dumitrescu and Săndulescu (1970), Visarion et al. (1976), and Paraschiv (1979). Seismic lines are also drawn (see also Figure 2).

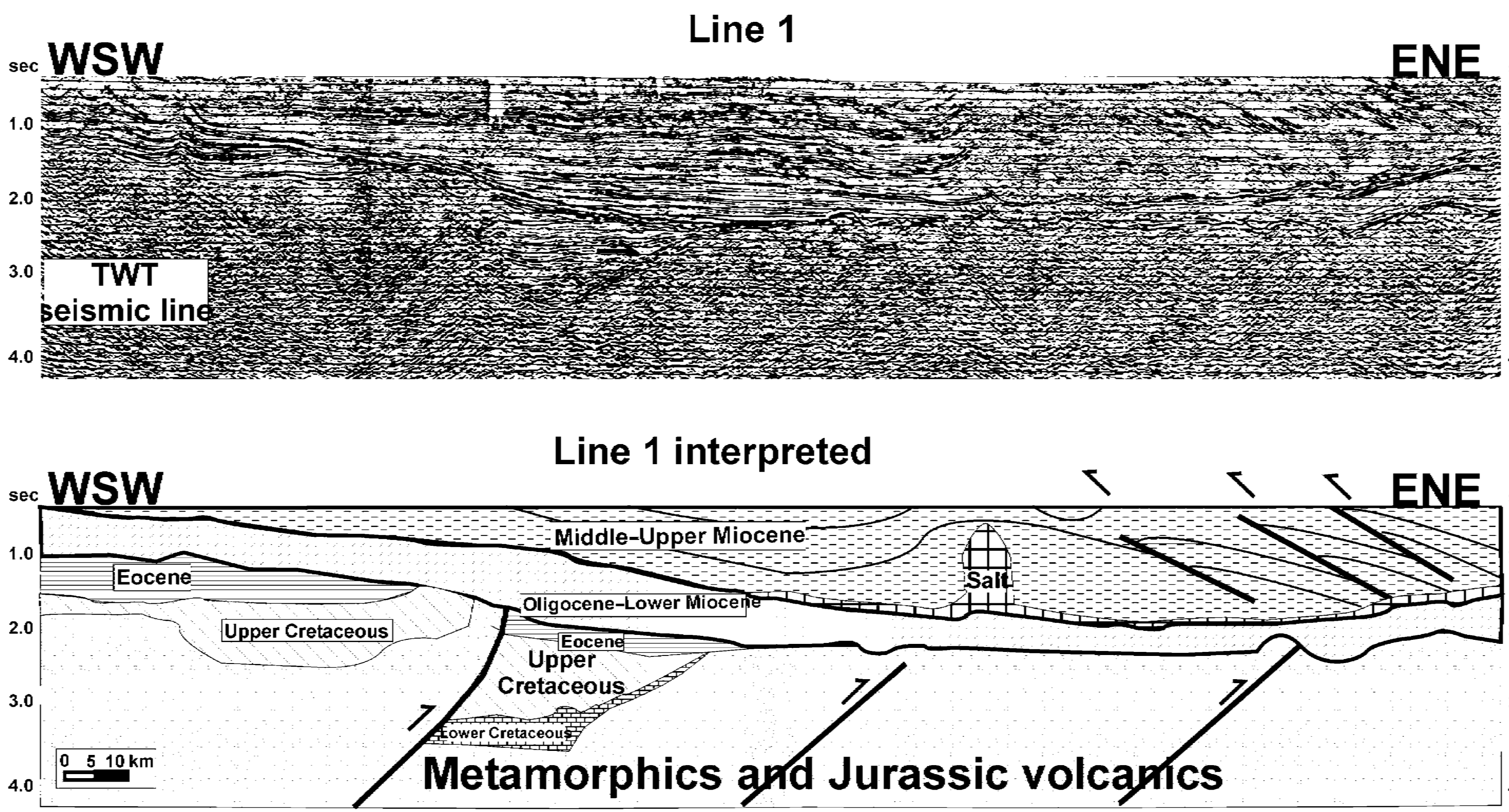


Figure 6. Seismic line 1 (see Figures 2, 5 for location). Several thrust faults have been interpreted in the basement of the Transylvanian basin. The thrust faults from the western sector have been reactivated during the late Eocene. The Oligocene–lower Miocene deposits seal older structures. A salt wall is interpreted as the result of basin floor tilting. West-southwest–vergence thrusts are interpreted in the middle–uppermost Miocene deposits.

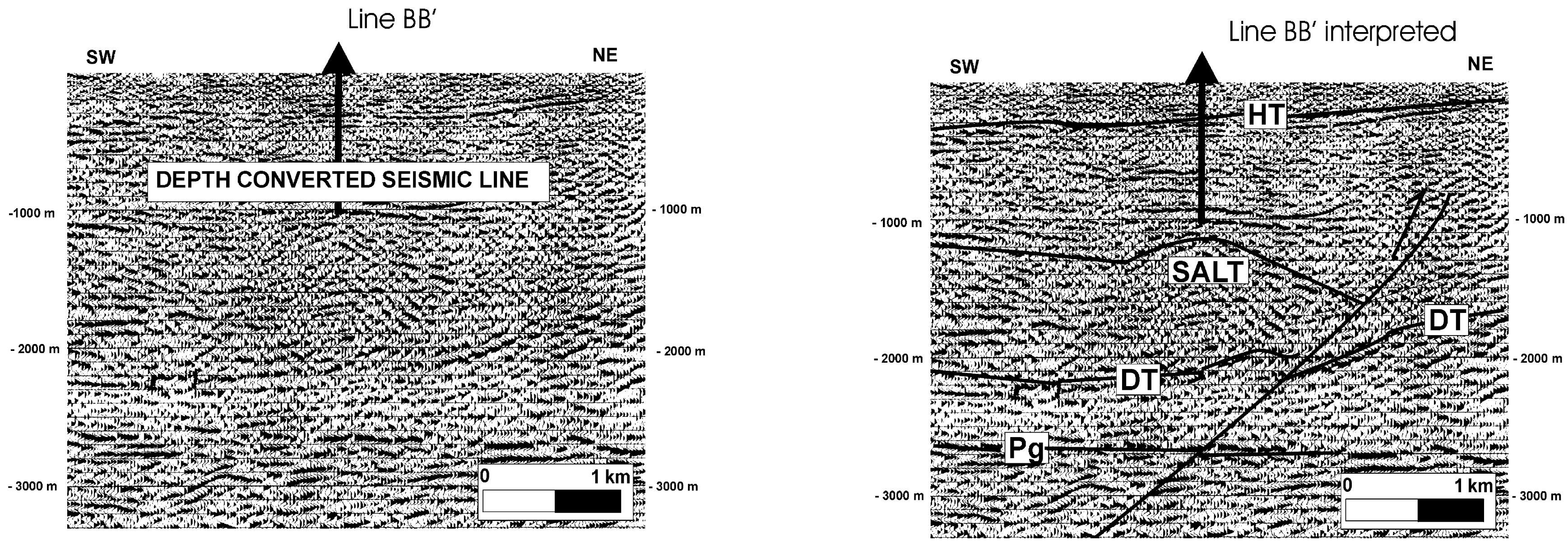


Figure 7. Seismic line BB′ (see Figures 2 and 5 for location). A northeast-verging reverse fault is interpreted. A salt diapir is interpreted in the hanging wall of the reverse fault. HT = Hadareni Tuff, DT = Dej Tuff, Pg = Paleogene.

