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Near-vertical seismic reflection image using a novel acquisition technique across the Vrancea Zone and Foscani Basin, south-eastern Carpathians (Romania)

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Abstract

The DACIA PLAN (Danube and Carpathian Integrated Action on Process in the Lithosphere and Neotectonics) deep seismic sounding survey was performed in August–September 2001 in south-eastern Romania, at the same time as the regional deep refraction seismic survey VRANCEA 2001. The main goal of the experiment was to obtain new information on the deep structure of the external Carpathians nappes and the architecture of Tertiary/Quaternary basins developed within and adjacent to the seismically-active Vrancea zone, including the Focsani Basin. The seismic reflection line had a WNW–ESE orientation, running from internal East Carpathians units, across the mountainous south-eastern Carpathians, and the foreland Focsani Basin towards the Danube Delta. There were 131 shot points along the profile, with about 1 km spacing, and data were recorded with stand-alone RefTek-125s (also known as “Texans”), supplied by the University Texas at El Paso and the PASSCAL Institute. The entire line was recorded in three deployments, using about 340 receivers in the first deployment and 640 receivers in each of the other two deployments. The resulting deep seismic reflection stacks, processed to 20 s along the entire profile and to 10 s in the eastern Focsani Basin, are presented here. The regional architecture of the latter, interpreted in the context of abundant independent constraint from exploration seismic and subsurface data, is well imaged. Image quality within and beneath the thrust belt is of much poorer quality. Nevertheless, there is good evidence to suggest that a thick (~10 km) sedimentary basin having the structure of a graben and of indeterminate age underlies the westernmost part of the Focsani Basin, in the depth range 10–25 km. Most of the crustal depth seismicity observed in the Vrancea zone (as opposed to the more intense upper mantle seismicity) appears to be associated with this sedimentary basin. The sedimentary successions within this basin and other horizons visible further to the west, beneath the Carpathian nappes, suggest that the geometry of the Neogene and recent uplift observed in the Vrancea zone, likely coupled with contemporaneous rapid subsidence in the foreland, is detached from deeper levels of the crust at about 10 km depth. The Moho lies at a depth of about 40 km along the profile, its poor expression in the reflection stack being strengthened by independent estimates from the refraction data. Given the apparent thickness of the (meta)sedimentary supracrustal units, the crystalline crust beneath this area is quite thin (<20 km) supporting the hypothesis that

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there may have been delamination of (lower) continental crust in this area involved in the evolution of the seismic Vrancea zone.

Keywords: Romania; Carpathian Orogen; Vrancea zone; Focsani Basin; Seismicity; Crustal structure; Continental lithosphere

1. Introduction

An explosive source seismic experiment (DACIA-PLAN) was carried-out in August–September 2001, in Romania, at the same time as a deep regional refraction survey (VRANCEA2001; cf. Hauser et al., 2002), as part of an international collaboration between the Netherlands Research Centre for Integrated Solid Earth Sciences (ISES, represented by the Vrije Universiteit, Amsterdam), the University of Bucharest, the Romanian National Institute for Earth Physics, the University of Karlsruhe, Germany, the University of South Carolina and the University of Texas, El Paso, USA. The DACIA-PLAN seismic profile is about 140 km long and has a WNW–ESE orientation, crossing the seismically-active Vrancea zone of the south-eastern Carpathians orogenic belt and the foreland Focsani Basin (Fig. 1). The primary goal of DACIA-PLAN was the acquisition of a stacked deep seismic reflection image using a novel acquisition technique involving deployment of stand-alone seismic recorders ("Texans"/RefTek 125 s). This paper describes the processing of the recorded data to form two stacked seismic sections, one comprising a subset of the DACIA-PLAN data, focused on the upper crustal structure of the Focsani Basin, and the other a full stack of the data to a depth of 20 s TWT, in order to bring new information about the deep structure under the Vrancea zone.

The Vrancea zone, which is directly crossed by the DACIA-PLAN seismic profile, is known for its intense and persistent seismic activity comprising crustal and intermediate earthquakes, with magnitudes smaller then 7.4. It has been traditionally divided into two vertical segments (e.g., Enescu et al., 1992), which can be seen

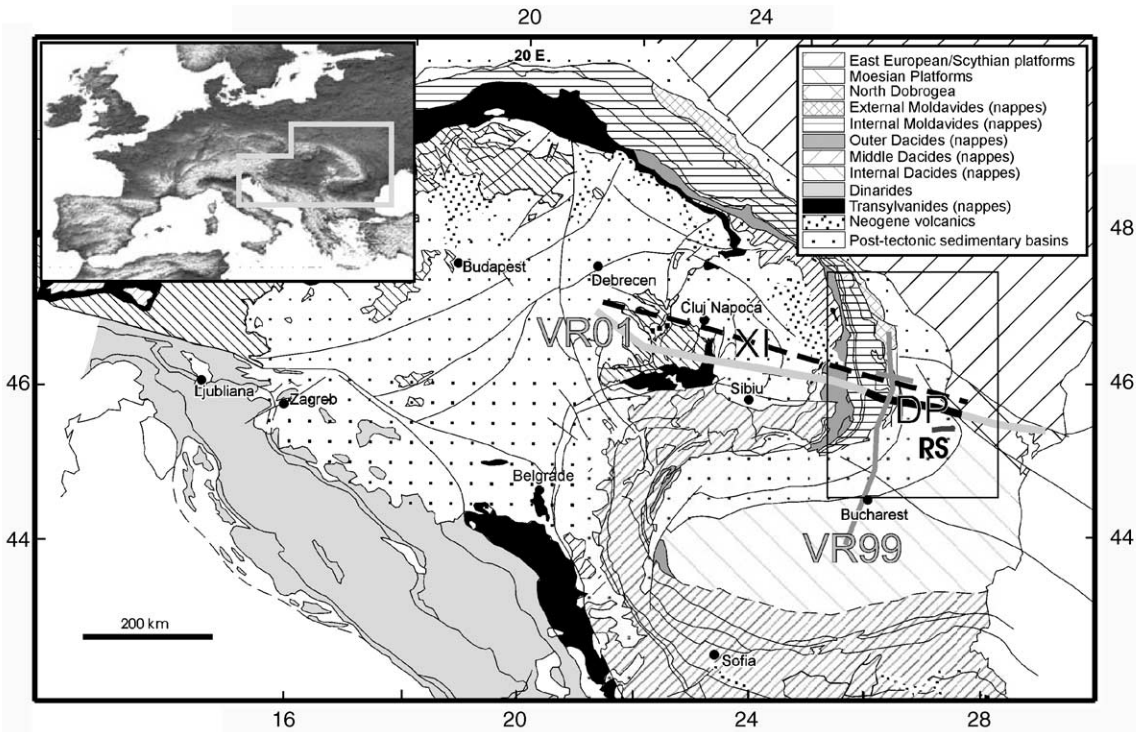

Fig. 1. Tectonic map of the Carpathians/Dinarides/Pannonian basin system in south-eastern Europe (modified after Sandulescu, 1984) showing the setting of the DACIA-PLAN profile (DP; thick black line) crossing the seismically active Vrancea zone of the south-eastern Carpathian Orogen and its foreland Focsani Basin, as well as the locations of deep refraction profiles XI (dashed black line; cf. Radulescu et al., 1976); VR99 — VRANCEA99 (thin dark grey line; cf. Hauser et al., 2001); VR01 — VRANCEA2001 (thick grey line; Hauser et al., 2002); and deep reflection profile RS — Râmnicu–Sarat (Răileanu and Diaconescu, 1998).

