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# Revised crustal architecture of the southeastern Carpathian foreland from active and passive seismic data

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[1] Integration of active and passive source seismic data is employed in order to study the nature of the relationships between crustal seismicity and geologic structures in the southeastern (SE) Carpathian foreland of Romania and the possible connection with the Vrancea Seismogenic Zone (VSZ) of intermediate-depth seismicity, one of the most active earthquake-prone areas in Europe. Crustal epicenters and focal mechanisms are correlated with four deep industry seismic profiles, the reprocessed Danube and Carpathian Integrated Action on Process in the Lithosphere and Neotectonics (DACIA PLAN) profile and the Deep Reflection Acquisition Constraining Unusual Lithospheric Activity II and III (DRACULA) profiles in order to understand the link between neotectonic foreland deformation and Vrancea mantle seismicity. Projection of crustal foreland hypocenters onto deep seismic profiles identifies several active crustal faults in the SE Carpathian foreland and suggests a mechanical coupling between the mantle located VSZ and the overlying foreland crust. The coupled associated deformation appears to take place on the Trotus Fault, the Sinaia Fault, and the newly detected Ialomita Fault. Seismic reflection imaging reveals the absence of west dipping reflectors in the crystalline crust and a slightly east dipping to horizontal Moho in the proximity of the Vrancea area. These findings argue against previously purported mechanisms to generate mantle seismicity in the VSZ including oceanic lithosphere subduction in place and oceanic slab break off, furthermore suggesting that the Vrancea seismogenic body is undetached from the overlying crust in the foreland. **Citation:** Enciu, D. M., C. C. Knapp, and J. H. Knapp (2009), Revised crustal architecture of the southeastern Carpathian foreland from active and passive seismic data, *Tectonics*, 28, TC4013, doi:10.1029/2008TC002381.

## 1. Introduction

[2] The SE Carpathian bend zone represents the site of the most recent and ongoing geodynamic activity in the

Carpathians. The spatial and temporal relationships between crustal structures related to the evolution of the post-Miocene Focsani Basin with mantle structures and seismicity of the Vrancea Seismogenic Zone pose an important and significant geodynamic problem.

[3] With a NE-SW surface orientation, the VSZ is the site of active mantle seismicity to depths of ~200 km, on a spatially restricted area and with a NW dipping seismogenic body. The seismogenic zone is defined by a 30 km wide by 70 km long area [Oncescu and Bonjer, 1997] located east of the Quaternary extensional Brasov Basin and just west of the Focsani Basin. A number of hypotheses [Royden, 1993; Artyushkov *et al.*, 1996; Linzer, 1996; Linzer *et al.*, 1998; Gırbacea and Frisch, 1998; Wortel and Spakman, 2000; Gvirtzman, 2002; Cloetingh *et al.*, 2005; Knapp *et al.*, 2005] attempt to explain the vertical geometry, depth and restricted lateral extent of the VSZ seismicity.

[4] Different authors present different variations but the three main competing models are “subduction in place” [Wortel and Spakman, 2000; Gvirtzman, 2002], “oceanic slab break off” [Linzer *et al.*, 1998], and “continental delamination” [Knapp *et al.*, 2005]. The type of data used in this study is ideal for validating or refuting both the subduction-in-place and slab break-off hypotheses.

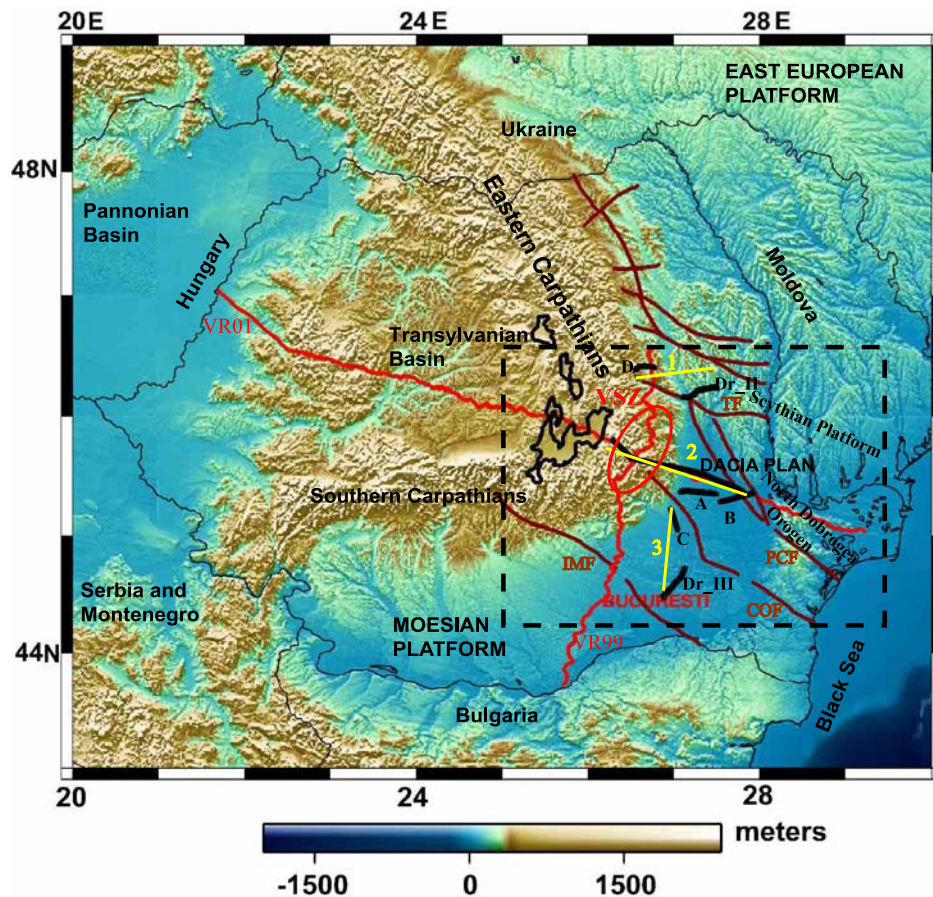
[5] The subduction-in-place hypothesis assumes that an oceanic crust floored basin was closed and subducted in the Miocene, and the presently active seismogenic area is a remnant oceanic slab hanging in the mantle right underneath the VSZ. The slab break-off hypothesis assumes that Miocene age oceanic subduction took place in the Miocene and since then the oceanic slab was detached from the crust and is presently foundering in the mantle underneath the VSZ [Linzer *et al.*, 1998]. Seismic reflection results of Mucuta *et al.* [2006] have already questioned the subduction-in-place hypothesis by presenting a slightly east dipping Moho interface east of Vrancea, at odds with expected westward dipping deep crustal structures.

[6] Because of small magnitude events in comparison with the Vrancea mantle events, foreland crustal seismicity is not extensively studied although it appears to be offset both laterally and vertically from the mantle seismicity. An important question that we try to address is how the crustal deformation in the foreland relates to the VSZ. An alternative “mechanical coupling” hypothesis (the opposite of slab break off) could help discriminate among the purported tectonic models for the origin of VSZ [Mucuta *et al.*, 2005].

## 2. Experimental Background and Objectives

[7] This study combines active and passive source seismic data from the SE Carpathians foreland to help determine the

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**Figure 1.** Digital elevation model (DEM) of Romania showing the location of processed seismic reflection profiles A, B, C, D, DACIA PLAN, DRACULA II (Dr\_II), and DRACULA III (Dr\_III) (all black lines); refraction profiles VRANCEA99 (red line, N-S orientation; marked as VR99) and VRANCEA2001 (red line, W-E orientation; marked as VR01); literature crustal-scale faults (brown lines (from north to south: TF, Trotus Fault; PCF, Peceneaga-Camena Fault; COF, Capidava-Ovidiu Fault; IMF, Intramoesian Fault)); cross sections presented in Figures 10a, 10b, and 10c (yellow lines marked 1, 2, and 3); and Vrancea Seismogenic Zone (VSZ, red oval). Dashed black rectangle marks study area shown in Figures 9a and 9b.

nature of the relationship between the crustal deformation in the SE Carpathian foreland and the VSZ. Imaging the upper and lower crustal structures and how/if they prolong in the mantle across the Moho, along with relocation and focal mechanism determination of selected crustal events, is considered to be an inexpensive and efficient method to address this issue.

[8] The three main objectives of this study are (1) to identify the distribution, geometry and type of active (crustal-scale) faults in the SE Carpathian foreland, (2) to elucidate the spatial relationships between crustal structures in the foreland and mantle seismicity, and (3) to define viable geodynamic mechanisms responsible for the spatial distribution of the Vrancea seismicity. Furthermore, this research is addressing the hypothesis of a mechanical coupling between the Vrancea mantle seismogenic body and the overlying crust, thus testing the current models of oceanic lithospheric subduction and slab break off.

[9] Four industry deep (17–20 s TWTT) seismic reflection profiles totaling 117 km collected in the Focsani Basin and the northern part of the eastern Carpathians were processed and interpreted. Additional to these seismic profiles we also present the reprocessed Danube and Carpathian Integrated Action on Process in the Lithosphere and Neotectonics (DACIA PLAN) profile, collected in 2001 and originally published by *Panea et al.* [2005]. The DRACULA II and III seismic reflection profiles collected in the summer of 2004 as part of the larger Deep Reflection Acquisition Constraining Unusual Lithospheric Activity (DRACULA) project are presented here for the first time (Figures 1 and 2).

[10] Project DRACULA consisted in the acquisition of three deep seismic reflection profiles with the goals of mapping the main structural detachment(s) of the eastern Carpathians, and their westward continuation into the hinterland, to provide reliable constraints from the geometry of