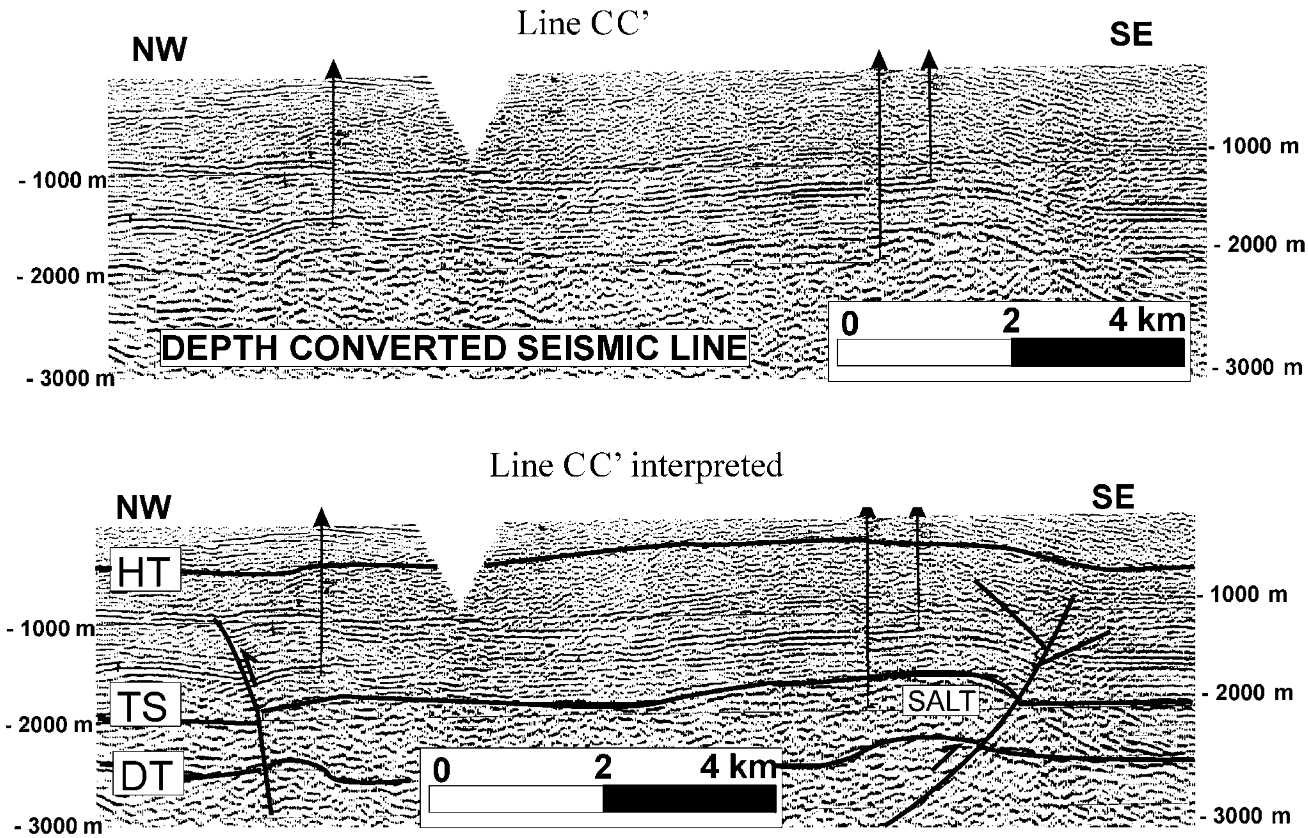


Figure 8. Seismic line CC′ (see Figures 2, 5 for location). A strike-slip fault is interpreted in the northwestern part of the line. A reverse fault is interpreted in the southeastern part of the line. Upward diverging splays are developed in the deposits above the Salt Formation. HT = Hadareni Tuff, DT = Dej Tuff, TS = Top Salt Formation.

movement is difficult to establish because the seismic line is oblique to the fault.

SURFACE DATA

Structural work has been undertaken to better constrain (1) the orientation and sense of movement of the regional-scale structures observed in seismic lines, as well as of the main structures from the basin borders; and (2) the paleostress field responsible for these structures. The locations of the outcrops are referred to in the following as T.

Data and Method Used

Structural data consist of (1) kinematic indicators associated with small-scale structures, (2) secondary structures related to the faults of regional importance, and (3) fault populations having a clear sense of movement for which inversion of fault slip data has been undertaken. For fault slip data inversion, which gives the stress direction, we used the methods summarized by Angelier (1994). Data have been processed using the computer software TENSOR by Delvaux (1993). The deviation angle between the measured sense of movement and the calculated sense of movement was chosen lower than 200. The ratio $R = (S_{hmed} - S_{hmin})/(S_{hmax} - S_{hmin})$ was used to highlight the tectonic regime because $R = 0$ implies a pure compression and $R = 1$ implies a pure tension. The terms S_{hmax}, S_{hmed}, and S_{hmin} represent the maximum, medium, and minimum principal stresses, respectively. Two fault generations, indicating two different tectonic regimes, have been found in a few outcrops. The software TENSOR also has been used for individual faults having a metric offset, to obtain a complete view of the paleostress field.