in Fig. 2. The first one comprises the principal zone of intermediate earthquakes with hypocentres located between 60 and 200 km depth with an epicentral area of about 40 km by 80 km (Oncescu and Bonjer, 1997). This volume forms a subvertical column and represents the main source for high energy earthquakes. The second segment, shifted east of the principal zone, is characterised by shallower earthquakes, with hypocentres between 20 and 60 km, and moderate magnitudes (≤5.6), which are considered to be “crustal events”. These two segments are separated between 40–70 km depth by an apparent seismic gap (Fuchs et al., 1979; Oncescu and Bonjer, 1997). Several hypotheses, implying various deep crustal geometries, have been proposed in order to explain the intermediate seismic activity in Vrancea zone (cf. Kiratzi, 1993; Wenzel et al., 1998, 2002; Cloetingh et al., 2004; Sperner et al., 2004; Knapp et al., 2005—this volume). Knapp et al. (2005—this volume) suggest that this area may uniquely offer evidence for the occurrence of active lithospheric delamination. Chalot-Prat and Girbacea (2000), based largely on geochemical characteristics of magmatic rocks, proposed a geodynamic model for the Mid-Miocene to Quaternary evolution of the south-eastern Carpathians in which an intra-mantle delamination process was initiated at the northern end of the East Carpathians at 9.4 Ma and then propagated laterally, normal to the strike of the delaminated slab, following the curvature of the Carpathian arc from north-west to south-east.

The study area has been investigated by a limited number of other deep seismic reflection and refraction surveys (e.g., Enescu et al., 1972; Rădulescu et al., 1976; Răileanu et al., 1994; Răileanu and Diaconescu, 1998) as well as by extensive exploration scale reflection profiling in the foreland and easternmost thrust belt segments of the DACIA-PLAN profile (e.g., Dicea, 1995; Stefanescu et al., 2000; Tărăpoancă et al., 2003). No seismic reflection profiling previously existed to the west of the Subcarpathians Nappe (see Fig. 3). Deep Seismic Sounding profiles, including Profile XI, which is subparallel and nearly (partially) coincident with the DACIA-PLAN profile (Fig. 1), were acquired in this part of Romania during the years 1970–1974. The broad crustal geometry shown in Fig. 2 is derived from the XI profile, which was designed to record refracted arrivals from the sedimentary cover-basement horizon as well as the Conrad and Moho discontinuities. These data indicated a thickness of 12 km for the Focsani Basin adjacent to the Vrancea zone (Rădulescu et al., 1976), consistent with modern seismic interpretations (Tărăpoancă et al., 2003), and reveal lateral crustal heterogeneity across the Peceneaga–Camena and Capi-

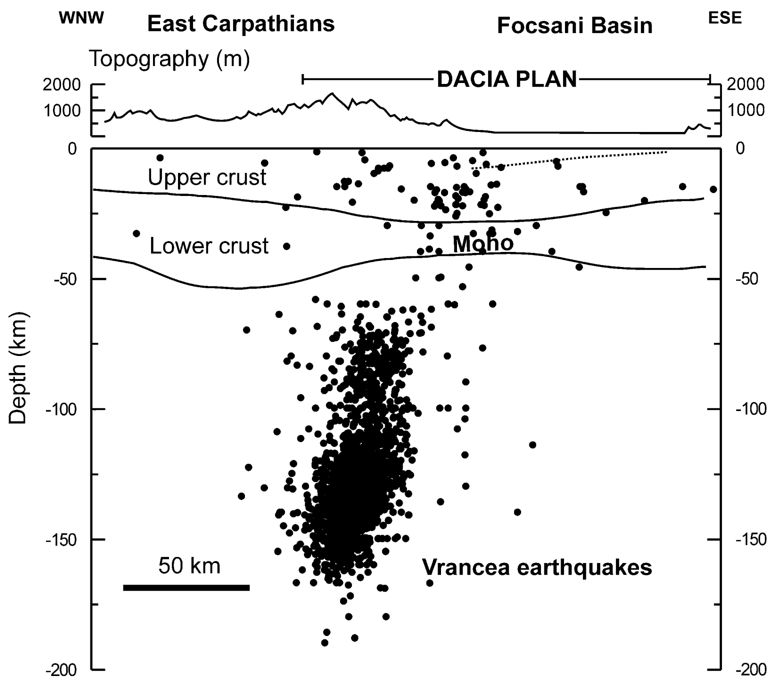

Fig. 2. Lithosphere scale cross-section across the east Carpathians from Radulescu et al. (1976). Solid dots represent earthquake hypocentres projected onto the plane of the cross-section within a corridor approx. 100 km wide. The location of the cross-section is shown in Fig. 1 (profile XI). Also indicated are topography and the position of the DACIA-PLAN seismic profile. The dashed line in the foreland upper crust represents the approximate depth to the base of Neogene sediments in the Focsani Basin.