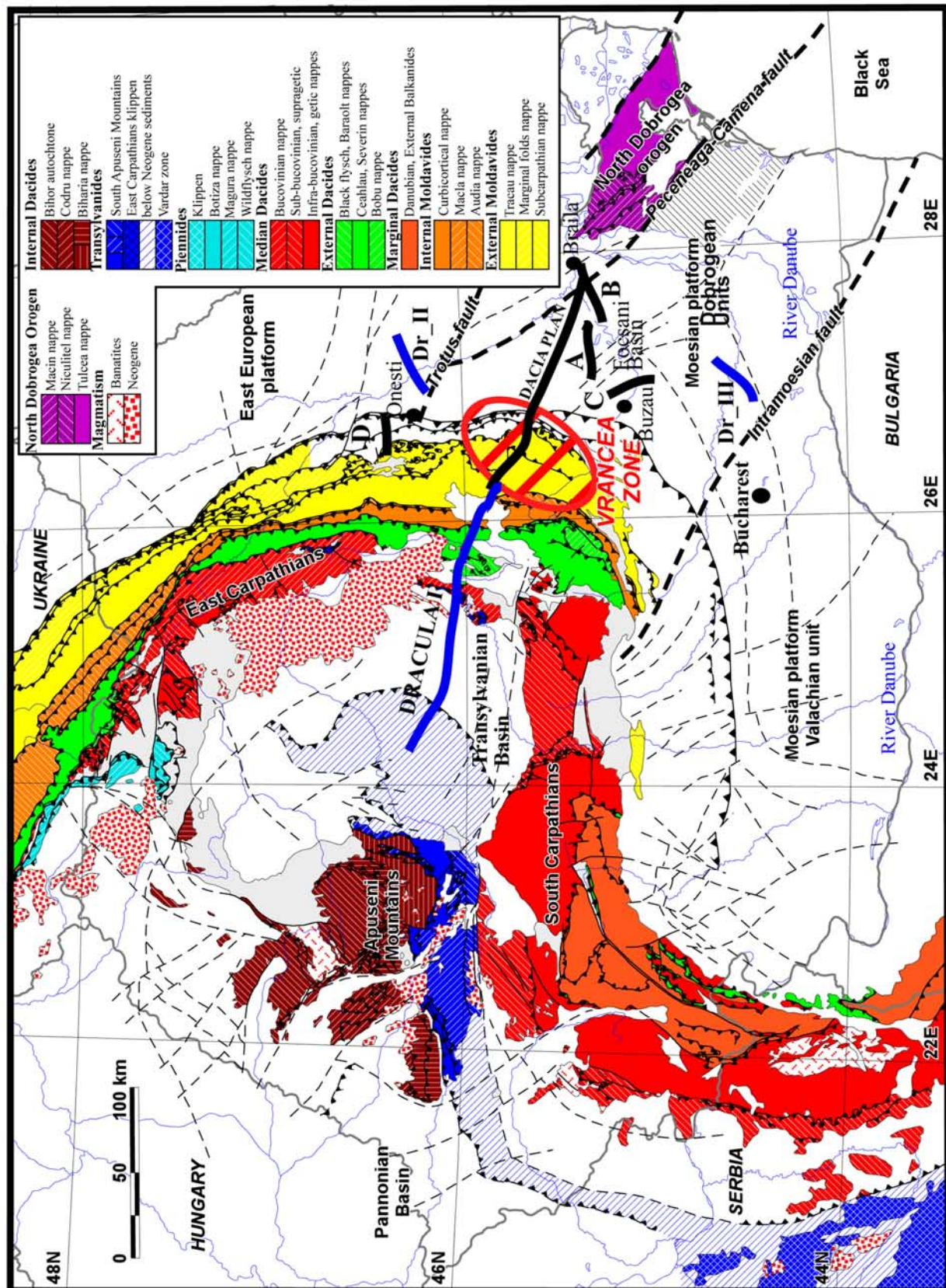


Figure 2

crustal reflectors on the postulated existence, position, and polarity of a Miocene age subduction zone within the Transylvanian crust, and to elucidate the geometric relationship between active faults in the Carpathian foreland and the seismogenic volume in the mantle. The drivers for the project were to test the hypothesis of a mechanical coupling of the foreland crust with Vrancea seismicity, and ultimately to evaluate competing subduction/delamination geodynamic models for the origin of mantle seismicity in the Vrancea zone on the basis of these results [Knapp *et al.*, 2004, 2005].

[11] The two DRACULA profiles acquired in the foreland are presented here, namely DRACULA II collected in the northern part of the foreland and DRACULA III in the south. DRACULA I was collected across the Transylvanian Basin and the SE Carpathians bend zone and is not presented here, being the subject of another study. These combined profiles (location shown in Figures 1 and 2) reveal crustal and uppermost mantle structures of interest for the understanding of the geodynamic processes responsible for the tectonic setting and spatial relationships between the SE Carpathians foreland and the Vrancea Seismogenic Zone (VSZ).

### 3. Tectonic and Geologic Setting

[12] The SE Carpathians are a highly arcuate orogenic feature made up of the NW-SE trending eastern Carpathians and the E-W trending southern Carpathians (Figures 1 and 2). They formed as the results of the Alpine orogeny that led to the collision of the Tisza-Dacia microplate in the west and the stable cratonic East European Platform in the east [Sandulescu, 1984, 1988]. This region, also known as the Carpathian bend zone, represents the site of the presently active Vrancea seismogenic area (VSZ, in text). The Focsani Basin is a small part of the SE Carpathian foreland and represents a topographic low (Figure 1).

[13] The geology of Romania, particularly that of the Carpathians has been described and discussed by numerous authors [Burchfiel, 1976; Sandulescu, 1984, 1988; Roure *et al.*, 1993; Royden, 1993] and can be divided into two major deformational phases, one in the Mesozoic and one in the Cenozoic. The Mesozoic phase, leading to the closure of the Tethys Ocean and the collision between the Eurasian and African plates is well documented [Sandulescu, 1988] and it led to a Late Cretaceous deformation in the eastern Carpathians evidenced by the emplacement of large crystalline thrust nappes (Getic, Supragetic and Bucovinian) that are now exposed in the inner Carpathians toward the Transylvanian Basin hinterland (Figure 2). The geologic make up of Romania also contains platforms of Precambrian age

(Moldavian Platform) and Proterozoic age (Moesian and Scythian Platforms).

[14] The second and most recent period of deformation was in the Early Middle Miocene time and involved the folding of a Cretaceous through Miocene stratigraphic sequence presently preserved in the outer nappes toward the foreland [Sandulescu, 1988] (Figure 2). The deformation of this sedimentary sequence did not involve the basement and records Miocene age thin-skinned shortening of 150–180 km [Roure *et al.*, 1993]. Final nappe emplacement was mid-Miocene (9–11 Ma), followed by continued compression and back thrusting in Pliocene time [Sandulescu, 1988; Matenco, 1997; Matenco and Bertotti, 2000]. The main detachment known as the Peri-Carpathian front is buried in the bend zone under Upper Miocene-Quaternary sediments but is exposed above the Trotus Fault in the north.

[15] The external most part of the SE Carpathians represents the foreland basin which started forming during the Alpine orogeny but most of its formation was subsequent to it [Sandulescu, 1984, 1988]. The Tertiary sedimentary sequence of the Focsani Basin sits atop three cratonic continental major units (platforms) of Precambrian crystalline basement and Paleozoic-Mesozoic cover, separated at crustal level by faults (Figure 2). From north to south, the East European and Scythian Platforms are separated by the Trotus Fault from the North Dobrogean Orogen. The Peceneaga-Camena Fault separates the North Dobrogean Orogen from the Moesian Platform which is in turn separated in different units by other crustal-scale faults (Capidava-Ovidiu Fault separates the Central Dobrogea section of the Moesian Platform, from the South Dobrogea section of the Moesian Platform). The Intramoesian Fault internally separates the Moesian Platform into a South Dobrogean section east of it from a Walachian type of basement west of it. These crustal-scale faults were identified from potential field (mostly magnetic and gravimetric), and refraction data [Enescu *et al.*, 1972]. According to Matenco and Bertotti [2000], the Peceneaga-Camena and Trotus fault system divides the actively subsiding Moesian Platform from the uplifting Dobrogea-Scythia-East European units.

[16] Previously recorded refraction profiles [Enescu *et al.*, 1972; Radulescu *et al.*, 1976; Pompilian *et al.*, 1993] identified offsets of ~5 km at the Moho level on the Peceneaga-Camena Fault. Other recent normal faults mapped on industry seismic reflection data appear to be mostly concentric to the Vrancea Zone and suggest active deformation of the SE Carpathian foreland [Matenco *et al.*, 2003; Tărăpoancă *et al.*, 2003].

[17] There is a wealth of literature on the Focsani Basin [Dicea, 1995; Matenco and Bertotti, 2000; Matenco *et al.*, 2003; Tărăpoancă *et al.*, 2003; Bocin *et al.*, 2005; Panea *et*

**Figure 2.** Simplified geologic map of Romania showing main tectonic units (see legend) and location of industry deep seismic reflection profiles A, B, C, and D (solid black lines) and project DRACULA lines (DRACULA I, Dracula II (Dr\_II), and Dracula III (Dr\_III) as blue lines). DRACULA I is not addressed in this paper. DACIA PLAN is also shown as a solid black line. Vrancea zone is marked by the red oval. Crustal-scale faults are marked by thin dashed black lines. Trotus Fault, Peceneaga-Camena Fault, and Intramoesian Fault are marked as thick dashed black lines. Also shown are the cities of Bucharest, Braila, Buzau, and Onesti for orientation. The Peri-Carpathian front is shown by the black line with triangles along the length of the Carpathians.

**Table 1.** Acquisition Parameters of Seismic Profiles

Profile Name	Length (km)	Source	Charge Size (kg/shot)	Shot Interval (m)	Receiver Interval (m)	Sample Rate (m)	Record Length (s)	Orientation
Line A	35	Dynamite	5	100	50	2	20	W-E
Line B	32	Dynamite	1	50	25	2	20	WSW-ENE
Line C	22	Dynamite	16	50	50	4	18	NNW-SSE
Line D	21	Dynamite	96	50	25	5	17	WSW-E
DACIA PLAN	140	Dynamite	28	1000	100	5	90	NNW-SSE
DRACULA II	35	Dynamite	24	1000	50	4	90	WSW-ENE
DRACULA III	35	Dynamite	24	1000	50	4	90	NNE-SSW

*al.*, 2005; *Leever et al.*, 2006; *Mucuta et al.*, 2006] because of both its economic and its scientific importance. Sitting atop thinned continental crust [*Mucuta et al.*, 2006], the sedimentary sequence reaches ~15 km at the depocenter with 10 km of Miocene-Quaternary age deposits and the upper 6 km being accumulated after the end of the Mid-Miocene contractional events [*Tărăpoancă et al.*, 2003; *Mucuta et al.*, 2006]. The Focsani Basin marks the area with the lowest topography of the SE Carpathians foreland and exhibits current subsidence rates of ~2 mm/a [*Radulescu et al.*, 1996] corroborated with the 1.5 mm/a average Quaternary deposition [*Van der Hoeven et al.*, 2005].

[18] In contrast, the uplifting areas are represented by the SE Carpathians as well as the Transylvanian Basin and the East European Platform north of the Trotus Fault (Figure 1). In the Early Quaternary, subsidence continued in the basin while the adjacent orogen experienced uplift [*Leever et al.*, 2006]. According to *Artyushkov et al.* [1996], the crustal uplift leading to the present orogen began 3 Ma and most of the basin subsidence took place in the absence of convergence.

[19] Shallow, low magnitude ( $M < 5$ ) and scattered seismicity is associated with the Focsani Basin. The seismicity is diffuse and occurs in the crust on a much broader area than the Vrancea seismicity. Additionally it is eastwardly offset from the mantle seismicity with no mantle earthquakes occurring in the foreland but restricted solely to the VSZ. The seismic region associated with the Ramnicu Sarat area was investigated by *Malita and Radulescu* [1999], who analyzed seismicity recorded between 1952 and 1994. Their study revealed a variety of focal mechanisms, most of which were reverse fault, but some with strike-slip and normal movements.

## 4. Seismic Data and Processing

### 4.1. Deep Seismic Reflection Profiles

[20] The seismic database used in this study comprises (1) four industry deep (17–20s TWTT) seismic reflection profiles acquired in the SE Carpathian foreland, (2) the reprocessed DACIA PLAN near-vertical seismic reflection profile collected across the SE Carpathians and VSZ [*Panea et al.*, 2005], and (3) the DRACULA II and III seismic reflection profiles (locations shown in Figures 1 and 2). The acquisition parameters for all profiles are presented in Table 1.

[21] Processing of the seismic reflection profiles included trace editing, amplitude recovery at large depths, deconvolution, velocity analysis, noise removal, signal enhancement, migration and conversion from time to depth. A general processing flow is provided in Table 2. More specifically, the prestack processing sequence consisted of assigning the geometry and input of required parameters, removal of noisy traces and muting of refracted energy. Since these are long record data and energy is lost with depth, True Amplitude Recovery was performed with stacking velocities, along with Trace Equalization down the entire trace length.

[22] Air Blast Attenuation proved useful in the removal of ground roll energy pervasive mostly on the DACIA PLAN profile and to a lesser extent on DRACULA II and III. First break picking and editing in the database was performed followed by refraction and elevation static corrections. Predictive deconvolution was applied with the role of removing unwanted multiples that could harm the interpretation along with resolution improvement of the data. In order to improve the lateral coherency of the reflectors, a

**Table 2.** General Processing Sequence of Seismic Profiles

Processing Steps	Description
<i>Prestack</i>	
Geometry	Straight line geometry
Top mute and trace edits	Applied
Band-pass filtering	Time variant and Ormsby
True Amplitude Recovery	w/stacking velocities
Trace Equalization	Applied, entire trace length
Air Blast Attenuation	331 m/s, 330 m/s; 3000 ms window
Datum Static Corrections	Elevation corrections, 0 m datum and 1600 m/s replacement velocity
Refraction Static Corrections	Applied
Predictive Deconvolution	Applied
2-D Spatial Filtering	Applied
Dynamic S/N Filtering	Applied
NMO	w/stacking velocities
CDP Stack	w/stacking velocities
<i>Poststack</i>	
F-X Decon (L2 Normal Adaptive)	Applied
Dip Scan Stack	Dip of 9 traces (DACIA PLAN only)
Dynamic S/N Filtering	Applied
2-D Spatial Filtering	Applied
FD Time Migration	w/stacking and refraction velocities
Depth Conversion	w/stacking and refraction velocities

series of signal enhancement filters such as 2-D Spatial Filtering and Dynamic S/N Filtering were applied.