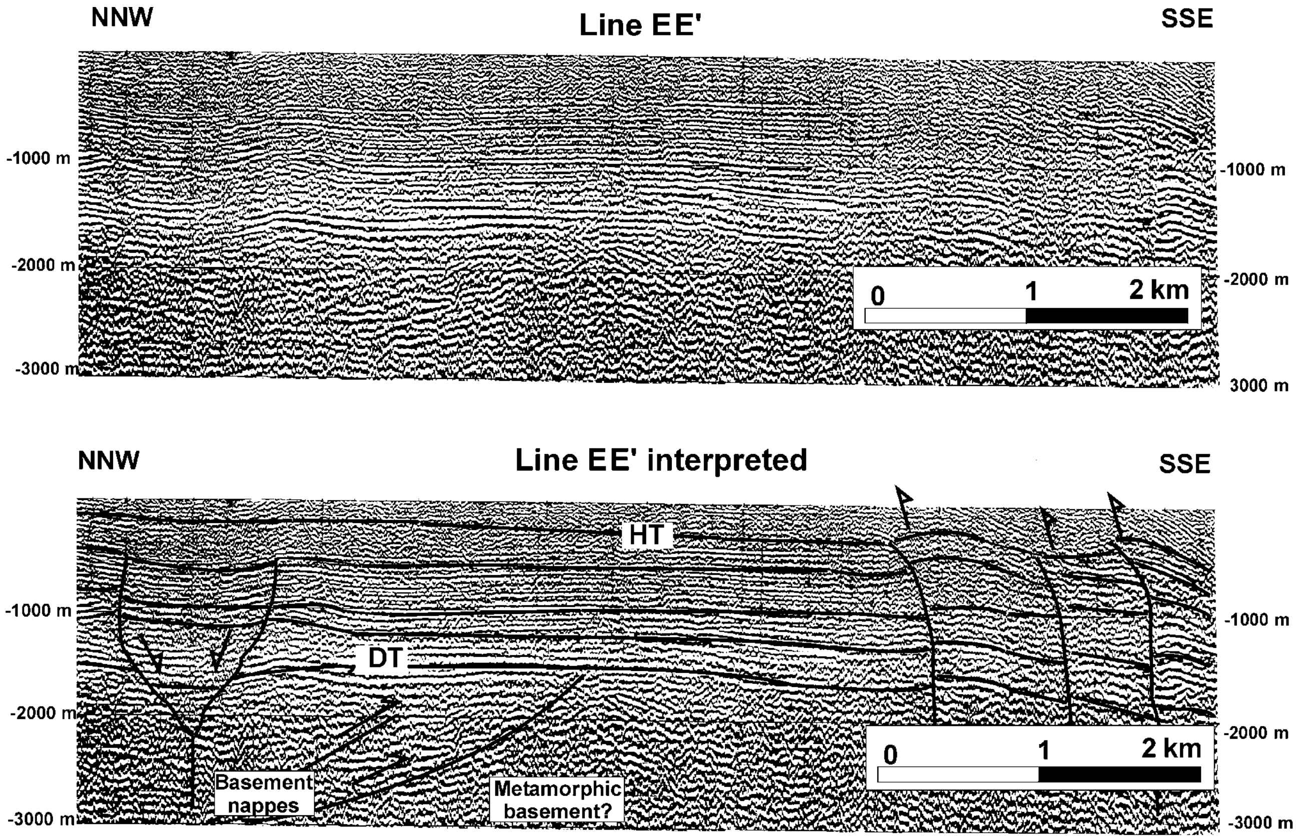


Figure 9. Seismic line EE′ (see Figures 2, 5 for location). Upward diverging splays having normal separation are interpreted in the north-northwestern part of the line. Three vertical, strike-slip faults having reverse components changing the dip angle and amplitude of offset are interpreted in the south-southeastern part of the line. HT = Hadareni Tuff, DT = Dej Tuff.

Data from the Basin

We have focused the structural work mainly in areas where a good seismic control does exist, that is, along the Cenade fault (Figures 2, 5) and in the northeastern part of the basin where we have interpreted Pliocene thrust faults in line 1 (see Figure 6). We have also acquired structural data in the southeastern part of the basin, west of the Persani Mountains.

The Cenade Fault

As previously pointed out, the Pliocene fault exposed in this area does not represent the continuation of the high-angle basement fault. However, this Pliocene fault can be followed in the field along the entire length of the basement fault, that is, for about 30 km. The Sarmatian deposits crop out in its northern block and are thrusted over the Pannonian strata. Structural observation along the central and eastern sectors of the fault indicates the occurrence of decameter, southwest-verging, fault-propagation folds in Sarmatian deposits (Figure 12). The slickensides and the fold axes indicate a southwestward (north 240°) transport direction. Meter-scale reverse structures are also recorded in the Pannonian sediments. The slickensides from the fault planes indicate northeastward and southwestward (north 36° and north 207°) transport direction.

Northeastern and Southeastern Parts of the Basin

Northwest-striking folds, involving Badenian to Pannonian sedimentary rocks, have been observed in the northeastern part of the basin. Flexural slip indicates northeast-southwest–directed shortening.

Normal faults, north to north-northeast–striking, are present in the southeastern corner of the basin. Offsets on these faults range between 2 and 10 m. The onset of normal faulting is late Pannonian in age.

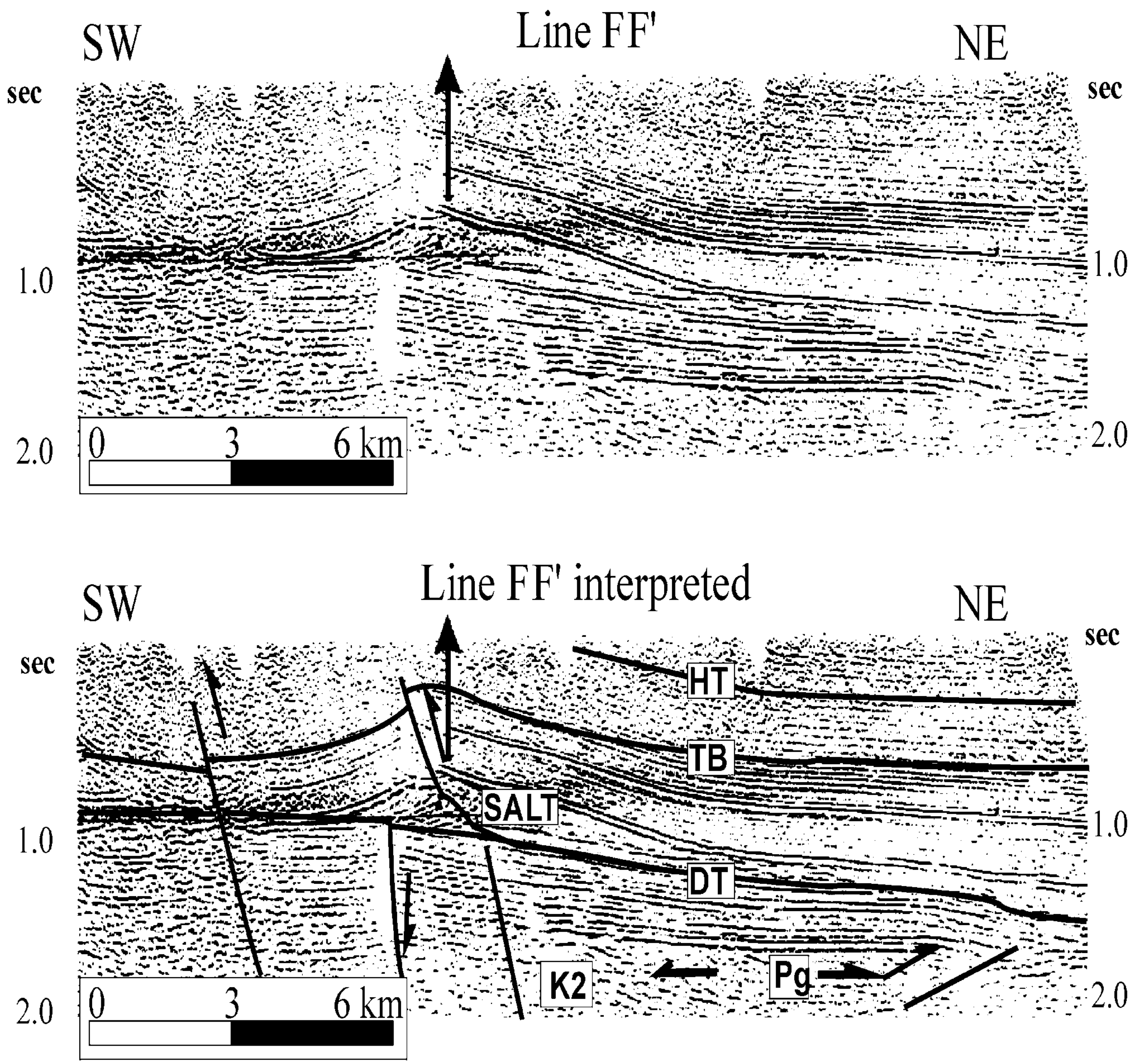


Figure 10. Seismic line FF′ (see Figures 2, 5 for location). A thrust fault controlling the salt diapir is interpreted in the central part of the line. The fault and the salt diapir are located above an almost vertical fault from the basement. One low angle reverse fault is interpreted in deep levels of the northeastern part of the line. The Dej Tuff is folded above the fault tip. A high-angle reverse fault and a high-angle normal fault are interpreted in the southeastern part of the line. HT = Hadareni Tuff, DT = Dej Tuff, TB = seismic marker in the Badenian deposits, Pg = Paleogene, K2 = Upper Cretaceous.