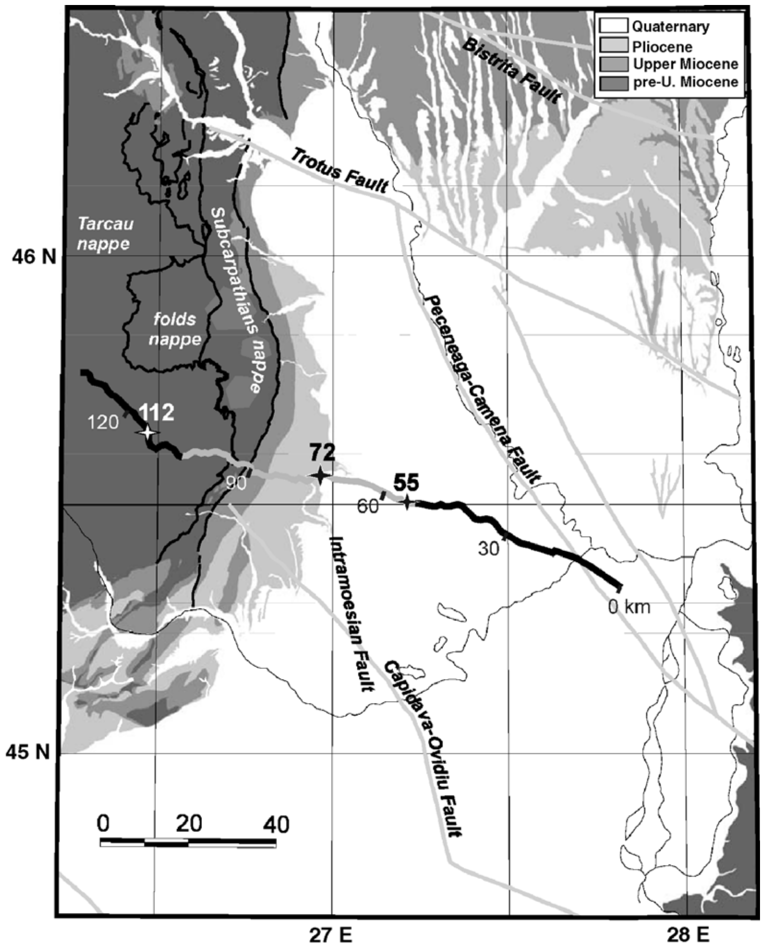

Fig. 3. Geological map of the south-eastern Carpathians, from Matenco (2003), with the location of the DACIA-PLAN seismic survey with the separate recorder deployments 1–3 indicated (black/grey/black segments). Raw and processed versions of shot gathers for shots 55, 72, and 112 (white and black stars) are shown in subsequent figures and discussed in the text.

dava–Ovidiu faults (Fig. 1). Among a series of experimental deep seismic reflection profiles of limited length acquired in the 1990s is the Râmnicu–Sarat profile (Fig. 1) on the centre-eastern flank of the Focsani Basin.

Two regional refraction/wide-angle surveys—VRANCEA99 and VRANCEA2001 (the latter acquired in conjunction with DACIA-PLAN)—were recently carried out in order to study the crustal and uppermost mantle structure of the Vrancea zone and surroundings. The VRANCEA99 profile (Hauser et al., 2001), 300 km long running in NNE–SSW direction (Fig. 1), revealed an upper crust characterised by velocities of 5.9–6.2 km/s and a lower crust defined by a velocity range 6.7–7.0 km/s separated by an intra-crustal discontinuity between 18–31 km depth. The depth to the Moho increases from 38 km at the northern end of the profile to 41 km beneath the Vrancea zone (where it crosses the DACIA-PLAN profile). Towards the southern end the depth to the Moho decreases again to about 30 km (Hauser et al., 2001).

Preliminary analysis of the VRANCEA2001 profile (Hauser et al., 2002) indicates a thickening of the sedimentary cover of the Focsani Basin, from east to west and a Moho depth under the Carpathians of about 40 km. The latter was based partly on the presence of a strong reflection from the crust–mantle boundary although, in general, seismic energy was highly attenuated in the Carpathian belt, related to structural complexity in the shallow geology. Tomographic travel-time inversion (Holle, 1992) of first arrivals along the VRANCEA2001 profile gave crustal velocities increasing up to 5.6 km/s above 10 km depth in the western part of line and similar velocities at depths less 20 km for central part (Hauser et al., 2002). A higher resolution velocity model of the upper crust from tomographic inversion of first arrival data along the DACIA-PLAN profile (Bocin et al., 2005—this volume) accurately images the transition from sediment to crystalline basement beneath the Focsani Basin, where industry seismic data are available for correlation, at depths down to about 10 km. Beneath the external Carpathians nappes, material with velocities >5.5 km/s and with apparent structural heterogeneity lies at depths as shallow as 3–4 km, which is less than previously surmised on the basis of geological observations.

2. Geological setting

The south-eastern Carpathians consist of imbricated thrust sheets of different ages belonging to the Romanian segment of the Carpathian Orogen, a highly arcuate belt formed between the European and Apulian plates and related microplates during Alpine orogenesis (Csontos et al., 1992; Girbacea and Frisch, 1998; Nemcock et al., 1998; Matenco et al., 2003). The present geometry of the south-east Carpathians is thought to be the result of the Tertiary collision between the Tisza–Dacia microcontinents (upper plate) and the European Plate (senso largo — lower plate), possibly preceded by a roll-back of the subduction zone (Royden, 1988, 1993) and closure of a basin floored by oceanic lithosphere (Csontos, 1995; Linzer, 1996). It is assumed that plate convergence ceased during the Sarmatian, at about 10 Ma (Săndulescu, 1988; Roure et al., 1993). The DACIA-PLAN profile has a WNW–ESE orientation and crosses both the external part of the south-eastern Carpathians nappe stack and its foreland units. The traversed nappe pile consists of the “external Moldavides system” (Săndulescu, 1988), which comprises thin skinned Lower Cretaceous–Miocene nappes, including the Tarcău, Marginal Folds, and Subcarpathian nappes (cf. Fig. 3). To the south-east, the profile crosses the Moesian Platform and the westward extension of the North Dobrogean orogen, which are separated by the crustal scale Peceneaga–Camena Fault (cf. Fig. 3).

The Tarcău and Marginal Folds nappes are made up mainly of Cretaceous marine basin sediments and Paleogene to Neogene flysch and other clastic sedimentary deposits. The Subcarpathian Nappe consists mainly of molasse, syn- and post-tectonic basin fill type sediments, deposited in a shallow marine to brackish environment. These nappes contain shales and sandstones with subordinate marls, limestones, tuffs, and conglomerates. In addition, the Marginal Folds and Subcarpathian nappes contain lower and middle Miocene evaporitic formations including salt and gypsum (e.g., Stefanescu et al., 2000). Previous geological and geophysical studies have suggested a thickness of about 8 km for the nappe stack in the area crossed by the DACIA-PLAN profile (e.g., Matenco and Bertotti, 2000). This was based on limited industry reflection seismic data and magnetotelluric surveys as well as geological cross-sections derived from the surface geology and some borehole data (Cornea et al., 1981; Demetrescu, 1982; Rădulescu and Răileanu, 1981; Rădulescu et al., 1984; Rădulescu, 1988; Enescu et al., 1988, 1993; Stănica et al., 1986; Răileanu et al., 1994; Matenco and Bertotti, 2000). However, the subsurface structure of the nappes is generally still under debate. As mentioned above, an upper crustal velocity model based on tomographic travel-time inversion of DACIA-PLAN first arrivals suggest that basement may be shallower than 8 km, perhaps less than 5 km beneath the westernmost segment of the DACIA-PLAN profile (Bocin et al., 2005—this volume).