[23] Stacking velocities picked on the edited and filtered common depth point (CDP) gathers were used to correct for the normal move out (NMO) for stacking. Some filters were applied after stacking in order to improve the signal-to-noise ratio, including Dip Scan Stack [Stoffa *et al.*, 1981]. Conversion from time to depth was performed using the stacking velocities adjusted with velocities from the refraction experiments VRANCEA99 and 2001 [Hauser *et al.*, 2001, 2007].

[24] The presented seismic sections are shown here in time with corresponding equivalent depth values. These sections show crustal and uppermost mantle structures of interest such as the sedimentary cover-basement contact, midcrustal reflectivity, and the crust-mantle boundary (Moho).

[25] The industry seismic lines were processed to the maximum extent of the record time and thus have depths of ~60 km (A and B) and ~52 km (C and D). The DRACULA II, DRACULA III, and DACIA PLAN profiles were processed to a depth of 60 km (20s TWTT) though the record length was 60–90s TWTT. All seismic sections are of good quality and processing steps were taken to improve signal coherency at depth in order to reveal the crustal and uppermost mantle structure. This sometimes affected the quality of the shallowest section (upper 1s) such that these images do not have the shallow resolution typical of shallow industry lines processed for hydrocarbon evaluation.

## 4.2. Interpretation

[26] The shallow section of these deep profiles (52–60 km deep) was interpreted in conjunction with well data and other seismic profiles in the area [Dicea, 1995; Matenco and Bertotti, 2000; Tărăpoancă *et al.*, 2003]. The deep section was interpreted in conjunction with regional seismic refraction profiles [Pompilian *et al.*, 1993; Hauser *et al.*, 2007].

### 4.2.1. Seismic Lines A and B

[27] Line A (Figure 3) is situated in the Focsani Basin in a region of minimum Bouguer gravity anomaly on the relatively stable Moesian Platform, between the Capidava-Ovidiu and Peceneaga-Camena faults. Line B (Figure 3) is situated partly on the Moesian Platform and partly on the North Dobrogean Orogen, crossing the surface expression of the Peceneaga-Camena Fault. These two profiles are presented and discussed together because of their proximity and potential for an integrated interpretation.

[28] Presented by Mucuta *et al.* [2006], lines A and B were collected approximately on an east to west transect slightly SW of the VSZ. Their interpretation reveals a sedimentary cover that becomes thicker from east to west (where it reaches ~14 km depth) while the crystalline crust appears to thin from east to west. With a total length of ~70 km and a depth of ~60 km this section also shows evidence for, what was interpreted to be, a Permo-Triassic graben underneath the Focsani Basin [Panea *et al.*, 2005].

[29] The cover-basement contact was placed at ~14 km in the west and <1 km in the east, with the upper 10 km of sediments considered to be of Tertiary age. Midcrustal reflectivity is pervasive throughout line A with the strongest

reflective package located underneath the inferred graben structure. Because of the nature of the processing, targeting deeper structures, the upper kilometer lacks sufficient resolution to interpret conclusively active shallow faults and their geometries. Interpretation of marked seismic horizons (Figure 3) was done in conjunction with shallow seismic profiles located nearby [Matenco and Bertotti, 2000].

[30] No significant new information is provided on the nature and geometry of the Peceneaga-Camena Fault at depth as this falls in a portion of poor data on line B. However, the eastern end of line B presents diffractions at the base of the sedimentary cover and a different reflective character (higher amplitudes, lower frequency) that may be interpreted as a series of shallow normal faults, offsetting the basement and possibly related to the Peceneaga-Camena Fault zone (Figure 3).

[31] Line B also shows a more transparent crust and less reliable constraints for the position of the Moho which is ultimately constrained by refraction results of Pompilian *et al.* [1993]. The eastern end of line B intersects the more recent VRANCEA2001 refraction profile for which Hauser *et al.* [2007] estimate a Moho depth of 43–44 km.

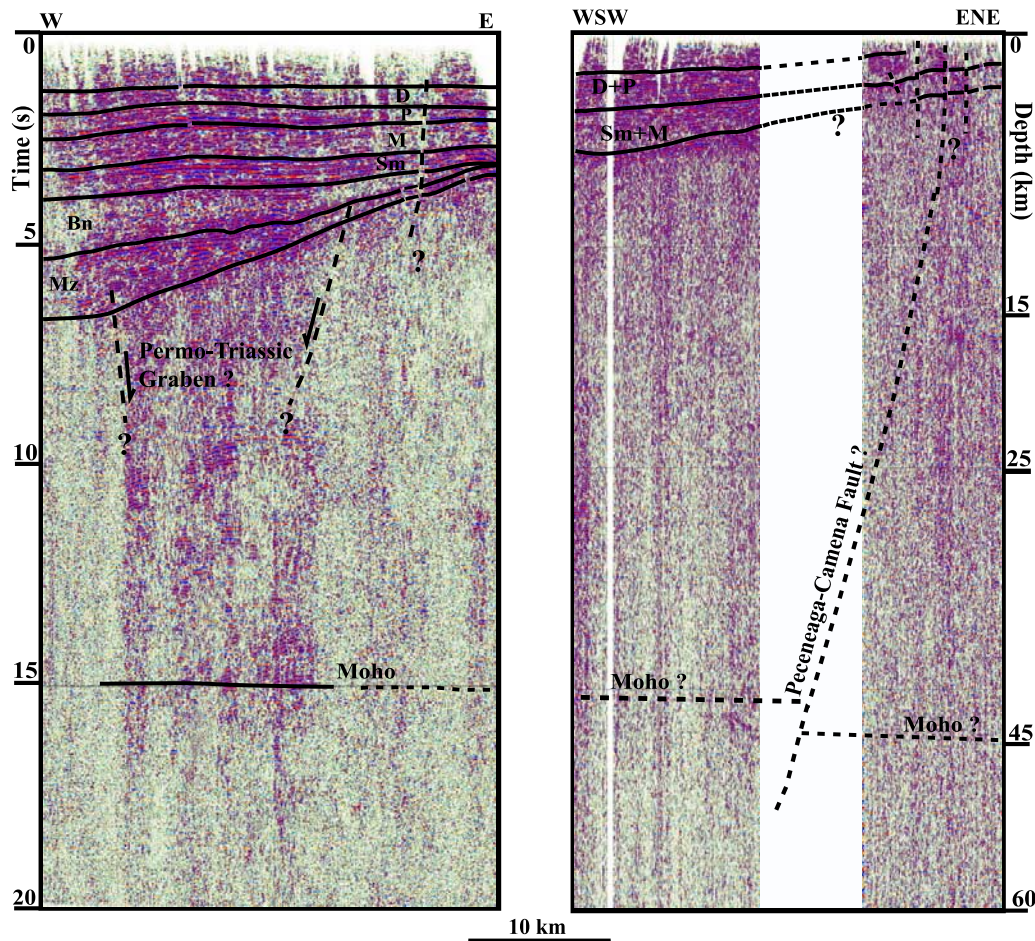
[32] Taken together, lines A and B are in good agreement with results from the DACIA PLAN deep seismic reflection profile [Panea *et al.*, 2005] that also show an east dipping Moho as well as a slight thinning of the crystalline crust toward the VSZ. However, Hauser *et al.* [2007], in one of their more recent models from the refraction profile VRANCEA2001, show a slight deepening of the Moho underneath the Focsani Basin before dramatically shallowing by ~10 km (over a distance of 40 km) below the eastern Carpathians fold and thrust belt and the Transylvanian Basin further to the west. We do not have a singular explanation for this discrepancy except that the solution to a refraction data modeling is nonunique whereas seismic reflection data offers a more direct image of the subsurface.

[33] Nevertheless, critical for the evaluation of the competing hypotheses are (1) the overall shallowing of the Moho in the vicinity of the VSZ toward the Transylvanian Basin and (2) the absence of throughgoing crustal west dipping reflections, both arguments pleading against the subduction-in-place hypothesis.

### 4.2.2. Seismic Line C

[34] Line C is ~22 km long and oriented NNW-SSE (Figure 4). This line was collected on the Moesian Platform, eastward of the NW-SE trending Capidava-Ovidiu Fault. It has a total record length of 18s TWTT representing 52 km of crust and uppermost mantle. The sedimentary section is represented by parallel, subhorizontal reflectors, slightly dipping to the NNW (0–5.5s TWTT; ~0–12 km) and the basement-cover contact is placed at ~5.5s TWTT (~12 km) in the NNW and ~4 s TWTT (~9 km) in the SSE (Figure 4).

[35] This is in good correlation with the western end of line A and is also in agreement with the general thickening of the sedimentary wedge toward the Carpathians. The NNW end of line C is situated at ~18 km distance from the western end of line A and there is a good correlation of the seismic horizons between the two profiles. The crystalline basement appears to be strongly fractured indicating a



**Figure 3.** Interpreted time and depth sections of lines A (W-E) and B (WSW-ENE) show the sedimentary cover thickening to the west, Moho depth, and inferred location of the Peceneaga-Camena Fault (discussion in text). Also marked on line A is an interpreted Permo-Triassic graben, possibly the same one seen by *Panea et al.* [2005] on DACIA PLAN. On the eastern part of line B a series of shallow normal faults (black dashed lines) are associated with the Peceneaga-Camena Fault. Interpreted seismic horizons have the following ages: Mesozoic (Mz); Badenian (Bn), 16–13.5 ma; Sarmatian (Sm), 13.5–10 ma; Meotian (M), 10–8.5 ma; Pontian (P), 8.5–5 ma; Dacian (D), 5–3.5 ma.

series of basement-cutting faults; however it is hard to determine conclusively their continuation to the surface.

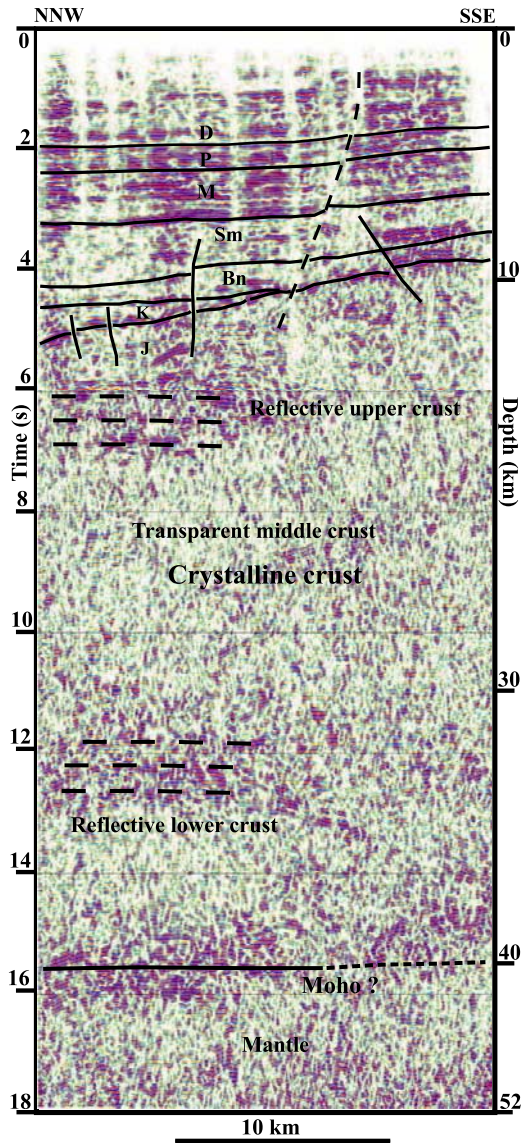
[36] The upper crystalline crust is partly reflective between 5 and 7 s TWTT and partly transparent between ~7–11 s TWTT (~12–27 km). The lower crust is rather reflective, shown by continuous layers of reflectors between 11.5 and 13 s TWTT (~32–33 km), suggesting a more ductile medium. The Moho depth is placed at ~40 km on the basis of subhorizontal, continuous reflectors at 15–15.5 s TWTT, slightly deepening toward the NNW. This correlates well with the Moho depth at the western end of line A. No constraints are directly provided by seismic refraction data. The uppermost mantle imaged by this line is characterized by short, high-amplitude reflectors, in agreement with other older industry deep seismic data collected nearby [*Diaconescu et al.*, 1996].