Basin Borders

Northern Border

Upper Cretaceous to lower Miocene sedimentary deposits from this area are folded and involved in thrusting (Figure 13). Younger sedimentary deposits are also folded. Even related to successive deformations, the folds involving Cretaceous to Pannonian sedimentary deposits are west-northwest–striking. The thrust faults are offset by a system of west-striking strike-slip faults, from which the Bogdan Voda and North Transylvanian faults are the most important (Figure 13) (e.g., Săndulescu, 1984). These faults are crosscut by conjugate northeast-striking sinistral and north to northwest–

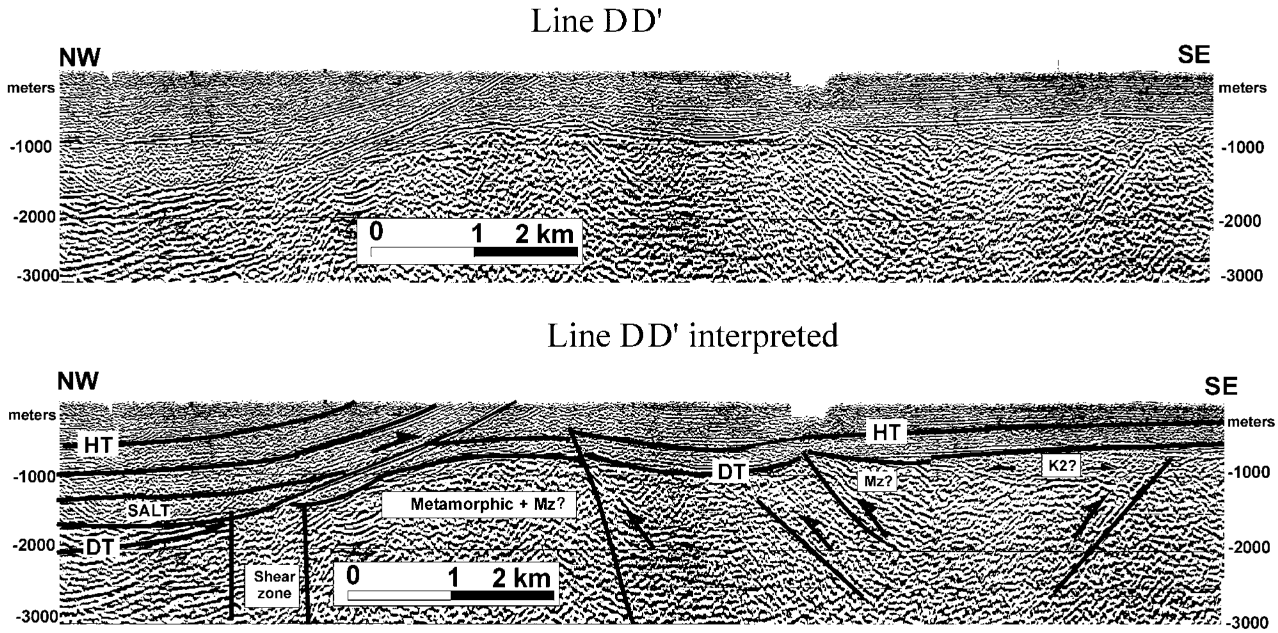


Figure 11. Seismic line DD′ (see Figures 2, 5 for location). A vertical shear zone represents the boundary between an uplifted block and a subsided block of the basement. The uplifted block from the central and southeastern parts of the line represents a ramp for the upper Miocene deposits involved in thrusting. The salt represents the decollement horizon. Four reverse faults, crosscutting the basement, are interpreted in the central part of the line. HT = Hadareni Tuff, DT = Dej Tuff, Mz? = possible Mesozoic deposits, K2? = possible Upper Cretaceous deposits.

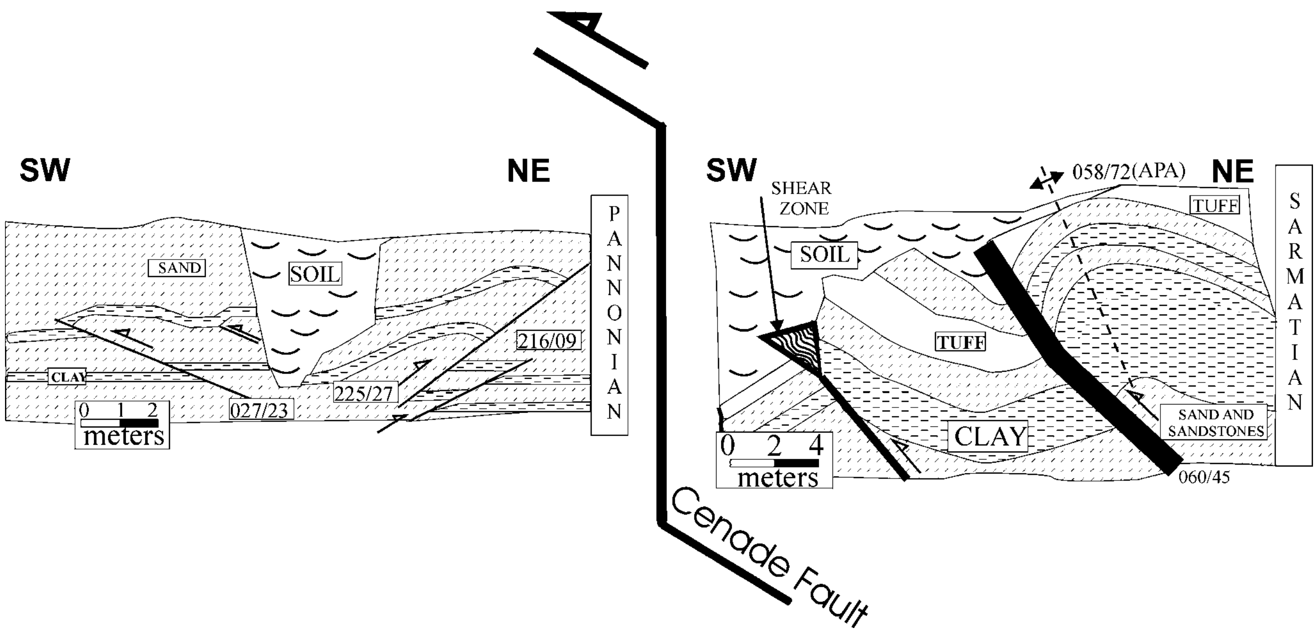
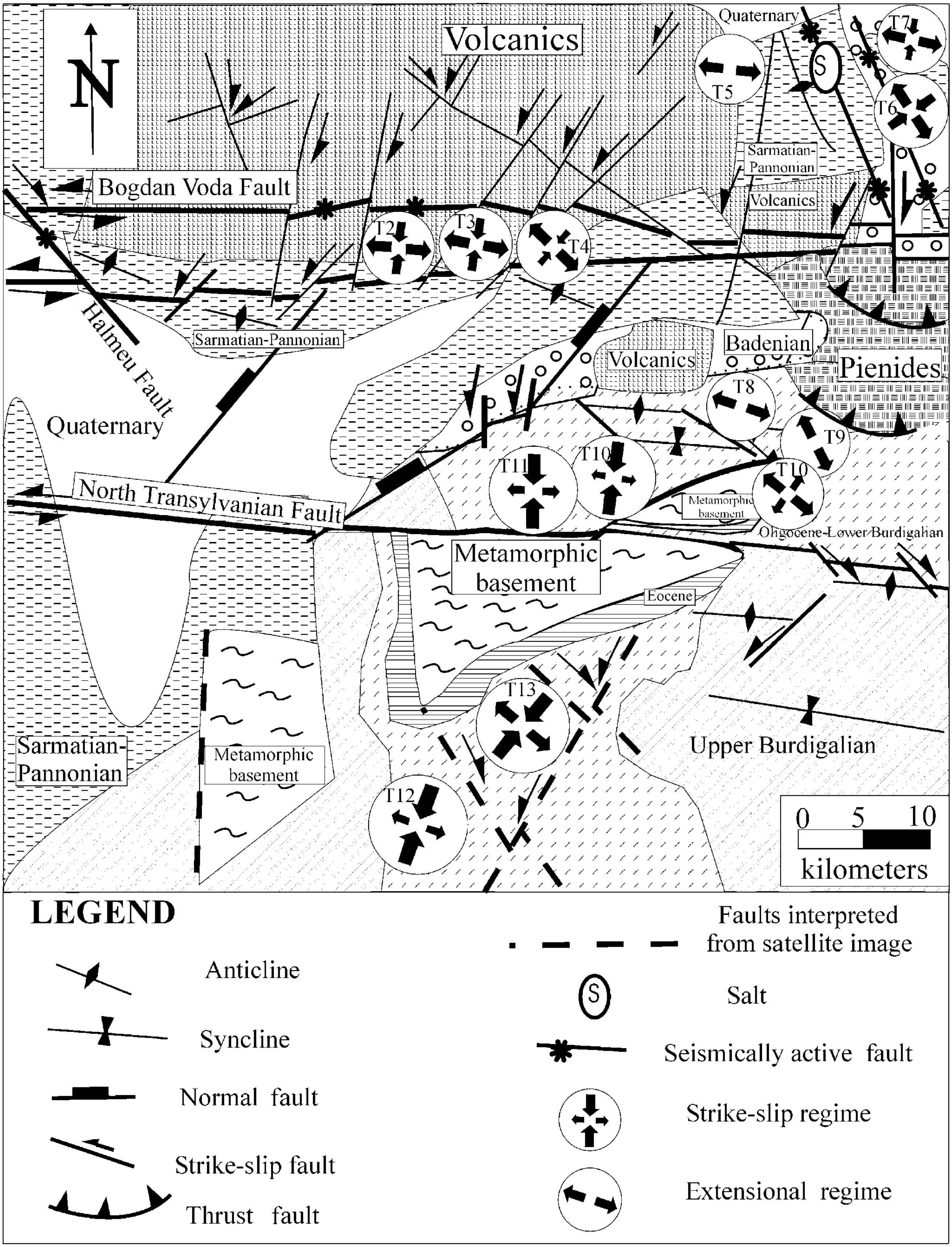