The Carpathian foredeep, developed in the front of the eastern and southern Carpathians is a syn- and post-orogenic depression; it forms a wedge of clastic rocks (molasse–conglomerates, shale and sandstones) and evaporites that thickens from east to west, towards the thrust belt. Its width ranges from about 10 km in the northern part of the eastern Carpathians, to more than 100 km at the southern Carpathian belt (Fig. 1). The thickest sediments are in the Focsani Basin, adjacent to the south-eastern Carpathians, where Pliocene–Miocene deposits are thought to be about 13 km thick (Tărăpoancă et al., 2003). However, the Focsani Basin displays unusual characteristics, compared with typical foredeep basins, in that more than half of its sedimentary succession was deposited after the cessation of thrusting. In addition, the two basin flanks display a symmetrical, syncline-type geometry rather than that of a typical wedge-shape foredeep (see Bertotti et al., 2003; Tărăpoancă et al., 2003 for more detailed descriptions). The contact zone between orogen and foredeep in the vicinity of the DACIA-PLAN profile is traditionally considered as a blind thrust, unconformably overlain by latest Miocene–Pliocene post-tectonic cover, this being indicative of the cessation of thrusting. However, the overall position and tilting of the sediments and particularly the eastward dip of the Upper Sarmatian unit suggest that the frontal contact between the orogen and the foredeep is a backthrust (Matenco and Bertotti, 2000). As a result, in the frontal area a triangle zone is formed, with the backthrust compensating displacement on a basal sole thrust, which is called the Pericarpathian Fault (senso Săndulescu, 1988).

The structure of the Carpathian foreland in the area of the DACIA-PLAN profile is composed of two, internally complex, relatively stable areas, the East European/Scythian and Moesian platforms, separated by the North Dobrogea orogenic zone (Fig. 1; further details in Săndulescu and Visarion, 1988; Visarion et al., 1988). The

East European and Scythian units are north of the Trotus Fault (Fig. 3), characterised by a thick crust (40–45 km, Enescu et al., 1992). South of the Trotus and west of the Peceneaga–Camena faults (Fig. 3), the Moesian block comprises a 35–40 km thick (Rădulescu, 1988) Precambrian-aged crustal unit (Săndulescu, 1984), buried under up to 13 km of Middle Miocene to Quaternary sediments. The Peceneaga–Camena Fault separates the North Dobrogea and Moesian units, with an estimated decrease in the crustal thickness of the latter of 10 km, as indicated by DSS profile XI (Rădulescu et al., 1976). This fault has been repeatedly displaced during the late Alpine evolution of the overlying foredeep (e.g., Tărăpoancă et al., 2003) and is currently active as part of a broad normal fault system with Moesia as the hangingwall (e.g., Matenco et al., 2005), with events occurring from its Black Sea extension all the way to the junction with the Trotus Fault system.

3. Seismic data — field acquisition, processing, and results

DACIA-PLAN deep seismic reflection profile crosses the Vrancea zone in a WNW–ESE direction, with elevations along its 140 km length as high as about 1240 m, over the mountainous zone in the north-west, to only about 40 m in south-eastern part of profile. Recording was carried out in three independent but overlapping (5–10 km) segments, deployments 1, 2, and 3, from west to east. Record length was 90 s with a sampling interval of 5 ms. Acquisition parameters are summarised in Table 1.

In general, the upper 7 s of data contain higher frequencies and many more coherent reflections than data recorded at greater times. This is particularly true for deployment 3, in the foreland Focsani Basin, where signal-to-noise ratio is much better than for deployments 2 and 3. Processing, therefore, was carried out as two independent streams leading to two separate CDP stacks, one focused on the foreland sedimentary and upper crustal architecture utilising the shallow (<10 s) deployment 3 data only, and the other aimed at a whole crust/upper mantle image along the entire DACIA-PLAN profile. Processing parameters are described in Tables 2 and 3, and discussed separately in the sub-sections below.

3.1. “*Partial stack*” (*deployment 3, time interval 0–10 s*)

Data from deployment 3 (57 shots) were processed independently to form a “partial stack” that provides the best possible image of the architecture of the foreland

Table 1
Acquisition parameters for DACIA-PLAN profile

Item	Parameter
Seismic source	Dynamite (28 kg/shot)
Source spacing	~1 km
Shot depth	20 m
No. of shots/deployment	29/deployment 1 47/deployment 2 55/deployment 3
Receivers	OYO 4,5 Hz
Data acquisition system	1D RefTek-125s
Receiver spacing	~100 m
No. of receivers/deployment	334/deployment 1 637/deployment 2 632/deployment 3
Record length	90 s
Sampling interval	5 ms
Length of profile	~140 km (WNW-ESE direction)

Table 2
The processing sequence used to produce the “partial stack” (deployment 3 only)

Processing sequence	Parameters
Input seismic data	10 s length sampling interval 10 ms
Geometry and static corrections	Replacement velocity 1600m/s Final datum 1000 m
Trace balancing	Time window = 5 s
Bandpass filter	Butterworth (4–24 Hz, 70 dB/octave)
Fx deconvolution filter	Yes
Top muting	Removal refractions
Build a 2D velocity model	Refraction data and 1D velocity laws from boreholes
NMO corrections	Yes
Stacking	Yes

Table 3
The processing sequence used to produce the “full stack” (0–20 s)

Processing sequence	Parameters
Input seismic data	20 s length, resampled to 8 ms
Crooked line geometry	Bin size 50 × 4500 m
Static corrections	Replacement velocity 1600 m/s Final datum 0 m
Time variant scaling	Time windows: 0–1; 0.5–3; 2–5; 4–10; 9–15; 14–20; 19–30 s
True amplitude recovery	Trace window 10 s
Trace equalisation	Trace window 20 s
Time variant bandpass filter	Ormsby: 0–7 s/6–10–45–50; 6–12 s/4–8–40–45; 11–30 s/4–6–15–20
Air blast attenuation	Velocity: 320; 340 m/s
FX deconvolution	Wiener Levinson filter
2D spatial filtering	2D Convolutional filter
Automatic gain control	Time window 2 s
Top muting	Removal of refracted arrivals
Velocity analysis	Yes
NMO correction	Yes
Residual/fractional statics	Yes
Stacking	Yes

Focsani Basin. The processing sequence is displayed in Table 2.

Fig. 4 shows a raw shot gather recorded at the westernmost end of deployment 3 (shot 55, see Fig. 3 for location). Sedimentary interfaces within the Focsani Basin are responsible for the presence of a packet of clear reflected and refracted waves. The main coherent-noise is represented as a cone of events interpreted as surface waves (Rayleigh-type, "ground-roll"); these are characterised by a frequency interval ranging between 2–12 Hz and apparent velocities of 110–380 m/s. The seismic data were recorded in one static deployment of about 60 km length with shots "rolling along" rather than receivers. The maximum offsets lie in the range ~5–60 km depending on shot position within the receiver deployment. For further processing and stacking a maximum offset window −10 to +10 km was adopted, this being constrained by the lateral extent of the observed reflection events. Elevation static corrections were applied after geometry set-up, trace editing (kill, reverse traces), and top muting (to remove refracted phases). This was done assuming a replacement velocity of 1600 m/s (based on apparent velocities observed at small offsets) and a final datum of 100 m. The effect of a low-velocity weathered layer, given the observed apparent velocities, was assumed to be negligible. This was followed by a bandpass filter (Butterworth, 4–24 Hz with 70 dB/octave), based on an analysis of the characteristics of coherent events of interest, FX deconvolution (to remove "ground roll") and, finally, trace balancing (5 s window). The result, for shot 55, is shown in Fig. 5, where it can be compared to the raw shot gather (Fig. 4).