#### 4.2.3. Seismic Line D

[37] The northernmost line in this study has a WSW-E orientation (Figure 5). It is situated in the northern part of

the eastern Carpathian foredeep, on the external nappes of the eastern Carpathians, on the Scythian Platform, between the Trotus and the Bistrita faults. Constraints on the interpretation of this line were provided by the northern end of the VRANCEA99 refraction profile [*Hauser et al.*, 2001]. This line is 22 km across and was recorded to 17 s TWTT (~52 km).

[38] Several strong amplitude but somewhat discontinuous dipping events were imaged in the upper 6 s, interpreted to be thrust ramps from the external eastern Carpathian nappes. While the eastern middle crust appears to be reflective, with a well imaged layer of parallel, horizontal reflectors (8–9.5 s TWTT), the western part abounds with steeply dipping high-amplitude reflectors from 7 to 13 s TWTT and to a lesser extend down to 17 s TWTT. Upon migration, these reflectors disappeared indicating that they may represent out of plane energy. These dipping reflectors are intersected at ~13 s TWTT by parallel subhorizontal reflectors that are interpreted as the crust-mantle boundary



**Figure 4.** Interpreted time and depth section of line C showing a thick sedimentary section, reflective upper and lower crust, transparent middle crust, and the crust-mantle boundary (Moho) around 40 km (discussion in text). Interpreted seismic horizons have the following ages: Jurassic (J); Cretaceous (K); Badenian (Bn), 16–13.5 ma; Sarmatian (Sm), 13.5–10 ma; Meotian (M), 10–8.5 ma; Pontian (P), 8.5–5 ma; Dacian (D), 5–3.5 ma.

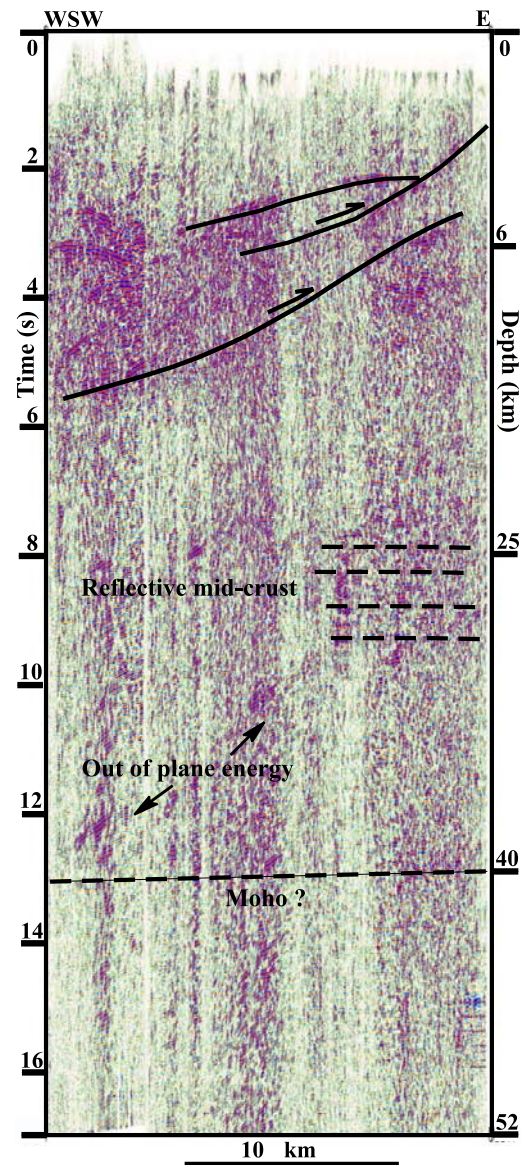
(Moho) at ~39–40 km depth. This interpretation is supported by refraction results of the VRANCEA99 profile [Hauser *et al.*, 2001].

#### 4.2.4. DACIA PLAN Seismic Line

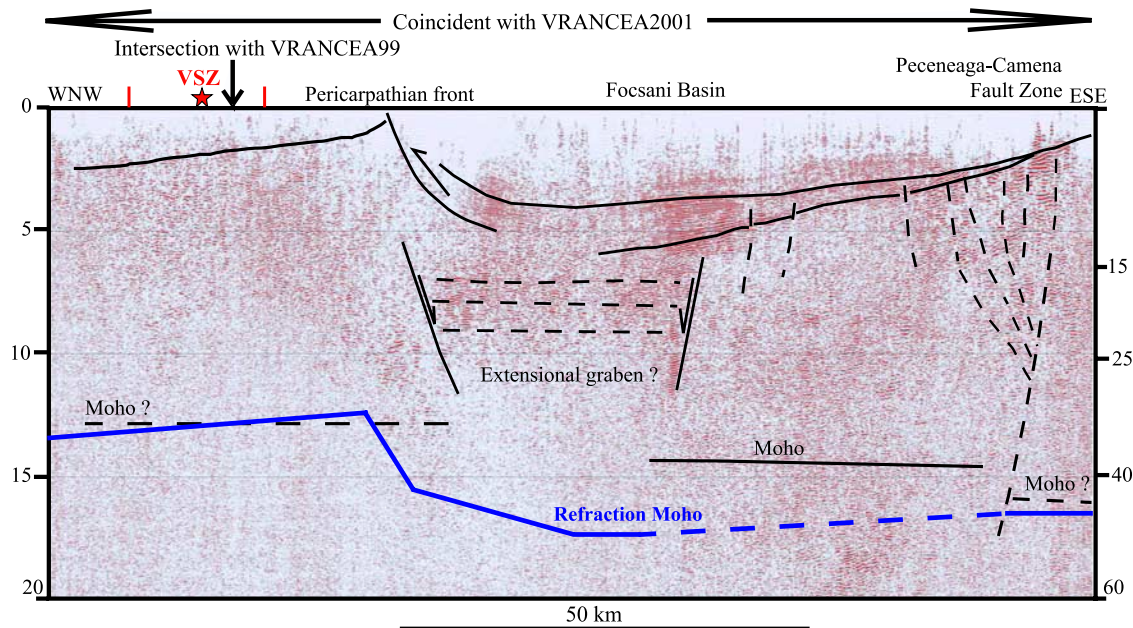
[39] The DACIA PLAN seismic reflection profile was acquired in the summer of 2001 and initial results were published by Panea *et al.* [2005]. The profile, originally collected down to 90 s TWTT, stretches ~130 km across the SE Carpathians, Vrancea region and Focsani Basin, with a

WNW-ESE orientation. Geologically, DACIA PLAN is situated half on the Moesian Platform and half on the North Dobrogea Orogen. It starts in the bend region of the SE Carpathians right above the VSZ and continues across the Focsani Basin. Its easternmost extremity meets line B and potentially good correlations should be possible between the combined profiles of lines A and B and the DACIA PLAN line. The reprocessed seismic section is shown in Figure 6.

[40] The DACIA PLAN profile was reprocessed in an attempt to derive more information regarding the deep structure in the proximity of the VSZ, one aspect being



**Figure 5.** Interpreted time and depth section of line D showing imbricate thrust and fold external nappes of the eastern Carpathians, reflective middle crust, and the interpreted crust-mantle boundary (Moho) around 40 km (discussion in text).



**Figure 6.** Interpreted reprocessed time and depth section of DACIA PLAN experimental seismic profile showing the Focsani Basin thick sedimentary section; an extensional graben located underneath the basin, the same one interpreted by *Panea et al.* [2005] on the same line; the inferred positions and splays of the Peceneaga-Camena Fault zone; and the crust-mantle boundary (Moho). The position of the VSZ is indicated by the red star on the western end. Note east dipping/horizontal Moho and absence of west dipping crustal reflectors underneath the basin and in the proximity of VSZ (discussion in text). The Moho interpretation from refraction results of *Hauser et al.* [2007] is shown in blue. The VRANCEA2001 refraction profile is coincident with DACIA PLAN, but the position/depth and slope/dip of the Moho is different between the two interpretations. Despite these differences, it is important is that both interpretations show a thinning of the crystalline crust from east to west and a shallowing of the Moho toward the Carpathian orogen and the VSZ.

potential structures in the crust, interpretable in terms of slab subduction, and the imaging of the Moho. Original processing steps were presented by *Panea et al.* [2005]. The reprocessing sequence is shown in Table 2. The profile is partly coincident with the VRANCEA2001 refraction profile. A tomographic study of the upper 10 km was presented by *Bocin et al.* [2005] while the refraction results were presented by *Hauser et al.* [2007].

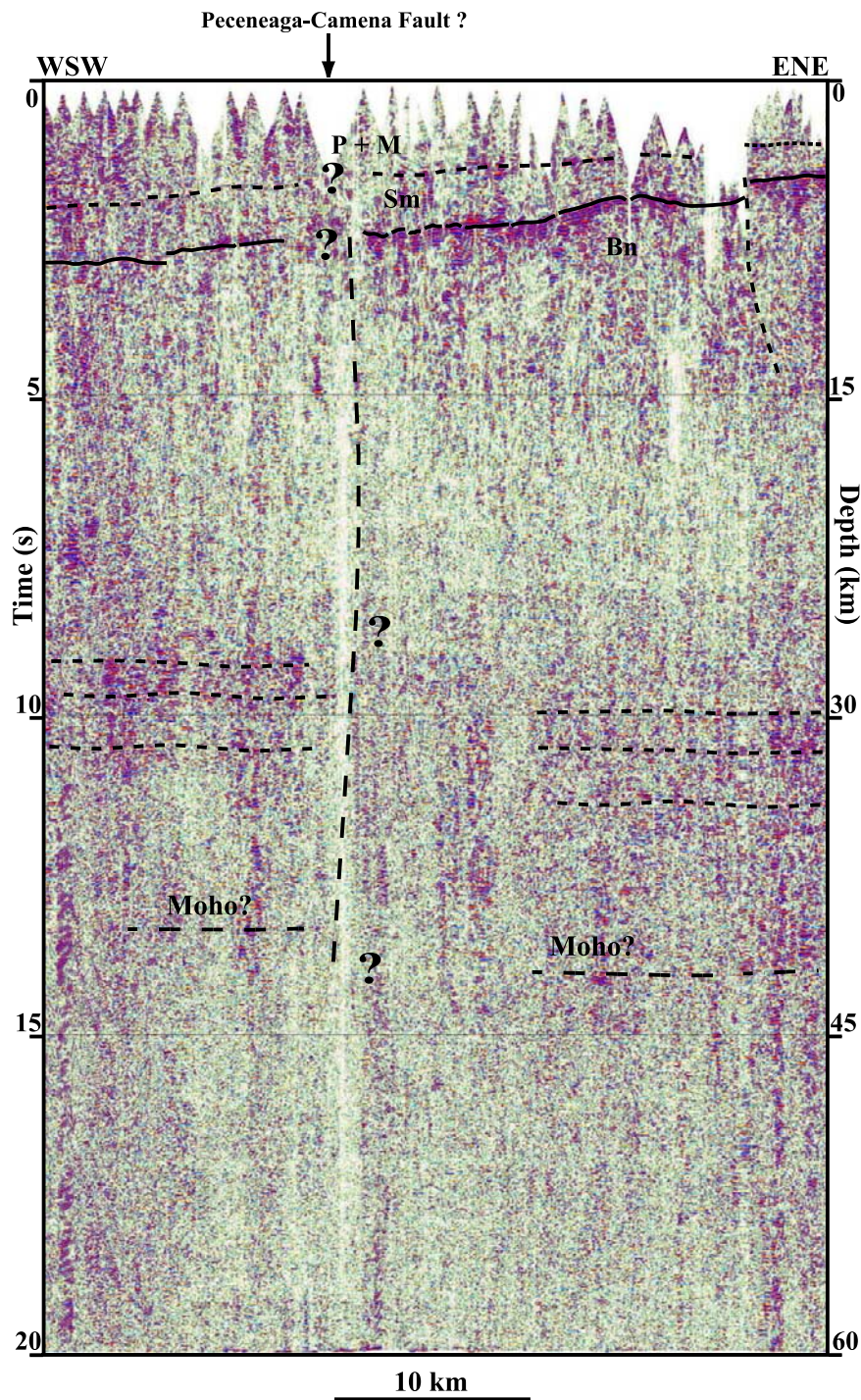
[41] The Peceneaga-Camena Fault is imaged as a fault zone rather than a single fault on the easternmost end of the profile (Figure 6). Its extent at depth is not conclusively observed in the seismic data. As published by *Mucuta et al.* [2006], Moho depth was placed at 43 km in the ESE, at 40 km underneath the eastern half of the Focsani Basin, and at 38 km in front of the VSZ. This is in a slight disagreement with *Hauser et al.* [2007], who place the Moho at ~45 km depth underneath the Focsani Basin before a very steep shallowing underneath the VSZ and further to the west, underneath the Transylvanian Basin. Interestingly, the refraction Moho appears to mimic the base of the sedimentary sequence (Figure 6). Apart from westward tilted sediments within the Focsani Basin, there is little, if any, evidence of west dipping reflectors in the crust and particularly at the Moho level that could lend weight to the slab subduction hypothesis. The interpreted extensional graben, apparently