Figure 12. Structures found near the Cenade fault (see Figures 2, 5 for location). Fault-propagation folds and west-northwest–trending reverse faults have been found. Shear zones related to thrusting are developed. The figures represent fault planes (dip direction). The Sarmatian deposits are thrusted over the Pannonian deposits. APA = axial plane of the anticline.



Volcanics
Quaternary
S
T5
T7
T6
Sarmatian-
Pannonian
Volcanics
Bogdan Voda Fault
T2
T3
T4
Halmeu Fault
Sarmatian-Pannonian
Badenian
Volcanics
Pienides
Quaternary
T8
T9
T11
T10
T10
North Transylvanian Fault
Metamorphic basement
Oligocene-Lower Burdigalian
Metamorphic
basement
Eocene
T13
Upper Burdigalian
Sarmatian-
Pannonian
Metamorphic
basement
T12
0 5 10
kilometers
LEGEND
Anticline
Syncline
Normal fault
Strike-slip fault
Thrust fault
Faults interpreted
from satellite image
Salt
Seismically active fault
Strike-slip regime
Extensional regime

striking dextral strike-slip faults (e.g., Săndulescu and Russo-Săndulescu, 1981; Ioane, 1998). A Neogene graben is developed between the Bogdan Voda fault and the North Transylvanian fault (Săndulescu et al., 1993). A system of latest Miocene north to northeast–trending normal faults having(?) left-lateral slip develops in this graben and seems to control its sedimentation, because the depocenter migrated westward (e.g., Săndulescu et al., 1993).

We interpret the youngest faults in this area to be the northwest-trending dextral strike-slip faults having a reverse component, such as the seismically active Halmeu fault (Figure 13). Well data indicate an uplift of the Halmeu fault northern block, having metamorphic rocks at only 675 m depth (e.g., Săndulescu et al., 1993).

We have acquired structural data on rocks of Pannonian to Precambrian(?) age. Most of the measured faults are meter-scale conjugate east-northeast–trending sinistral and northwest-trending dextral strike-slip faults. A few of them are meter-scale northeast-trending normal faults having oblique movement. The normal faults are crosscut by the strike-slip faults. This relationship is very clear in the metamorphic basement (T 10 in Figure 13). Structural data indicate (1) mostly strike-slip regime having north to northeast–orienteddirection of maximum principal stress, and (2) west-northwest–oriented tension (S_{hmin}).

Eastern Border

Neogene volcanic activity from this area took place along a north-northwest–oriented fault system (Figure 14). The southern fault from this system is seismically active (e.g., Cornea and Lăzărescu, 1980; Incorporated Research Institute for Seismology – Washington). Neogene volcanic activity is younger southward and seems to be left-lateral shifted by west-striking faults (e.g., Cornea and Lăzărescu, 1980). These faults were pointed out by gravimetry, and one of them is also seismically active (e.g., Cornea and Lăzărescu, 1980). The west-striking faults represent the northern and southern boundary of two Pliocene–Pleistocene basins (Figure 14). Sedimentation in these basins is interpreted to be controlled by north-striking normal faults (Stefănescu, 1986). The folds involving Paleogene to Pannonian deposits have a west-northwest direction (Figure 14).