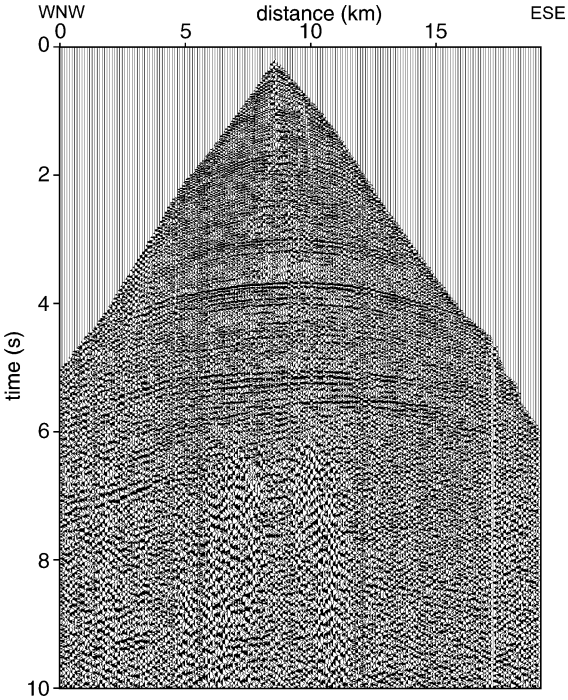

Fig. 5. Processed shot gather (cf. Table 2) for shot 55, recorded in deployment 3 (Focsani Basin). The surface wave cone and refracted waves seen in Fig. 4 are removed by filtering and top muting. Processing has been applied only to a −10 to +10 km offset window.

What are presumably sedimentary horizons show good reflectivity, with clear and continuous events down to about 6 s; strong coherent events deeper than this are seen but are short and discontinuous (Fig. 5). A

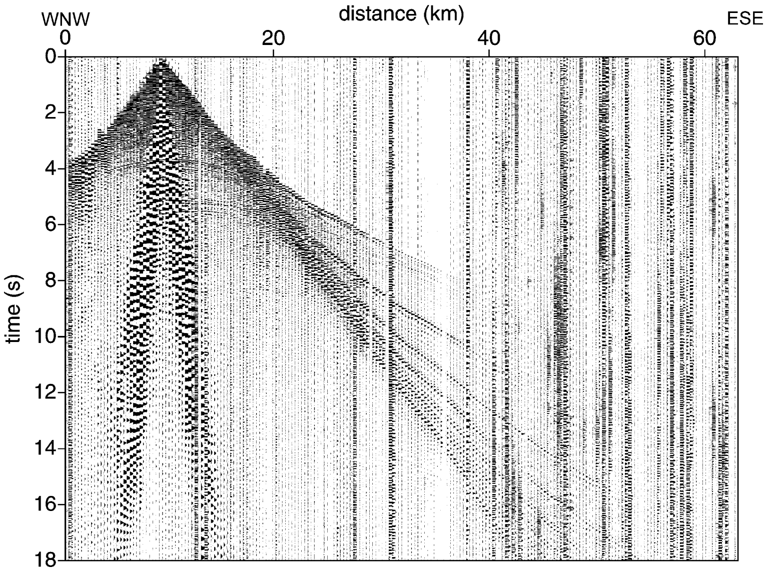

Fig. 4. Raw shot gather for shot 55, recorded in the foredeep area (Focsani Basin) showing clear reflections down to 6 s.

rigorous velocity analysis proved problematic due to the lack of coherent events at depth. Nevertheless, a velocity model for move-out and stacking was built from a preliminary interpretation of the coincident refraction profile (i.e., VRANCEA 2001 — Hauser et al., 2002) and from velocity data from nearby boreholes (e.g., Tărăpoancă et al., 2003). The final "partial stack" is shown in Fig. 6a.

3.2. "*Full stack*" *(all deployments, time interval 0–20 s)*

The purpose of the "full stack", based on 20 s of data for all three deployments, was to provide the best possible image of the crustal architecture of the external south-eastern Carpathians and its foreland. The processing sequence is displayed in Table 3.

Processing was carried out using "crooked line geometry" with an inline bin size of 50 m and a cross-line size of 4500m, providing the maximum CDP coverage possible. The locations of bins compared to line geometry as well as CDP fold distribution are displayed in Fig. 7. Maximum fold is about 60, in the central part of deployment 3. Thanks to the overlap of receiver deployments, the fold is of 5–10 between deployments. Receiver and shot statics were calculated using a datum