flanked by normal faults is evidenced again in our reprocessing, as are the upwardly flexed structures on the western edge of the basin [*Leever et al.*, 2006]. This tilting happens at the Peri-Carpathian front. There is a good correlation with line A located some 18 km along strike southward of it, especially regarding the graben structure, the thickness of the sedimentary section and the Moho depth. There is also good correlation with line B for the inferred Peceneaga-Camena Fault Zone, with the same fractured, high-amplitude reflectors being observed on both sections.

#### 4.2.5. DRACULA II and DRACULA III Seismic Lines

[42] DRACULA II and III are two of the three profiles acquired as part of the DRACULA project in the summer of 2004. These two profiles were acquired in the northern and southern parts of the SE Carpathian foreland, respectively, with the aim of imaging potential reactivated/active crustal-scale faults potentially related to the geodynamic setting of VSZ. The recording instruments were stand-alone TEXAN seismometers with 50 m spacing while the shot spacing was 1 km. Each line is ~35 km long. They were recorded to 60 s TWT but only the upper 20s are shown here.

[43] DRACULA II (Figure 7) has a WSW-ENE orientation and is situated on the Scythian Platform, between the Trotus and Bistrita faults. The main geologic target for this profile was, what appeared to be based on surface geologic



**Figure 7.** Interpreted time and depth section of the DRACULA II experimental profile showing the basement contact, a reflective midcrust, and the position of the crust-mantle boundary (Moho); the inferred position of the Peceneaga-Camena Fault is indicated at crustal level, but no offsets are obvious in the sedimentary section (discussion in text). Interpreted seismic horizons have the following ages: Badenian (Bn), 16–13.5 ma; Sarmatian (Sm), 13.5–10 ma; Meotian (M) to Pontian (P), 10–5 ma.

observations, the northern continuation of the Peceneaga-Camena Fault.

[44] The time section shown to 20 s TWTT (Figure 7) and approximate depth of 65 km (depth conversion done

with a mean crustal velocity of 6 km/s) presents a strong, east to west dipping reflector at ~2–3 s TWTT (~5–7 km) in the sedimentary section and a relatively reflective underlying crust between ~9–14 s. The high-amplitude shallow

reflector can be followed almost continuously for most of the ENE half of the line where a bend in the acquisition geometry occurs. It is more difficult to follow its continuation toward the WSW. Through correlation with other industry seismic lines in this area, this reflector is interpreted as the top of the Badenian (15–13 Ma).

[45] The upper crust could be characterized as almost transparent with sparse short reflectors. The lower crust is characterized by short, continuous and parallel reflectors between 10 and 12 s TWTT (~30–33 km) on the eastern end and a similar packet of reflectors, seemingly offset on the western side at 9–11 s TWTT (~28–31 km). A similar character is displayed at what is interpreted to be the crust-mantle boundary (Moho), at 13.5 s TWTT (~42 km) on the eastern end with a step at 13 s TWTT (~40 km) toward the west. This step is quite similar in size and direction with the step in the lower crust reflectivity and appears to coincide with the northern extension of the Peceneaga-Camena Fault. However, the interpreted trace of the Peceneaga-Camena Fault on this line indicates that while this fault may be a crustal-scale feature, relatively little displacement appears to have occurred during the Cenozoic time.

[46] DRACULA III profile was acquired in the southeastern region of the SE Carpathian foreland, and is the southernmost profile in this study (Figure 8). It has a NNE-SSW orientation and was collected on a transect ~40 km long on the eastern half of the Moesian Platform. The shallow section (upper 2.5 s TWTT) was remarkably well imaged considering the acquisition geometry targeted deep events. It reveals the sedimentary cover and top of basement as continuous, parallel and subhorizontal reflectors down to 2.5 s (~3 km) most likely of Mesozoic and younger age. The topmost 1 s is inferred to be Tertiary in age. A striking feature of this section is the very distinctive change in the reflectivity pattern across the ~30 m step in the topography. The reflective character changes from flat reflectors dipping slightly to the south of this topographic step, to a pronounced arcuate and higher-amplitude reflective sequence northeast of it. Given the step in the topography as well as the subsurface change in the reflectivity across this boundary, this steeply dipping feature was interpreted as a fault zone, and named the Ialomita Fault after the nearby river.

[47] The obscured reflectors below the surface location of the interpreted Ialomita Fault suggest that this might behave as a fault zone at depth. The crust underneath the basement-cover contact appears to be transparent. Between 10 and 12 s TWTT in the north and 9–11 s TWTT in the south, the lower crust is characterized by short layers of reflectors, mostly horizontal, separated by a mid region of apparent transparency. The reflectivity stops ~15 s TWTT north of the proposed fault and ~14 s south of the fault and this is where the Moho was interpreted, at 38–40 km depth. These Moho depths are in general agreement with known values for the Moesian Platform [Diaconescu et al., 1996].

## 5. Foreland Seismicity

[48] Relocated crustal earthquakes together with their focal mechanisms from the foreland region for the period

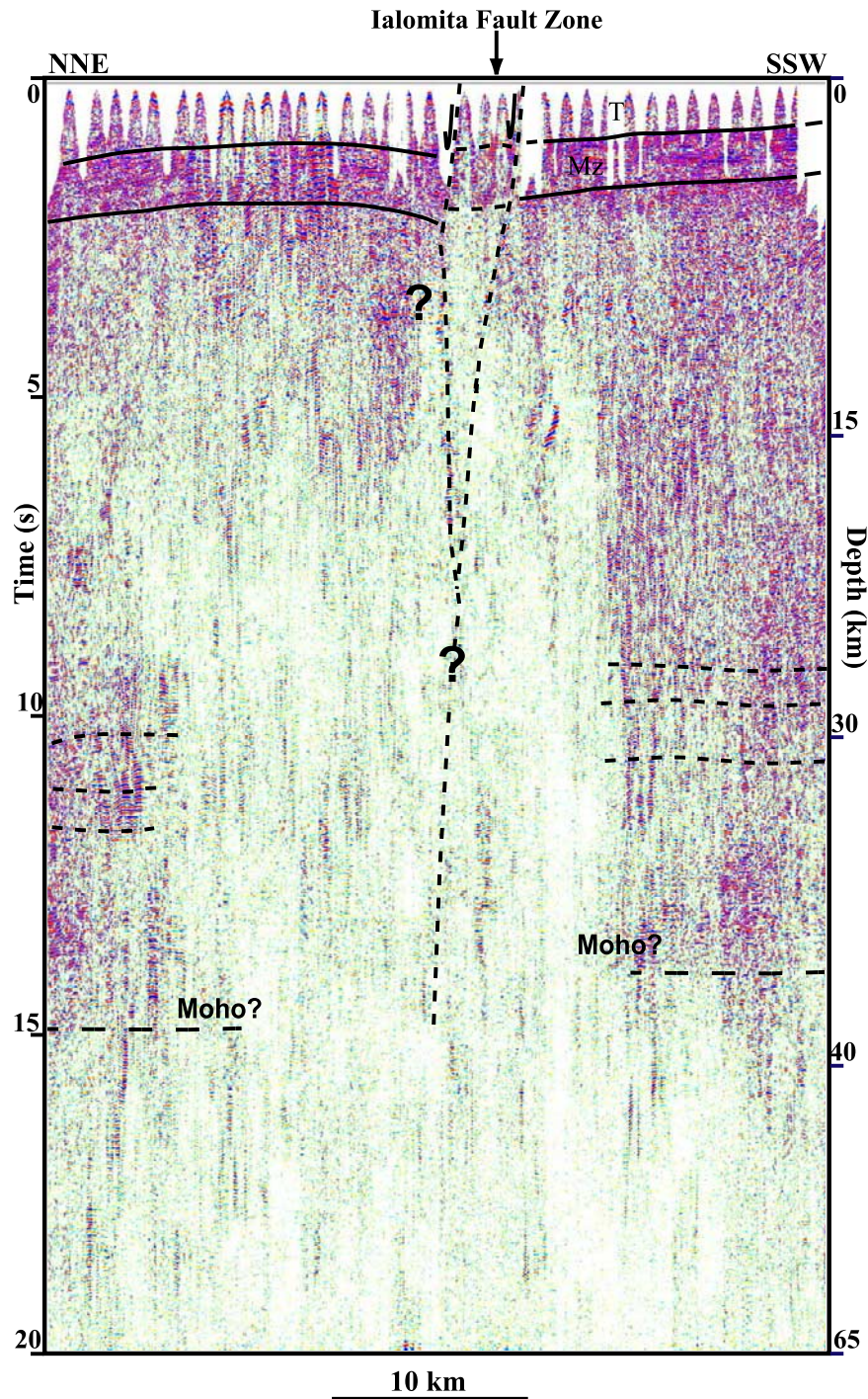
1990–2005 were analyzed in conjunction with the deep seismic profiles in order to better identify the distribution, type, geometry, and potential age of the crustal faults. The areal positioning of the relocated earthquakes [Enciu, 2007] shows two main trends: (1) clustering along the Trotus Fault and (2) a broad distribution in the middle of the Focsani Basin with a less well defined correlation with the Peceneaga-Camena Fault itself.

[49] Focal plane solutions of 18 relocated events with at least 6 clear P arrivals and magnitudes between 3 and 4 were computed with the USGS software FPFIT [Reasenber and Oppenheimer, 1985] and the results are presented in Table 3 [Enciu, 2007]. The depth extent of this group of earthquakes is between 5 and 49 km that is, crustal events. Table 3 presents these seismic events and qualifies them as either sedimentary or basement depending on their hypocenter depth. While earthquakes with depths of 7–15 km could qualify as sedimentary if they are located in the Focsani Basin (red stars in Figures 9a and 9b), events with the same depths would qualify as basement if they are located elsewhere on the East European or Moesian Platforms (blue stars in Figures 9a and 9b). Events deeper than 15 km qualify as basement earthquakes regardless of location. Figure 9a shows the map view distribution of these earthquakes, with the basement events primarily associated with the Trotus Fault, while the shallow events (sedimentary section) are primarily found in the middle of the Focsani Basin.

[50] Generally, the focal mechanisms generated from these earthquakes exhibit a strike-slip behavior often with an oblique transpressional component (Figure 9). Two events appear to have pure normal fault focal mechanisms, one located on line B, and another on the Trotus Fault, but at different depths. One purely thrust event is actually located in what is spatially defined as the VSZ. This earthquake occurs at ~47 km depth, and is consistent with the thrust mechanisms of the Vrancea mantle earthquakes although it occurs at a shallower depth than typical VSZ events.