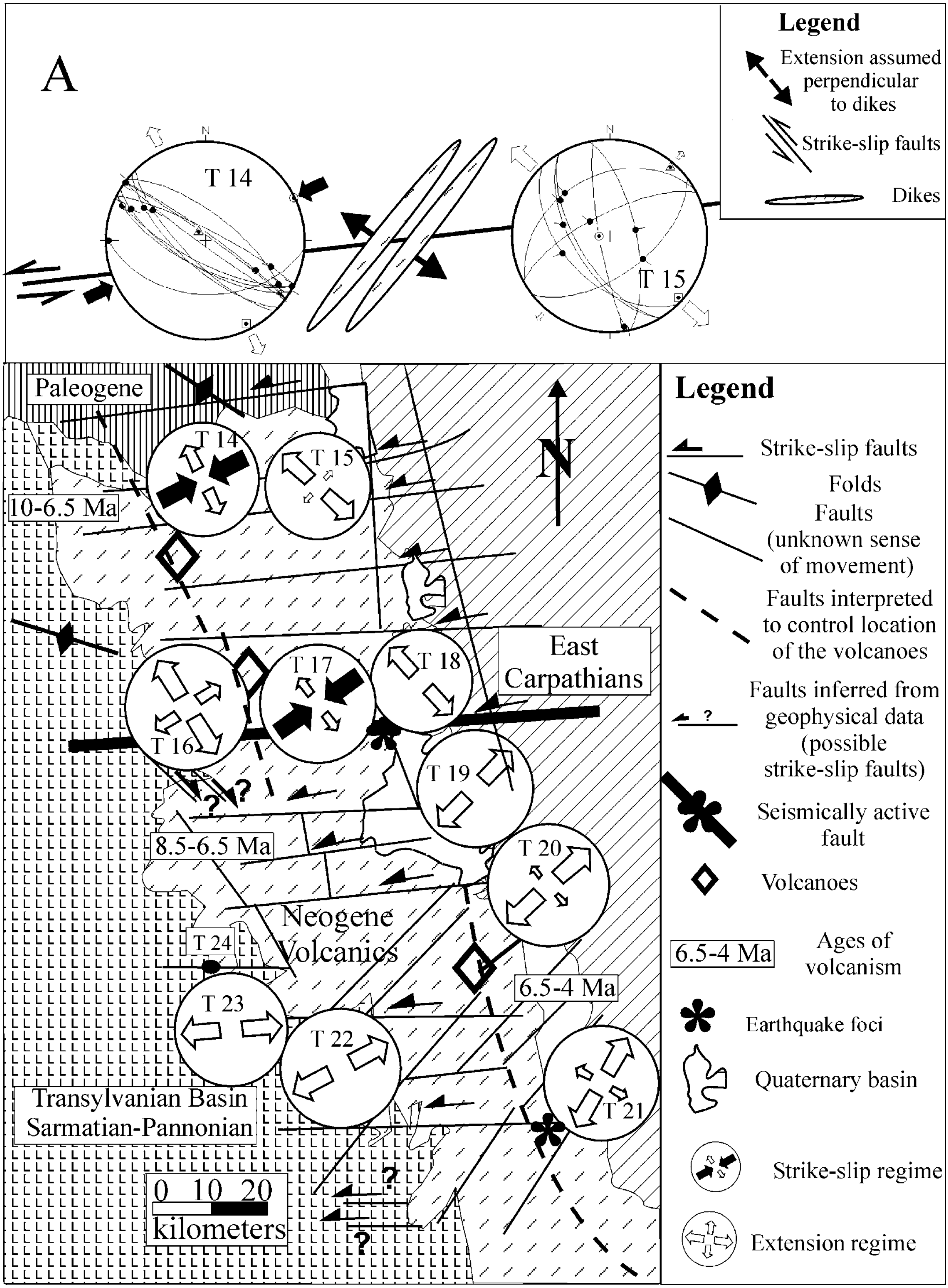
Structural data acquired in andesites that are 9 m.y. old (Pecskay et al., 1995) along and north of the west-striking seismically active fault indicate (1) a strike-slip regime having an east-northeast direction of maximum principal stress, and (2) northwest oriented tension (minimum principal stress). A typical outcrop is represented by northeast-striking dikes intruded in the andesites (Figure 14). The attitude of dikes indicate northwest-southeast–oriented tension (inset A in Figure 14). Fault slip data on meter-scale normal faults indicate the same northwest-southeast–oriented tension (inset A in Figure 14). These structures are crosscut by northwest-striking dextral strike-slip faults having reverse component.

Only decameter normal faults, in Precambrian(?) to Pliocene rocks, have been found south of the west-striking seismically active fault (Figure 14). Structural data indicate northeast- and northwest-oriented tension (Figure 14). At the boundary between Neogene volcanics and the Transylvanian basin, west-striking faults can be supposed from the presence of springs of free CO_2 aligned on this direction, as found in T 24.

Southeastern Border

Three late Miocene–Quaternary basins are developed in the south-eastern border of the Transylvanian basin (Figure 15). The onset of the subsidence of these basins is late Pannonian (Kusko and Buda, 1985). Deformation has also been active after the Pleistocene, because the Pleistocene deposits are vertically offset by about 500 m (Săndulescu, 1984). These three basins are developed along deeply rooted north-northeast–striking

Figure 13. Geological map of the northern border of the Transylvanian basin (see Figure 2 for location) (simplified after Giușca et al., 1967b; Borcos, 1994). The fault system was drawn using geological-geophysical data (Borcos, 1994; Săndulescu et al., 1993) and satellite data. West-striking faults having left-lateral displacement are crosscut by northeast to east northeast–trending sinistral strike-slip faults and north to northwest–trending dextral strike-slip faults. The uplifted blocks of metamorphic basement have a triangular shape close to the North Transylvanian fault. Northeast-trending normal faults having left-lateral slip are developed between the North Transylvanian and Bogdan Voda faults. The fold axes have a west-northwest trend. The insets represent the result of the inversion of fault slip data.



A
T 14
T 15
N
Legend
Extension assumed perpendicular to dikes
Strike-slip faults
Dikes
Paleogene
10-6.5 Ma
8.5-6.5 Ma
6.5-4 Ma
T 14
T 15
T 16
T 17
T 18
T 19
T 20
T 21
T 22
T 23
T 24
East Carpathians
Neogene Volcanics
Transylvanian Basin Sarmatian-Pannonian
0 10 20
kilometers
N
Legend
Strike-slip faults
Folds
Faults (unknown sense of movement)
Faults interpreted to control location of the volcanoes
Faults inferred from geophysical data (possible strike-slip faults)
Seismically active fault
Volcanoes
6.5-4 Ma
Ages of volcanism
Earthquake foci
Quaternary basin
Strike-slip regime
Extension regime

Figure 14. Geological sketch map of the eastern border of the Transylvanian basin, simplified after Seghedi et al. (1994) (see Figure 2 for location). The fold axes have a west-northwest trend. The insets represent the result of the inversion of fault slip data. Inset A represents data from an area where dikes and normal faults are offset by dextral strike-slip faults having reverse slip. Fault slip data are plotted on a lower hemisphere diagram.

normal faults. Few earthquake foci and springs of free CO_2 are known to occur along these faults (Atanasiu, 1961; Kusko and Buda, 1985). Alkaline Quaternary basalts west of the Persani Mountains seal a normal fault having an offset about of 1500 m and the same attitude as in the three basins (Popescu et al., 1976). West-striking sinistral strike-slip faults crosscut the normal faults and the East Carpathians structures as well.

The same structural relationship has been found in a coal quarry (T 30 in Figure 15), where steeply dipping, north-trending normal faults, more than 50 m in length, were mapped in Pliocene deposits. The total offset of the Pliocene deposits deduced from wells is