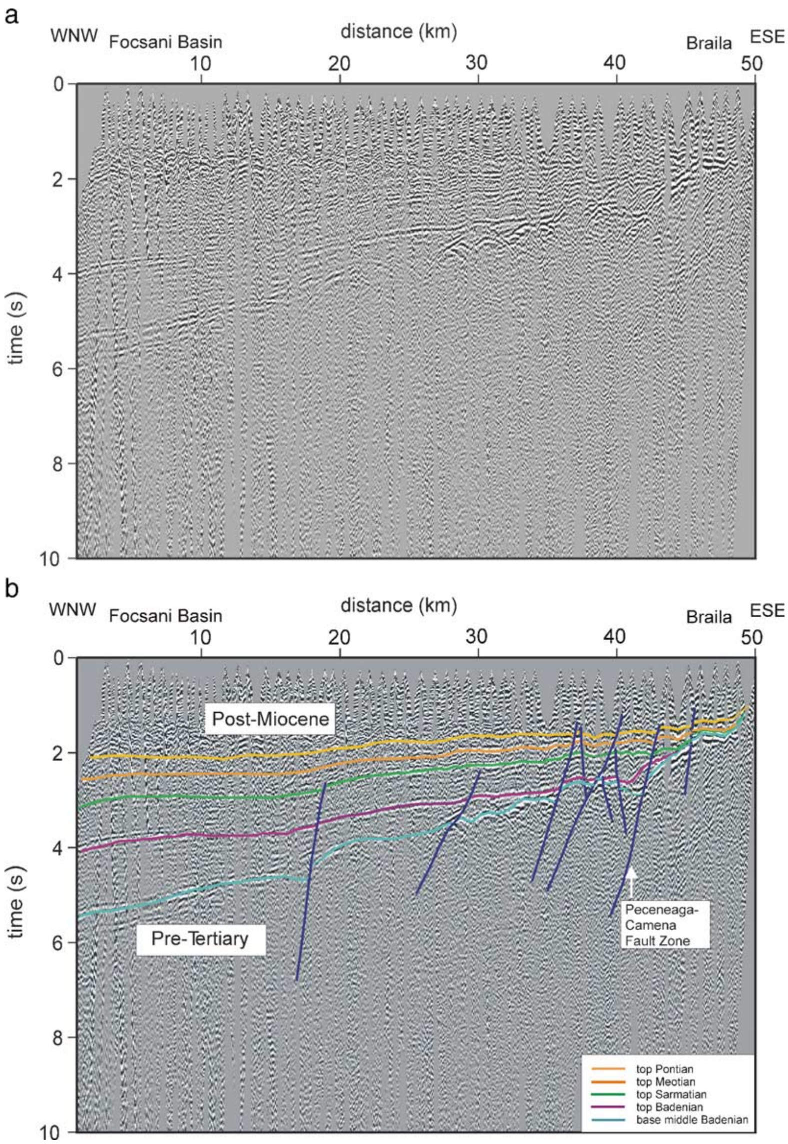

Fig. 6. (a) Uninterpreted and (b) interpreted time seismic sections obtained for the eastern segment (deployment 3) of DACIA-PLAN profile (processed to 10 s). The interpretation of sedimentary horizons within the Focsani Basin conforms with Tărăpoancă et al. (2003).

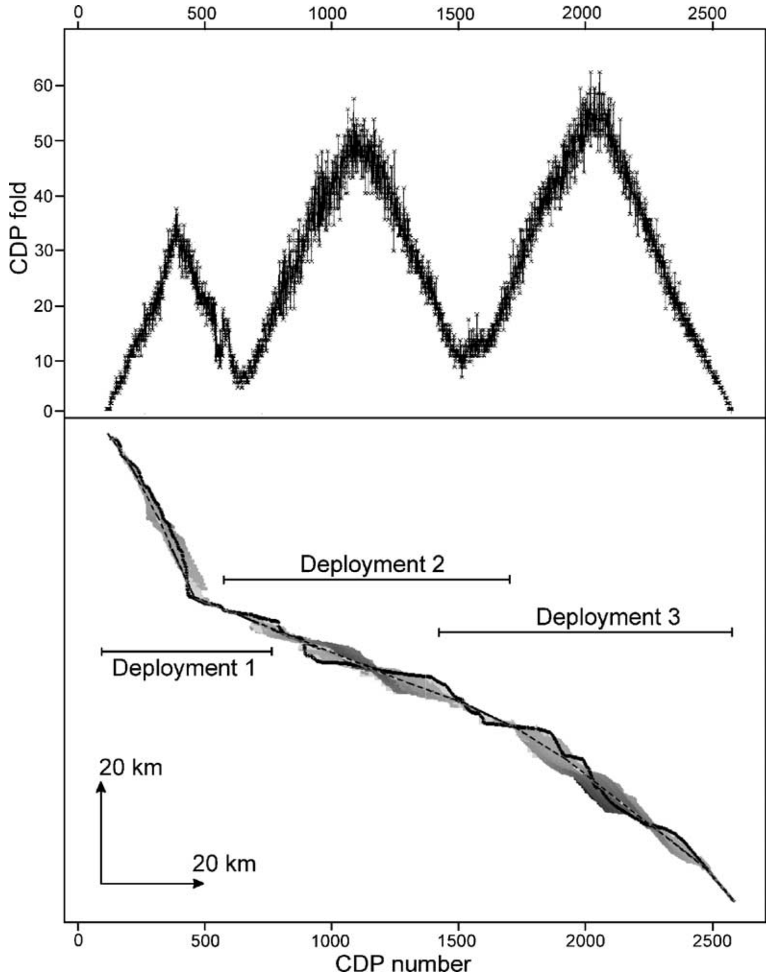

Fig. 7. The (crooked) acquisition line (black line, comprising dots representing shotpoints), the trace of the "crooked line geometry" processed stack (dashed line; cross-line bin extends to 2250 m on either side), the number of CDPs per bin (the darker the grey the higher the number of CDPs), all in the lower panel, and CDP fold along the profile (upper panel).

of 0 m, a weathering layer velocity of 500 m/s, and a replacement velocity of 1600 m/s.

Data quality is highly variable along the seismic line. Although reflected phases are well imaged from the sub-horizontal sedimentary deposits of the Focsani Basin in deployment 3 (cf. Section 3.1), well resolved reflected phases are scarce to absent in shot gathers within the more geologically complicated sedimentary nappes of the south-eastern Carpathians. Among the worst of the recorded shot gathers is 112, shown in Fig. 8. Although first arrivals are easily seen out to an offset of about 15 km (cf. Bocin et al., 2005—this volume), no reflected phases can be identified, in part because of the wide surface wave cone. A time variant bandpass filter (8–24 Hz), true amplitude recovery, and trace balancing were applied but the surface wave cone was not significantly suppressed. Furthermore, because of the spatial aliasing intrinsic to the acquisition geometry, ground-roll was also not attenuated by (f,k)-domain filtering. Subsequent steps consisted of top-muting followed by FX deconvolution and 2D spatial filtering, and the result for shot 112 is shown in Fig. 9a.

Fig. 9b and c show filtered shot gathers (i.e., Table 3) for deployment 2 (shot 72; cf. Fig. 3) and deployment 3 (shot 55; cf. Fig. 3), respectively. Fig. 9c differs from Fig. 5 in terms of processing stream and processed record length. Besides the intra-basinal reflectors in Fig. 9c (Section 3.1), there are clear coherent events within the basement to a depth of about 12 s. Some coherent energy can be seen on the filtered shot gather 72 between 6–11 s (see Fig. 9b).

Data quality and the imaging of discrete coherent reflection events in the filtered shot gathers deteriorate from east to west (foreland basin to thrust belt) and the

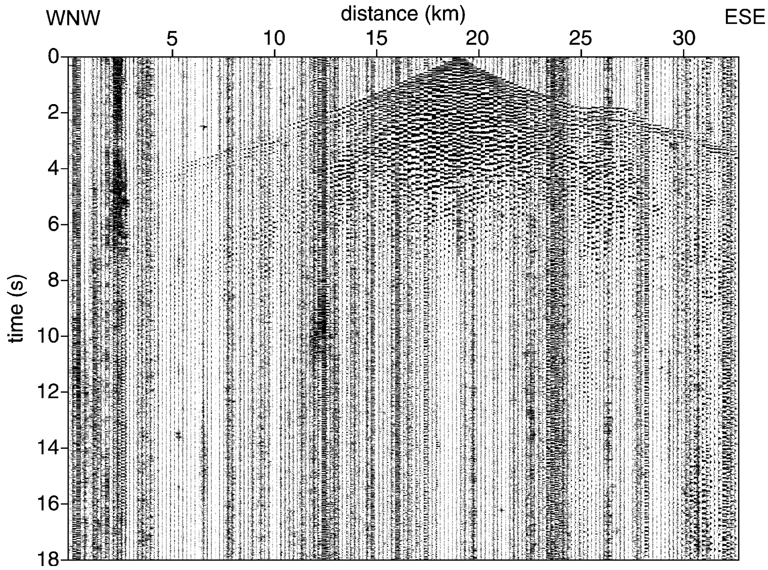

Fig. 8. Raw shot gather for shot 112, recorded in deployment 1 (western part of DACIA-PLAN, within the Vrancea zone), showing a large cone of surface waves and a lack of reflected phases.

effect of this is seen in the final stacked DACIA-PLAN section in Fig. 10a.