## 6. Discussion

[51] The main goals of this study are to analyze the relationships between the interpreted geologic structures observed on the seismic profiles and the crustal seismicity, identify post-Cenozoic faults, and ultimately propose a model for the neotectonic deformation of the SE Carpathians foreland in relation to the neighboring VSZ. Given the areal distribution of the seismic reflection profiles and the relocated epicenters, we divided the study area in (a) a northern cross section that connects line D and DRACULA II seismic profiles (Figure 10a); (b) a midlatitude cross section, shown primarily along the DACIA PLAN profile but corroborated with seismic evidence from lines A and B (Figure 10b); and (c) a N-S oriented section in the south incorporating results from line C and DRACULA III profiles (Figure 10c). Seismological observations, primarily fault plane solutions of the relocated earthquakes, are integrated with the seismic reflection data.



**Figure 8.** Interpreted time and depth section of DRACULA III experimental profile showing the position of the newly imaged Ialomita Fault with surface offsets and normal character separating arcuate reflectors north of it and parallel subhorizontal reflectors south of it, a transparent crust under the faulted region, and offsets at both the midcrustal and crust-mantle boundary (Moho) level (discussion in text). Sedimentary cover is interpreted to be of Mesozoic (Mz) and Tertiary (T) age.

[52] Five of the seven seismic lines presented (from north to south, line D, DRACULA II, DACIA PLAN, lines A and B) have a perpendicular orientation to the NE-SW strike axis of the Vrancea Seismogenic Zone.

[53] Structures imaged on lines D and DRACULA II were projected on a northern cross section (Figure 10a; for location see Figure 1) with a W-E orientation, located between the two profiles but above the Trotus Fault as no

**Table 3.** Focal Plane Solutions of Relocated Seismic Events<sup>a</sup>

Date	Name	Latitude	Longitude	Depth (km)	Magnitude	Azimuth	Dip	Slip	Event Type
29 Sep 1990	A	45.2359	27.1661	7 ± 2.5	3	291	20	89	Sediments
11 Nov 1990	B	46.2464	27.4114	7 ± 1.8	3.4	66	54	117	Basement
19 Jun 1993	C	45.3304	27.253	15 ± 3.2	3.1	260	70	30	Sediments
29 Sep 1993	D	44.4357	27.253	7 ± 2.1	3.1	175	70	120	Basement
4 Oct 1993	E	44.3684	27.1008	8 ± 2.6	3	278	46	55	Basement
25 Nov 1997	F	45.5446	27.5772	8 ± 3.6	4	130	64	30	Sediments
7 Oct 1998	G	46.0104	27.4094	10 ± 1.4	3	105	90	−180	Basement
11 Mar 2002	H	45.1393	26.0779	7 ± 3.3	3.1	130	70	−120	Basement
15 Jul 2004	I	44.3005	27.1271	8 ± 0.9	3.1	135	65	−10	Basement
31 Jan 1995	J	45.54	27.2895	12 ± 2.4	3	270	75	180	Sediments
9 Jun 2005	K	45.471	27.4658	5 ± 0.3	3.3	90	60	30	Sediments
27 Oct 2005	L	45.2617	27.5991	6 ± 0.7	3.3	205	35	−70	Basement
28 Jan 1992	M	46.100	27.1403	22 ± 4.4	3.4	15	80	30	Basement
3 Mar 1992	N	46.013	27.2125	49 ± 2.4	3.4	140	25	20	Basement
6 Jan 1996	O	46.166	26.5824	17 ± 3.5	3.4	125	85	−150	Basement
29 Nov 1998	P	45.3269	26.3082	47 ± 4.6	3.6	185	30	80	Basement
28 Apr 2003	Q	46.0885	27.0647	26 ± 2.6	3.2	170	70	40	Basement
3 Dec 2005	R	46.0229	27.473	33 ± 4	4	235	80	−80	Basement

<sup>a</sup>Latitude is north, and longitude is east.

profile actually crosses the Trotus Fault. Line D shows Moho depths from east to west of ~40 km, constrained by the VRANCEA99 refraction results [Hauser *et al.*, 2001]. The DRACULA II profile located southeastward of line D reveals a Moho depth of ~43 km in the east, consistent with known values for the East European platform and ~40 km in the west, consistent with the eastern end values for line D. The step at the Moho level is potentially attributed to a Paleozoic crustal-scale fault, possibly a splay of the Peceneaga-Camena Fault.

[54] Although the new refraction results of VRANCEA2001 [Hauser *et al.*, 2007] do not show a step at the Moho level on the Peceneaga-Camena Fault, south of this cross section, there is evidence for a break and offset in the reflective character at both middle to lower crustal level and Moho level, with the same sense of motion and magnitude on the DRACULA II profile; whether this is actually related to the Peceneaga-Camena Fault or another basement fault, remains under discussion. Whatever this crustal fault is, it does not appear to offset the Tertiary section, suggesting that it is buried and no longer active.

[55] Industry seismic profiles located nearby also do not present evidence for post-Badenian deformation. The imbricate shallow structure of line D reflects its position on the external nappes of the eastern Carpathians while the upper 4 km are better imaged on the DRACULA II profile because of its location on the flat-lying sediments of the East European Platform. Despite the ~25 km distance (gap) between the two profiles, there is also good correlation at middle to lower crustal level with seemingly the same packet of reflectors at ~27–28 km on the western end of DRACULA II being imaged on the eastern end of line D at approximately the same depth.

[56] This northern crustal-scale cross section extending from the external nappes of the eastern Carpathians onto the foreland East European Platform shows the Moho at

43–40 km depth, and the inferred position of the outcropping of the Peri-Carpathian front in the gap between the two lines. One crustal seismic event can potentially be projected on the eastern end of the on the DRACULA II profile, with a thrust fault mechanism, at a basement depth of 7 km. The seismic event is in map view. Though it is associated with an interpreted fault there is no conclusive evidence that this fault continues through the crust; apparent offsets associated with this fault on the other hand, are observed in the shallow Tertiary section suggesting that this may be an unnamed active shallow fault without playing a role at a deeper crustal level.

[57] Immediately south of the DRACULA II profile is the mapped expression of the Trotus Fault. This crustal-scale fault has not been imaged on any of the two profiles as it runs parallel to them. Several crustal events occur on or very close to it. Two events appear to fall right on the fault: one with a strike-slip or oblique thrust focal mechanism at a depth of 22 km (M in Table 3 and Figure 9) and one with a pure strike-slip mechanism at a depth of 10 km (G in Table 3 and Figure 9). This is well corroborated with the strike-slip event located toward the end of the fault (event O in Figure 9), west of the Peri-Carpathian front, occurring at a depth of 17 km. This potentially indicates that the Trotus Fault is an active right lateral transtensional crustal fault that plays an active role in accommodating the stable and uplifting East European Platform from the actively subsiding Focsani Basin. This interpretation is also supported by GPS results of Van der Hoeven *et al.* [2005] which revealed a significant change in GPS vector velocities across this fault.

[58] The sense of movement on the Trotus Fault is however contrary to that inferred by Matenco [1997], and Matenco and Bertotti [2000]. They note that the Trotus Fault is a left lateral strike-slip fault mainly based on kinematic indicators from outcrops close to the prolongation

of the Trotus Fault under the East Carpathian orogen. This discrepancy could be due to the methodology used (modeling predictions, slickenside [Matenco and Bertotti, 2000] versus fault plane solutions (this study)) as well as to the site locations, availability of seismic events and the depths

prospected (shallow versus deep). Matenco *et al.* [1997] discuss a sudden change in the Bouguer gravity measurements near the Trotus Valley but observe no significant horizontal displacements in the overlying sedimentary record. Nevertheless, the Trotus Fault appears to play an

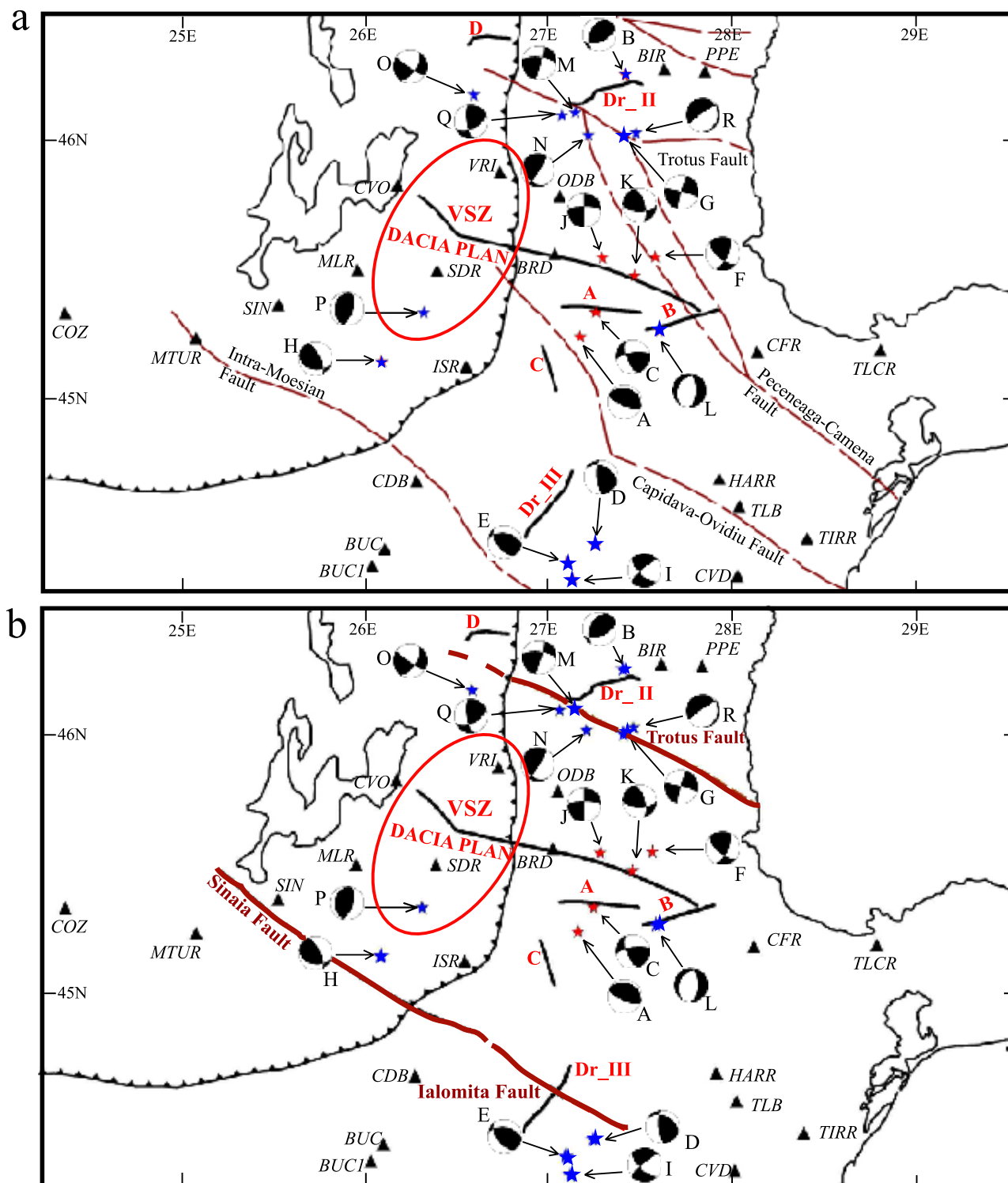


Figure 9

important role at crustal level as documented also by *Matenco et al.* [1997], who show that the E-W trending Trotus Fault is a crustal-scale fault which separates the East European Platform from the Scythian and Moesian Platform, and is most likely involved in the Pliocene subsidence of the Focsani depression and the uplift on the East European Platform.