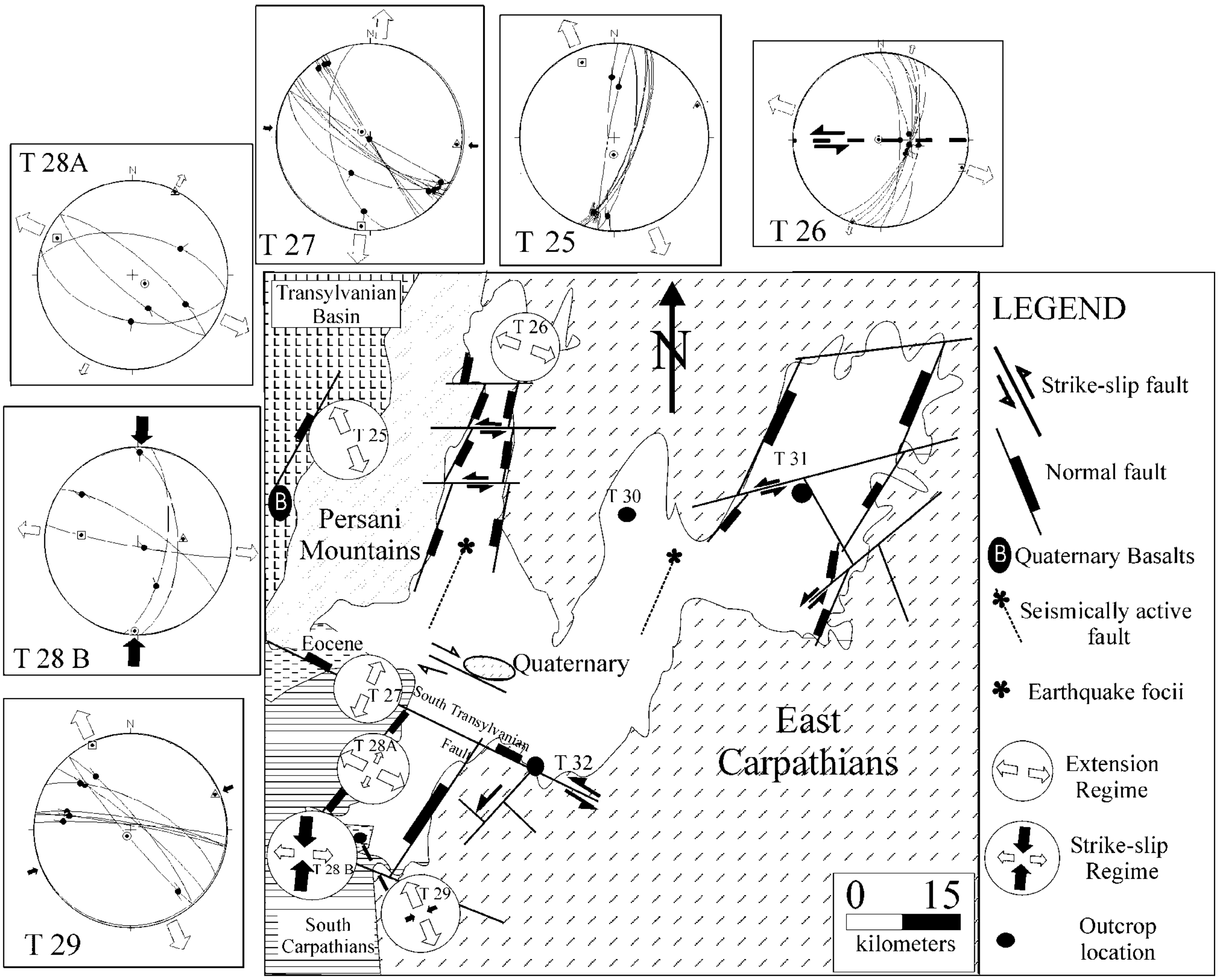


Figure 15. Geological sketch map of the southeastern border of the Transylvanian basin, simplified after Patrulius et al. (1968) (see Figure 2 for location). The faults are compiled from Kusko and Buda (1985) and personal field observation. Uplifted blocks of Lower Cretaceous crop out along sinistral and dextral strike-slip faults inside the basin. The insets around the map represent fault slip data (lower hemisphere diagram), and the insets inside the map represent the result of the inversion of fault slip data.

about 10 m in this outcrop (I. Bordecs, 1996, personal communication). The normal faults are crosscut by west-east–trending sinistral strike-slip faults having a measurable length of about 60 m and an offset of about 20 m.

The same structural pattern has been found in locations T 29 to T 31 (Figure 15). Strike-slip faults or normal faults having oblique slip have been found in the other locations.

Structural data indicate (1) west and north-northwest–oriented tension, and (2) strike-slip regime having north-south–oriented maximum principal stress.

DISCUSSIONS AND CONCLUSION

Seismic and structural data from the Transylvanian basin indicate a tectonic origin of the Neogene structures of the Transylvanian basin.

A Burdigalian southward thinning clastic wedge is recognized in the northern sector of the basin (de Broucker et al., 1998). We could interpret this sedimentary wedge as a retro-foreland basin, related to the early Miocene nappe emplacement from the Pienides. A north to northeast–oriented compressional stress field is inferred from structural data (Huismans et al., 1997).

No early Badenian structures have been found.

Since the middle–late Badenian, the Transylvanian basin started to acquire its present shape. Thrust and strike-slip faults have been imaged in the basin. De Broucker et al. (1998) pointed out the middle–late Badenian southward tilting of the northern border and/or sector of the basin.

Late Miocene to Pliocene structures in the Transylvanian basin are far more abundant then previously described. These structures are controlled by the basement faults or inherited discontinuities. The late Miocene to Pliocene structures we interpret in the Transylvanian basin are (1) northeast- and southwest-dipping thrust faults, and (2) east-northeast– and west-northwest–striking strike-slip faults having normal or reverse slip (Figure 16). Most of the thrust faults are developed in the Miocene–Pliocene sedimentary sequence (e.g., the Cenade fault), but a few of them crosscut both basement and Neogene sedimentary sequence. Thrust faults are predominantly interpreted in the southwestern sector of the basin (Ciulavu et al., 1998) and in the central and eastern sectors of the basin. Development of the thrust faults, like the Cenade fault, in the Transylvanian basin is similar to the results of analogue modeling of reactivation along a steep fault (Vially et al., 1994). The steep fault usually remains inactive but controls development of the newly formed decollement level. Reactivation of a high-angle, basement-involving fault might control development of the Cenade fault.

The strike-slip faults continuously offset the basement to Miocene sedimentary sequence. Strike-slip movement is predominantly interpreted in the western sector of the basin. Coeval strike-slip faults having reverse and normal slip are probably the result of the curvature of the inherited discontinuities. Strike-slip movement also could be interpreted from the en echelon folds from the south-southeastern part of the Transylvanian basin. These folds are similar to laboratory clay models, which indicate en echelon folds in the sediments above a wrench fault, which crosscuts the basement (e.g., Wilcox et al., 1973). This geometry indicates left-lateral movement in this part of the basin.

Late Pannonian to Pliocene north-northeast–striking normal faults have been found in the southeastern sector of the basin. A Pliocene northwest-dipping thrust fault parallel with them has been interpreted westward.

Structural data indicate a Neogene north to northeast–oriented compressional/transpressional stress field.

Basin Borders

Structural data acquired in the northern border and in the northern part of the eastern border of the basin indicate late Miocene to Pliocene strike-slip deformation having left-lateral movement along west-striking strike-slip faults (Figure 16). The veins, dikes, and the conjugate, roughly northwest- and northeast-striking strike-slip faults are interpreted as secondary structures of the west-striking faults (insets in Figure 16). The west-striking faults crosscut the metamorphic basement to Miocene rocks. The uplifted basement blocks having triangular shape, like the Preluca Mountains, could be interpreted as corks related to strike-slip movements (Zolnai, 1991). The existence of northwest-trending dextral strike-slip faults having reverse slip indicates a transpressional regime. Transpressional regime at the northern border is also sustained by the almost perpendicular direction of maximum principal stress to the west-striking faults. The northwest-trending folds from these regions are oblique to the west-striking sinistral strike-slip faults.