4. Interpretation and discussion

The final "partial stack" is shown in Fig. 6a and its interpretation in Fig. 6b. Thickening of the highly reflective sedimentary succession (Focsani Basin) towards the Carpathian thrust front to the west is clearly seen. It increases from 2.2 s in the east to about 6 s in the west. Following the interpretation of Tărăpoancă et al. (2003) and Tărăpoancă (2004), which conform to interpretations from industry seismic profiling in the Carpathian foreland, the imaged sedimentary succession is Neogene and younger. Its oldest horizon, overlying pre-Tertiary basement, is thought to be of Middle–Late Miocene age (Badenian). The uppermost 1–2 s of the section, having a saw-tooth shape as an artifact of the processing stream, comprises Pliocene and Quaternary sediments. The top of the basement is locally visible (especially on the right half of the partial stack, see Fig. 6ab); its interrupted discontinuity on the seismic section is interpreted to be an effect of a high level of fracturing and, according to Răileanu and Diaconescu (1998), the possible presence of local intrusive bodies (on the eastern half of deployment 3, see Fig. 6ab).

The interpreted DACIA-PLAN full stack is shown in Fig. 10b. It reveals, unambiguously given the mapped surface geology and shallow exploration seismic lines from the area (Dicea, 1995; Leever et al., 2003; Forest Oil International, pers. comm.), the upwardly flexed western margin of the basin. The fault systems known to offset the base of the basin in its eastern extreme, correlated with the Peceneaga–Camena Fault, are generally thought to be of crustal-scale (e.g., Rădulescu et al., 1976) but the DACIA-PLAN data do not display any evidence that can support or, for that matter, refute this.

There is clear evidence in the DACIA-PLAN full stack for sedimentary successions beneath the Focsani Basin west of approximately common depth point (CDP) no. 1000, in the time range 4–8 s, laterally adjacent to transparent crust further east. The velocity within this sedimentary package ranges from 5.2 to 5.8 km/s, based on the VRANCEA2001 model (cf. Fig. 3; Hauser et al., 2002; DACIA-PLAN is located approximately between shotpoints U and R). Accordingly, the total thickness of the package is more 10 km, lying roughly in the depth range 10–20 km. The inferred velocities are not atypical of clastic sediments buried to such depths. An analogous unit is the thick sedimentary succession, unambiguously identified in deep seismic reflection data (Cook et al., 1987) and having velocities 5.8–5.9 km/s determined from coincident seismic refraction profiling (Stephenson et al., 1994) that is associated with a fair degree of certainty (from the regional geology) with a thick clastic wedge deposited on a Proterozoic or Palaeozoic continental margin.

The eastern margin of this sub-Focsani sedimentary basin appears to be controlled by a series of normal faults, suggesting that it is of extensional origin. The

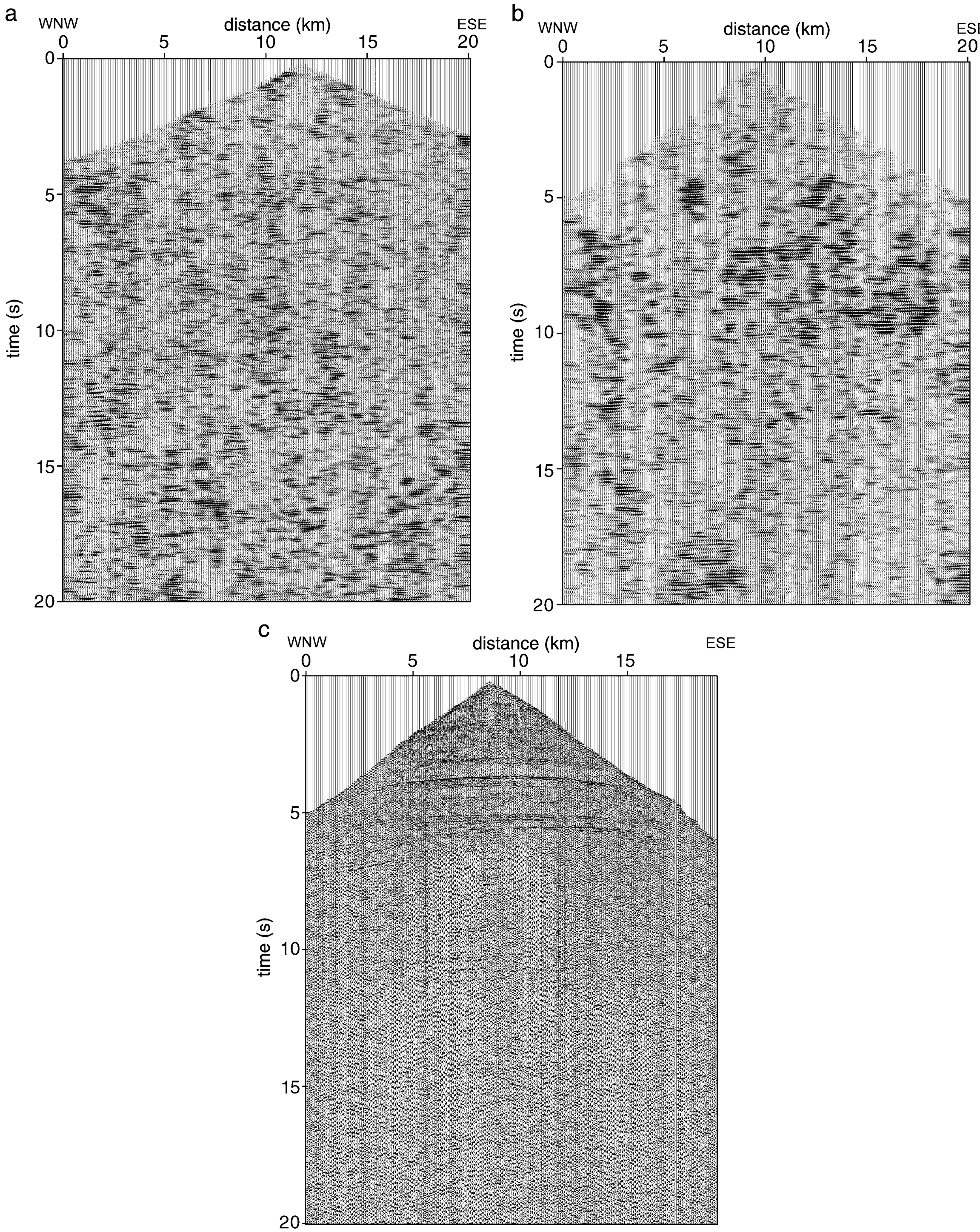

Fig. 9. (a) Processed shot gather (cf. Table 3) for shot 112, recorded in deployment 1 (western part of DACIA-PLAN, within the Vrancea zone); (b) processed shot gather (cf. Table 3) for shot 72, recorded in deployment 2 (westernmost Focsani Basin); and (c) processed shot gather (cf. Table 3) for shot 55, recorded in deployment 3 (Focsani Basin).