[59] The central tectonic cross section was built on the basis of the combined and corroborative results of lines A and B and DACIA PLAN profile (Figure 10b; for location see Figure 1). Since imaged crustal structures on these profiles found very close to each other often reveal the same structures, the cross section presented in Figure 10b reflects all the crustal structures along the DACIA PLAN profile. The Focsani Basin sediments thicken from east to west, reaching a maximum sedimentary thickness of ~15 km. This fact is also well documented by *Matenco and Bertotti* [2000] and *Tărăpoancă et al.* [2003]. Underneath the basin is potentially the same imaged graben (*Panea et al.* [2005] on DACIA PLAN and *Mucuta et al.* [2006] on line A) of Mesozoic or older age. The western edge of the basin shows east dipping tilted reflectors at the contact with the Peri-Carpathian front which tilts the basin flank to an almost vertical position [*Leever et al.*, 2006]. Moho depth shows a slight eastward dip [*Panea et al.*, 2005; *Mucuta et al.*, 2006].

[60] Conspicuous is the absence of west dipping reflectors that would be required in order to support the subduction-in-place hypothesis along with a west dipping crust-mantle boundary (Moho). The reflection seismic data presented shows that this is not the case. Location of Vrancea mantle seismicity is indicated within the external nappes of the eastern Carpathians. Changes in the reflective character on both the DACIA PLAN and line B, with apparently normal displacements at the basement-cover contact were associated with the Peceneaga-Camena Fault zone. The Moho step was not imaged on the seismic data but our interpretation honors older refraction data [*Pompilian et al.*, 1993] although the newer refraction results of *Hauser et al.* [2007] interpreted no offsets in the Moho on the Peceneaga-Camena Fault.

[61] A series of seismic events (A, C, F, J, K and L) appear to correspond with the Focsani Basin, with the majority occurring in the sedimentary/shallow section, except for event L (depth 6 km) that appears to occur in the basement. Their focal mechanisms vary from strike slip (J), to reverse thrust (C and K), to pure thrust (A) and pure

normal (L). Event F (also reverse thrust) appears to occur in the crystalline basement and projects along the Peceneaga-Camena Fault but its projection comes too far out of plane to be unequivocal. These heterogeneous focal mechanisms suggest active internal activity and modern deformation within the Focsani Basin. The fact that all these events appear to occur in the shallow section (above the basement) suggest that the internal deformation is not tied to crustal-scale deformation right underneath the basin. In the alternate case that there is crustal seismicity in the basement, potentially on crustal faults for which there is no clear evidence in the seismic data, then this would argue even stronger against a detached slab model.

[62] No seismicity is associated in this part with the Peceneaga-Camena or the Capidava-Ovidiu faults. The Capidava-Ovidiu Fault is known to be inactive and presently buried underneath the basin and is not imaged on any seismic line presented. The two events that fall on the Peceneaga-Camena Fault (F and N (Figure 9b)) show a similar reverse thrust mechanism but appear to occur at different depths (F at 8 km, possibly in the shallow section and N at 49 km, apparently in the mantle).

[63] These results combined with the northern cross section indicate that the Peceneaga-Camena Fault has no significant offsets in the Tertiary (as revealed by DRACULA II results) and no clear seismicity on it. This suggests that it has not been reactivated since the Paleozoic and that it does not currently play any role in the active tectonics of the region. The results of *Bala et al.* [2003], using the earthquake catalog data also point to the fact that the Peceneaga-Camena Fault does not appear to have significant seismic activity, as do the results of *Popescu and Radulian* [2001].

[64] Moving to the south in a region bound by the Capidava-Ovidiu Fault in the north and the Intramoesian Fault in the south, the seismic data from line C and DRACULA III profile are integrated with the seismicity on a N-S cross section (Figure 10c). Line C presents a seemingly continuous crust-mantle boundary at ~40 km depth consistent with the refraction results of VRANCEA99 [*Hauser et al.*, 2001]. A thick (~8 km) package of sediments, increasing in thickness toward the north and consistent with values on line A overlies a strongly fractured basement and potentially a listric fault that might or might not affect the sedimentary sequence. The first-order observation is that the sedimentary sequence has the same reflective character throughout with parallel, subhorizontal,

**Figure 9.** (a) Study area (dashed black rectangle in Figure 1) with location of analyzed seismic profiles (A, B, C, D, Dr\_II, Dr\_III, and DACIA PLAN; shown as black lines), relocated seismicity (stars), and corresponding focal mechanisms (lower hemisphere projection). Blue stars mark basement events, and red stars represent sedimentary events; naming notation of seismic events conforms to that in Table 3. Black triangles show positions of stations that are part of the Romanian Seismic Network. The position of the VSZ (red oval) is indicated. Literature crustal faults are shown by brown dashed lines: Trotus Fault, Peceneaga-Camena Fault, Capidava-Ovidiu Fault, and Intramoesian Fault (discussion in text). (b) Study area with location of proposed and revised active crustal-scale faults Trotus and Sinaia-Ialomita shown as thick brown lines. Seismic lines and seismic events are same as in Figure 9a. We interpret that there is a compact lithospheric block containing the VSZ and Focsani Basin which is bounded by these two faults (discussion in text). We interpret that the deformation in the Vrancea Seismogenic Zone also drives the internal deformation of the Focsani Basin and argue against a slab break-off model.

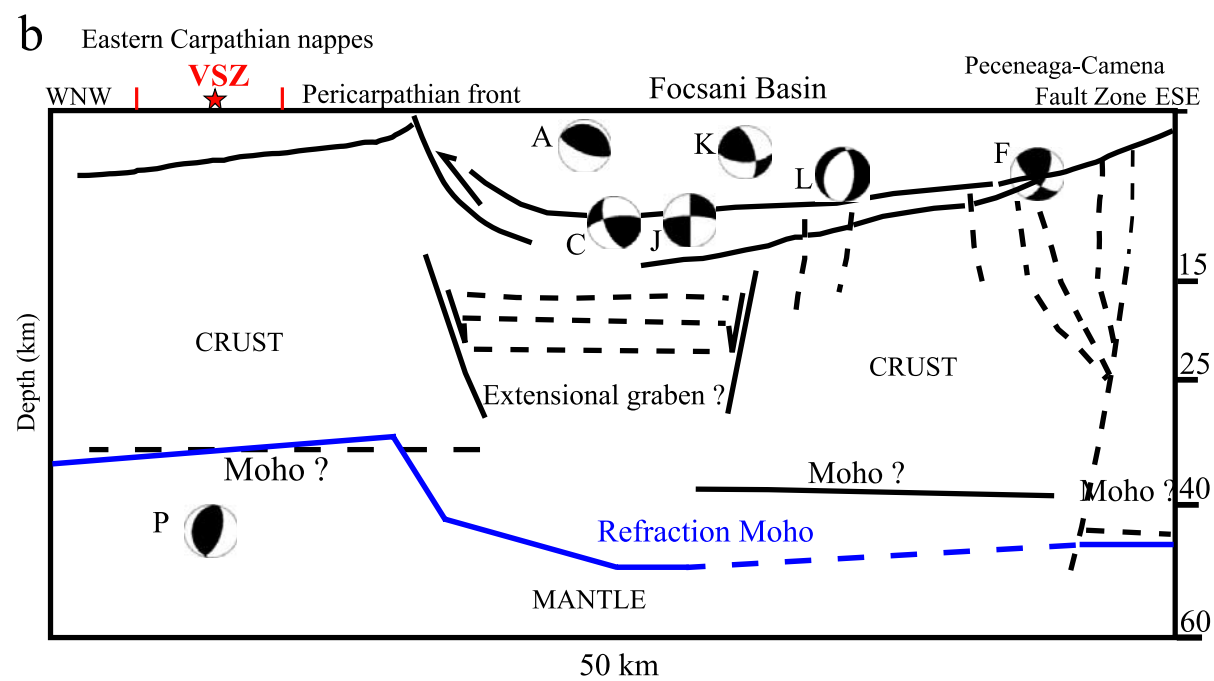
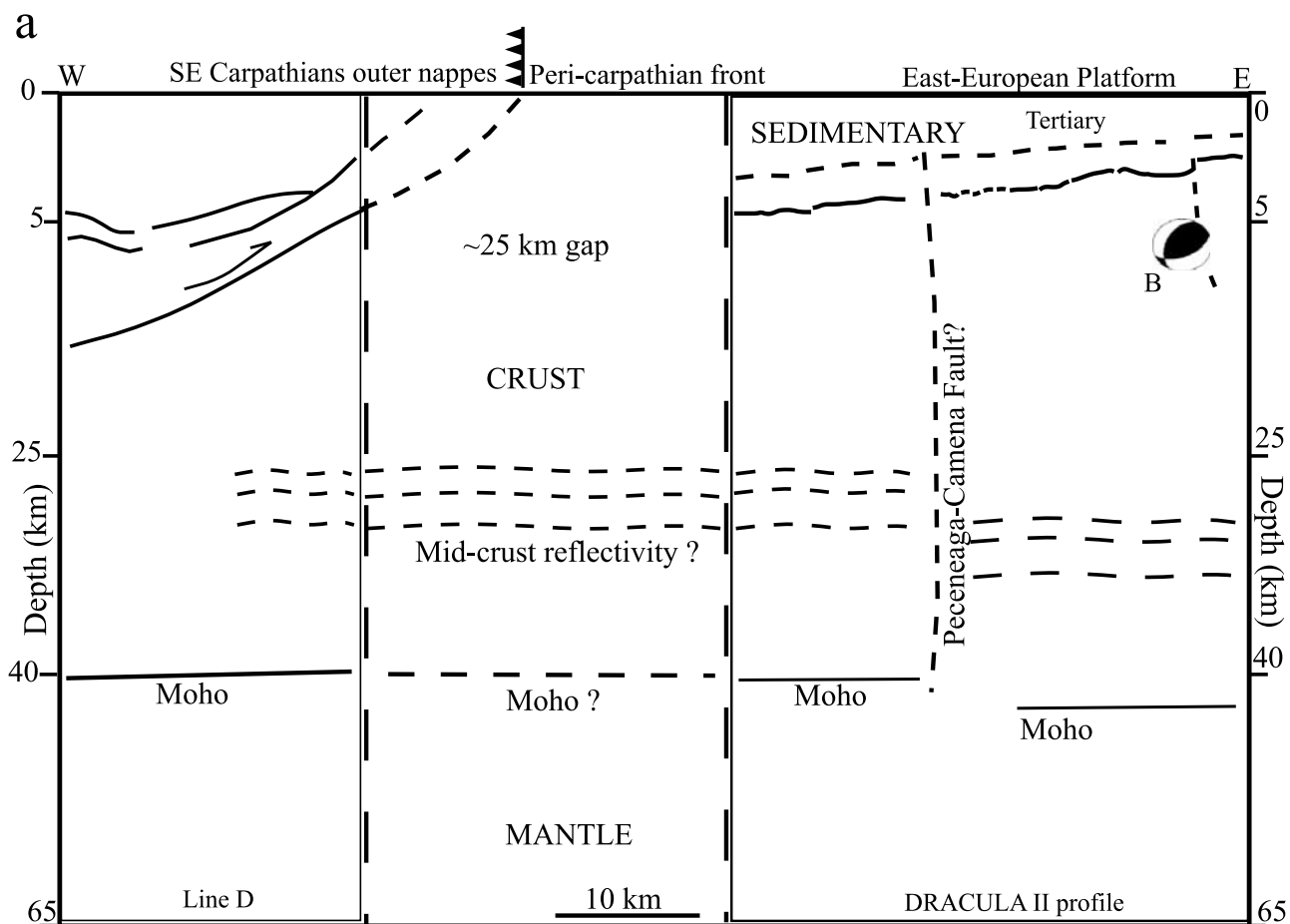


Figure 10

same amplitude reflectors suggesting lack of Tertiary disturbance. On the other hand, the DRACULA III profile reveals what appears to be a crustal-scale fault with Tertiary offsets in the upper 3–4 km, named the Ialomita Fault for the river that crosses it. A coincident escarpment was observed in the field during the 2004 acquisition of DRACULA III. Two splays of the same fault at depth appear to offset the sedimentary Tertiary section on normal faults at the surface.