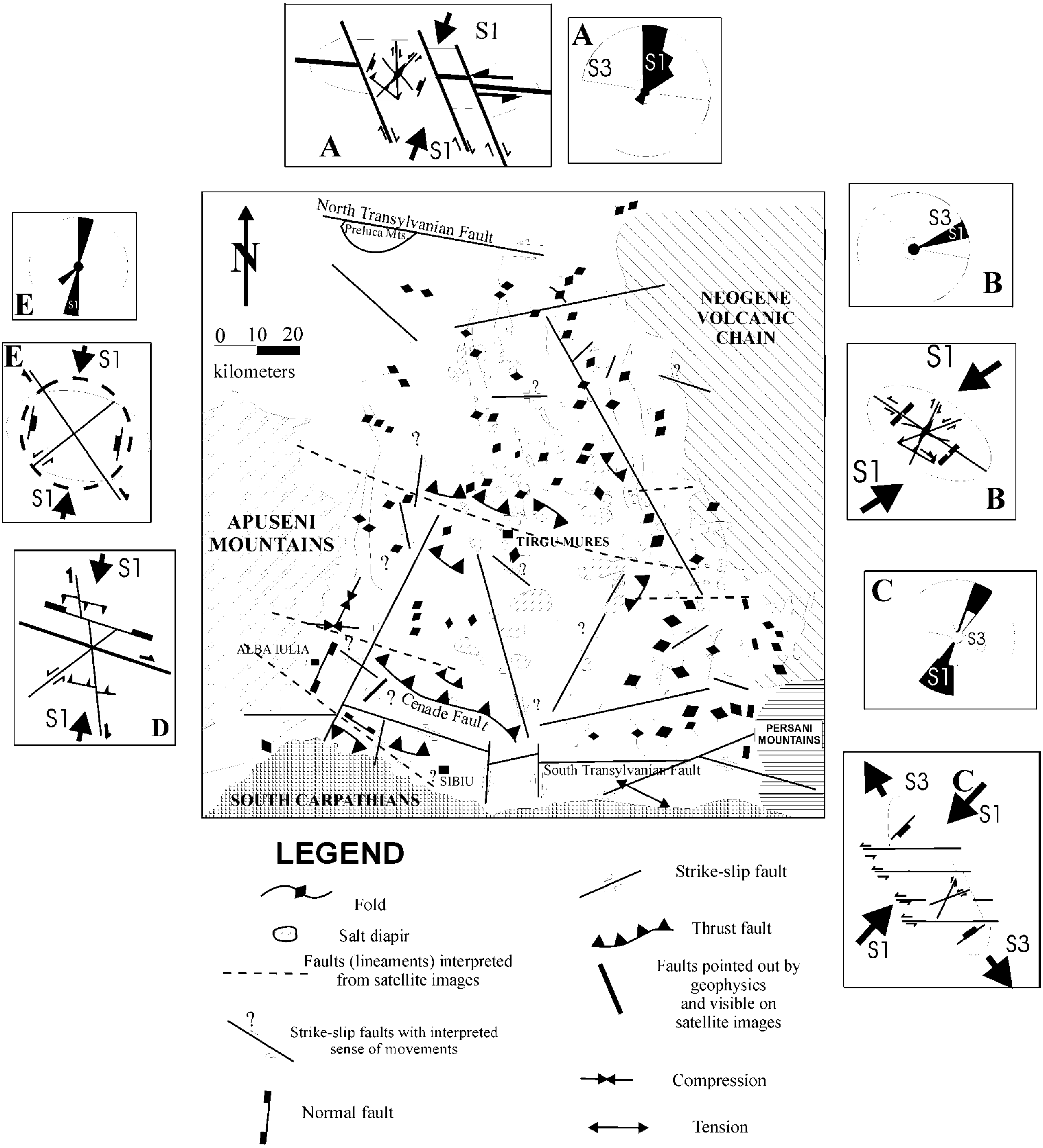


Figure 16. Structural pattern of the Transylvanian basin (see also Figure 5). Surface and subsurface data are also drawn. The insets represent structural pattern and Rose diagram (20° interval) of maximum principal stress (S1) and minimum principal stress (S3) direction for the northern border (A), eastern border (B), southeastern border (C), and southwestern sector (D) of the Transylvanian basin (after Ciulavu et al., 1998) and the southeastern part (E) of the Apuseni Mountains (after Ciulavu et al., 1998).

Therefore, we interpret them as related to strike-slip deformation.

Late Miocene to Pliocene extension has been found in the southern part of the eastern border of the basin (Figure 16). Similar extensional structures were also found in the southeastern sector of the basin. West-striking sinistral strike-slip faults offset the Pliocene extensional structures. Thus, the west-striking faults along the northern, eastern, and southeastern borders of the basin are younger southward, like the volcanism. These strike-slip faults crosscut the basin and its borders as well.

We interpret the late Miocene–Quaternary basins from these areas as pull-apart basins because of the (1) radial extensional regime, (2) existence of the strike-slip faults at the borders and within the basins, and (3) their rhombohedral shape. This interpretation is also sustained by the study of the Quaternary alkaline basalts, which indicates a west-east–oriented transtensional regime (Seghedi et al., 1998).

Strike-slip deformation has been found in the Apuseni Mountains (Ciulavu et al., 1998).

Petroleum Systems

Previously, a Miocene gas system, a Mesozoic petroleum system, and an Upper Cretaceous–Oligocene petroleum system have been interpreted in the Transylvanian basin (e.g., Popescu, 1995). No oil and gas accumulations of economic importance have been discovered in the Upper Cretaceous–Oligocene petroleum system. Using a definition of the petroleum system as "the combined presence of source rocks, reservoirs, and seals" (Perrodon, 1980) and structural data, we redefine the Miocene gas system and the Mesozoic petroleum system. We propose two petroleum systems in the Transylvanian basin: a gas system and an oil system. The gas system comprises the Mesozoic and the Miocene shales as the source rocks. Reservoirs are Miocene sands, sandstones, and marly sands. The biogenic gas is generated in the Miocene sedimentary sequence. The thermogenic gas could be generated in the Mesozoic shales and result from burial due to the rapid Miocene sedimentation and the thermal conductivity of salt. The mixing between the biogenic and thermogenic gas is the result of vertical migration favored by the reactivation of the inherited faults. The oil system comprises the Mesozoic shales of the Middle Dacides as source rocks. Reservoirs are the Jurassic limestones. If thermogenic gas from the gas system is generated in the Mesozoic shales, the oil from the Mesozoic sequence of the Middle Dacides is a heavy oil, in a small quantity, without economical importance.

Regional Scale

Structural data indicate that the Neogene tectonic movements from the Carpathians are recorded in the Transylvanian basin.

Early Miocene thrusting of the Pienides led to loading and flexure of the northern sector of the basin. Consequently, a retro-foreland basin developed in the northern sector of the basin.

We can interpret a middle–late Miocene "block" composed of the Transylvanian basin and its borders. Major strike-slip faults crosscut the basin and also its borders. Structural data indicate north to east-northeast–orientedmaximum principal stress around the basin, similar to the orientation of the same stress deduced from the trend of the fold axes and flexural slip data in the basin.

Pliocene north-south–oriented maximum principal stress was also found in the South Carpathians (Ratschbacher et al., 1993) and in the East Carpathians (Hippolyte and Săndulescu, 1996). This direction of compression could explain the existence of the Pliocene thrust and strike-slip faults in the Transylvanian basin. Thrust faults were formed when the direction of the compression was perpendicular to the inherited structures, whereas strike-slip faults were formed when this compression was oblique to the inherited faults. The change in the strike of the salt diapirs and folds from northeast to west-east seems to be controlled by the west-northwest–striking discontinuity from the central sector of the basin. The strongest intensity of the earthquakes from the Tirgu Mures area is recorded on this discontinuity.

Coeval (1) strike-slip movement in the western part, (2) shortening in the northern, central, and southern parts, and (3) extension in the southeastern part of the basin could be explained by the geometry of the preexisting margins of the basin. The bend of the East Carpathians was developed during the Cretaceous (Săndulescu, 1984). The Transylvanian basin occupied the space surrounded to the north, east, and south by the Moesian and East European platforms. Continuous north-northeast–oriented compression led to shortening, which was accommodated by strike-slip movement in the western part of the basin. The Transylvanian basin was squeezed between the Carpathians. Its southeastern sector escaped southeastward to fill up the preexisting bend of the East Carpathians. This escape led to extension. The boundary between the Pliocene thrusting and Pliocene extension seems to be the line where northeast-striking salt diapirs are developed. The extension in the Transylvanian basin and inner East Carpathians was accommodated by small-scale shortening in the external part of the bend area of the East Carpathians.

We interpret a Neogene compression/transpression in the Transylvanian basin because (1) the structures within the basin and at the borders are the result of the same oriented maximum principal stress, and (2) the strike-slip faults crosscut the borders and also the basin. This compressional/transpressional regime could explain the low heat flow, high elevation, and the normal crustal thickness.

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