[65] At depth, the fault is remarked by a conspicuous zone of transparency in the crust and offsets both at middle to lower crustal level and what is interpreted to be the crust-mantle boundary (Moho). As such, the Moho depth is placed at 38 km south of the fault and 40 km north of it. The seismic character suggests this to be a potentially active crustal-scale fault. The three events located near the profiles (events D, E, and I in Table 3 and Figure 9b) appear to occur at 7–8 km, that is, in the basement. Their focal mechanisms suggest oblique thrust for E and D and sinistral strike slip for I. However, it is ambiguous as to where to project them. Figure 10c presents this cross section with the projected imaged crustal structures. Two of the seismic events (D and E) can potentially, though nonuniquely be projected on this cross section although none occurs right on the proposed fault.

[66] Figure 9b presents an interpretation of what are believed to be the active crustal faults in the SE Carpathian foreland intimately related to both the Vrancea Seismogenic Zone and the Focsani Basin deformation. The Trotus Fault, known to be a crustal fault [Gvirtzman, 2002], appears to be presently active as inferred from the seismicity and GPS vectors [Van der Hoeven *et al.*, 2005]. It bounds both the seismogenic Vrancea area and the Focsani Basin in the north. Buried underneath the Focsani Basin, the Capidava-Ovidiu Fault does not appear to have been reactivated nor play a role in the seismotectonics of the SE Carpathians bend zone. A similar conclusion can be drawn for the Peceneaga-Camena Fault, believed to be presently inactive, both from the seismic reflection studies and seismicity presented here as well as the refraction results of VRANCEA 2001 [Hauser *et al.*, 2007]. It appears that the middle and deepest part of the Focsani Basin is affected by internal deformation at the sedimentary section level, not necessarily related to crustal-scale faults under the basin, as evidenced both by the seismicity and the reflection results.

[67] A newly proposed crustal-scale fault that appears to be presently active is the Ialomita Fault evidenced on the DRACULA III profile. This new fault appears to be a continuation of the Sinaia Fault. The Sinaia Fault is known to be seismically active mostly from the Sinaia earthquake series of 1993 [Enescu *et al.*, 1996] and has a sinistral strike-slip sense of movement (similar to that of event I) [Girbacea and Frisch, 1998]. We propose that the Sinaia-Ialomita Fault marks the southern boundary of the SE Carpathians present-day deformation.

[68] The existence of present-day movement at a crustal scale of a lithospheric block located between the Trotus [Matenco *et al.*, 1997; Gvirtzman, 2002] and Sinaia-Ialomita faults suggests that the crust and the uppermost mantle in the SE Carpathian foreland are still coupled. This finding would argue against the slab break-off hypothesis. There appears to be a coupled movement of a block located between the Trotus Fault to the north (with a dextral movement) and the proposed Sinaia-Ialomita Fault to the south (with a sinistral sense of motion). This lithospheric block contains the actively subsiding Focsani Basin which we believe is deformed by the pull of a delaminating body related to VSZ.

[69] These observations combined with the conspicuous absence of west dipping crustal reflectors and/or a west dipping crust-mantle boundary (Moho) toward the Vrancea Seismogenic Zone argue against both subduction-in-place and slab break-off hypotheses, suggesting continuity of continental crust from the foreland through the SE Carpathians bend zone. As a result, a new mechanism has to be invoked to address both the crustal deformation in the Focsani Basin and the mantle seismicity of Vrancea. Potentially continental delamination of the continental lithosphere could explain both the mantle seismicity of the VSZ and the associated foreland internal deformation.

## 7. Conclusions

[70] Results from processing and interpretation of active and passive seismic data from the SE Carpathians were integrated to understand the active deformation of the Focsani Basin and its link with the Vrancea mantle seismicity. Relocated crustal earthquakes and focal mechanisms were correlated with four deep industry seismic profiles, the reprocessed DACIA PLAN deep seismic profile, and the

**Figure 10.** (a) W-E depth cross section (yellow line 1 in Figure 1) showing projected crustal structures imaged on line D and DRACULA II profiles and the location of the Peceneaga-Camena inactive crustal fault. One seismic event is projected on this cross section, at scale (discussion in text). Despite a ~25 km gap between the two projected profiles there is good correlation at midcrustal and Moho levels. (b) WNW-ESE depth cross section (yellow line 2 in Figure 1) across the VSZ, the SE Carpathians bend zone, and the entire Focsani Basin. The cross section shows the most important features imaged on lines A and B and the DACIA PLAN profile. Foreland seismicity is projected as lower hemisphere projection of fault plane solutions for events A, C, F, J, K, L, and P, showing that most of the deformation is internal to the Focsani Basin and occurs in the sedimentary section. The refraction Moho is shown as a blue line, at scale (discussion in text). The absence of west dipping crustal reflectors argues against a westward dipping subducting slab. (c) N-S depth cross section (yellow line 3 in Figure 1) with projected imaged structures of line C and the DRACULA III profile showing the position of the proposed crustal-scale Ialomita Fault, sedimentary structures, midcrustal reflectivity, and position of the crust-mantle boundary (Moho). A gap of ~35 km in between the two profiles is indicated, and two earthquakes (D and E) are projected as lower hemisphere fault plane solutions, at scale (discussion in text). The Ialomita Fault is considered an important crustal fault.

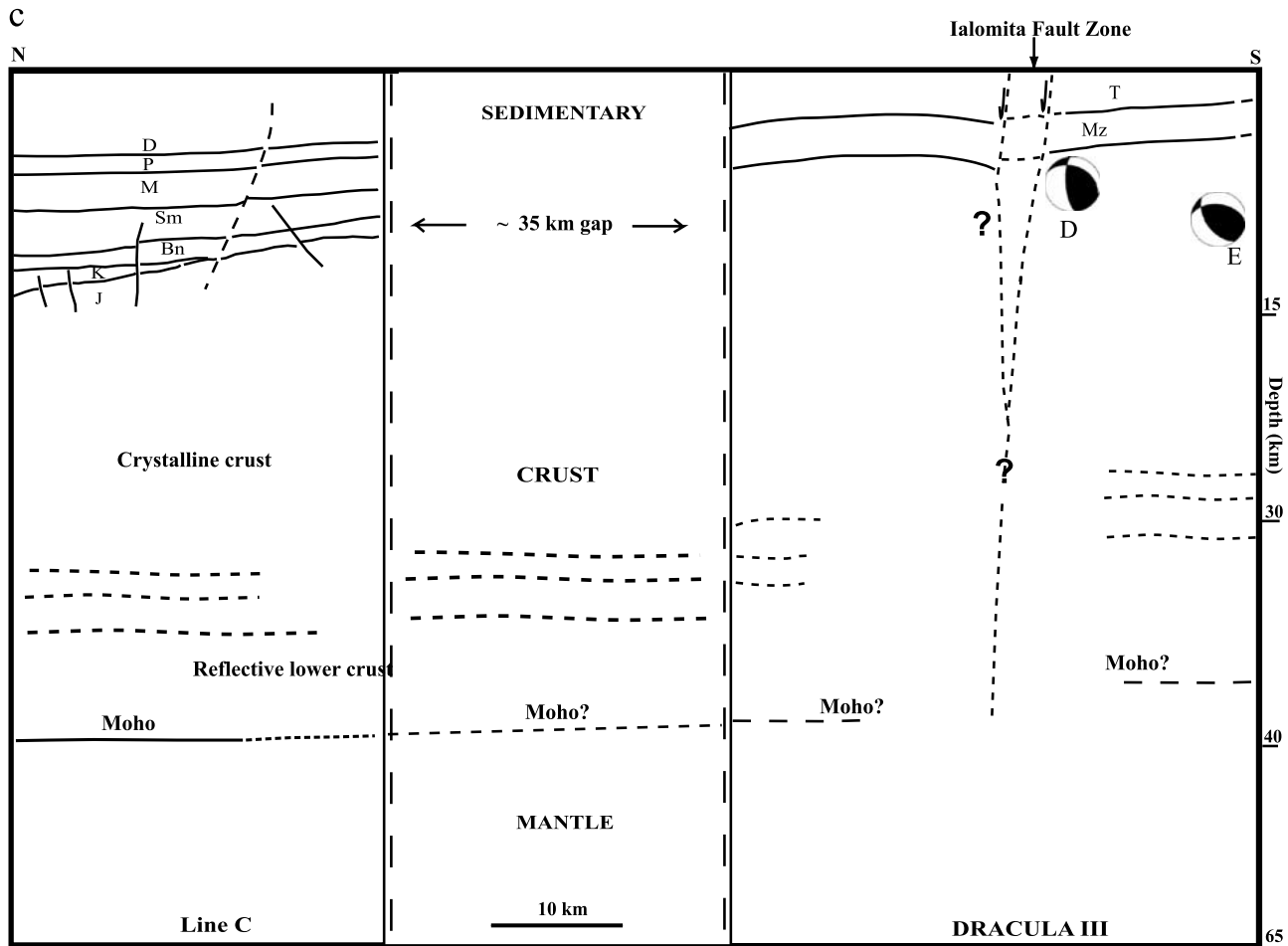


Figure 10. (continued)

DRACULA (Deep Reflection Acquisition Constraining Unusual Lithospheric Activity) II and III profiles. Projection of foreland crustal hypocenters onto the deep seismic lines correlates well with previously identified crustal faults such as the Trotus and Sinaia, as well as the newly identified Ialomita Fault.

[71] Specifically, results of this study (1) image the full crustal and uppermost mantle structure of the Focsani Basin in the close proximity of the VSZ; (2) show evidence for a subhorizontal, slightly east dipping Moho in the vicinity of the VSZ and thinning of the crust toward the Carpathian orogen; (3) illustrate the conspicuous absence of west dipping fabrics or structures in the crust and across the Moho; (4) present evidence that the Trotus Fault is a crustal-scale active fault with a dextral sense of motion; (5) suggest that the Paleozoic age Peceneaga-Camena and Capidava-Ovidiu faults have not been active in post-Paleozoic time; and (6) show evidence for a new active crustal-scale sinistral fault named the Ialomita Fault.

[72] Both the seismogenic Vrancea body and deformation in the Focsani Basin appear to be concentrically bound by the Trotus Fault in the north and east and the Sinaia-Ialomita Fault in the south, suggesting a coupled deformation be-

tween the VSZ and the foreland deformation, possibly accommodated on these two major fault systems. These results contradict both the subduction-in-place and slab break-off hypotheses as feasible explanations for VSZ intermediate-depth seismicity, and lend additional support to a lithospheric delamination model to explain both the origin of the VSZ and the crustal architecture of the southeast Carpathian foreland.

[73] Relocated hypocenters suggest active internal deformation in the Focsani Basin thick sedimentary sequence, not necessarily related to basement faults underneath the basin.

[74] The Peceneaga-Camena Fault is an old Paleozoic Fault that appears to be presently inactive. No offsets were imaged in the Tertiary section on the seismic profiles that cross it. Additionally there is no defined seismic activity on this fault to suggest that it has been reactivated post-Miocene. Similarly, known to be buried under the Focsani Basin, the Capidava-Ovidiu Fault does not play an active role today and was not imaged on any of the seismic profiles.

[75] We propose that the Trotus Fault marks the northern limit of the foreland deformation. This fault appears active

at crustal levels as indicated by the seismicity, GPS vectors and velocity discontinuity, suggesting deformation in the crust. Most likely a major crustal fault, it accommodates stresses related to the coupled uplift subsidence between the SE Carpathians and the Focsani Basin. Fault plane solutions indicate that it is a right lateral strike-slip fault, contrary to published information.

[76] We also propose that the potentially related Sinaia and Ialomita faults mark the southern boundary of this coupled deformation. There is good evidence for Tertiary deformation on the Ialomita Fault as evidenced by the DRACULA III profile. Crustal seismicity on the Sinaia Fault documents an inferred left lateral strike-slip motion.

[77] On the basis of the patterns seen in the seismic reflection data, westward oriented oceanic lithosphere subduction is not a tenable hypothesis. Moho geometry in the foreland adjacent to VSZ appears to be inconsistent with proposed models of westward oceanic lithosphere subduction to account for the mantle seismicity. The coupling

between the crust and the mantle along the Trotus and Sinaia-Ialomita faults suggests that the slab break-off hypothesis should also be reviewed. Southeastern Carpathian foreland deformation suggests a mechanical coupling of the Vrancea mantle seismogenic body with the overlying crust, arguing against a detached slab model.

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