western margin of this sequence is not clearly imaged. However, there is a clear evidence, given the reflectivity pattern, that sediments extend to the west beneath at least the easternmost part of the Carpathian nappes (west of ~CDP no. 1800), although the image is more ambiguous than further east and structures evidently more complex. The geometry of the normal faults on the eastern margin of the rift basin (the shallow expression of two of them is seen in the partial stack — Fig. 6b) suggests that sediments at the base of the Focsani Basin in this area, generally interpreted as Middle Miocene in age (Tărăpoancă et al., 2003; cf. Fig. 6b), could be older, belonging in fact to the underlying "rift" basin sequence. This is supported, although not unambiguously, by velocities derived from the tomographic inversion of the DACIA-PLAN first-arrival data, with the thick dashed red line in Fig. 10b representing approximately the 4.5 km/s velocity contour in the tomography model (Bocin et al., 2005—this volume). The actual age of the inferred extensional basin cannot be determined. Tărăpoancă et al. (2003) have reported smaller, fault-bounded sedimentary basins in the adjacent foreland interpreted to be of Badenian age. Thus, the sediments in the rift basin seen in Fig. 10b could be as young as this if this age is correct and if there is a correlation. Otherwise, the Moesian crust underlying this basin is of Precambrian age (e.g., Visarion et al., 1988) and was in an extensional tectonic environment in the Late Palaeozoic–Triassic (e.g., Rabagia and Tărăpoancă, 1999; Pharaoh, 1999) as well as during Late Jurassic–Cretaceous times (Matresu and Dinu, in press), the latter being associated with the opening of the western Black Sea (Dinu et al., 2005—this volume).

Of great significance is that the secondary zone of Vrancea zone seismicity, characterised by crustal events of magnitude less than 5.6 (e.g. Enescu et al., 1992), coincides in position and depth with the deeper parts of the rift-like basin imaged on the DACIA-PLAN profile. In this respect, it seems likely that the generally weaker rheology of sedimentary rocks compared to crystalline crustal rocks as well as pre-existing structures in the crust associated with rifting play a role in localising

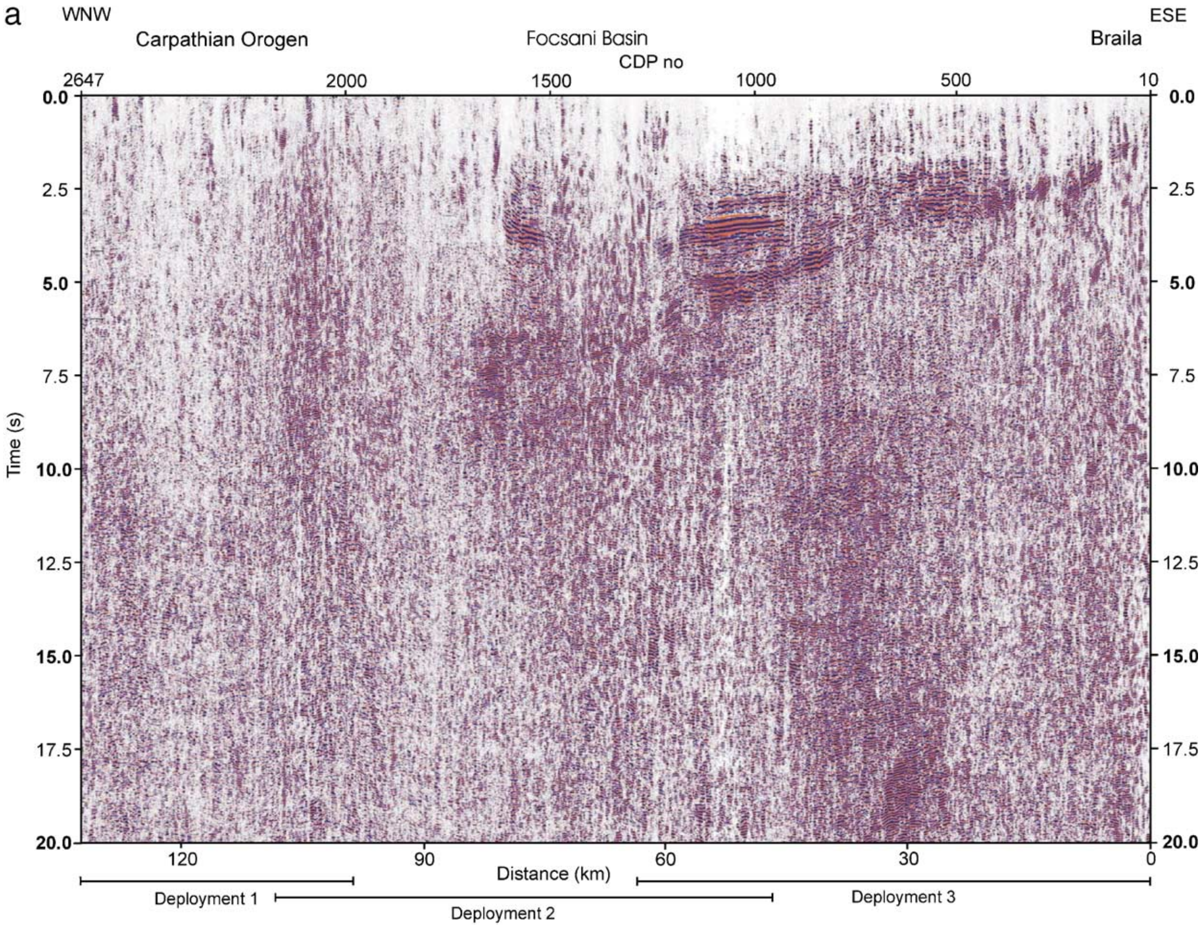

Fig. 10. (a) Uninterpreted and (b) interpreted time seismic section for entire DACIA-PLAN profile, up to 20 s; the thick dashed red line represents approximately the 5.0 km/s velocity contour in the tomography model of Bocin et al. (this volume) and the dark blue velocity interfaces are from the crossing VRANCEA99 velocity model (Hauser et al., 2001). Yellow lines are geological interfaces and blue lines faults. Further interpretation and discussion is in the text.

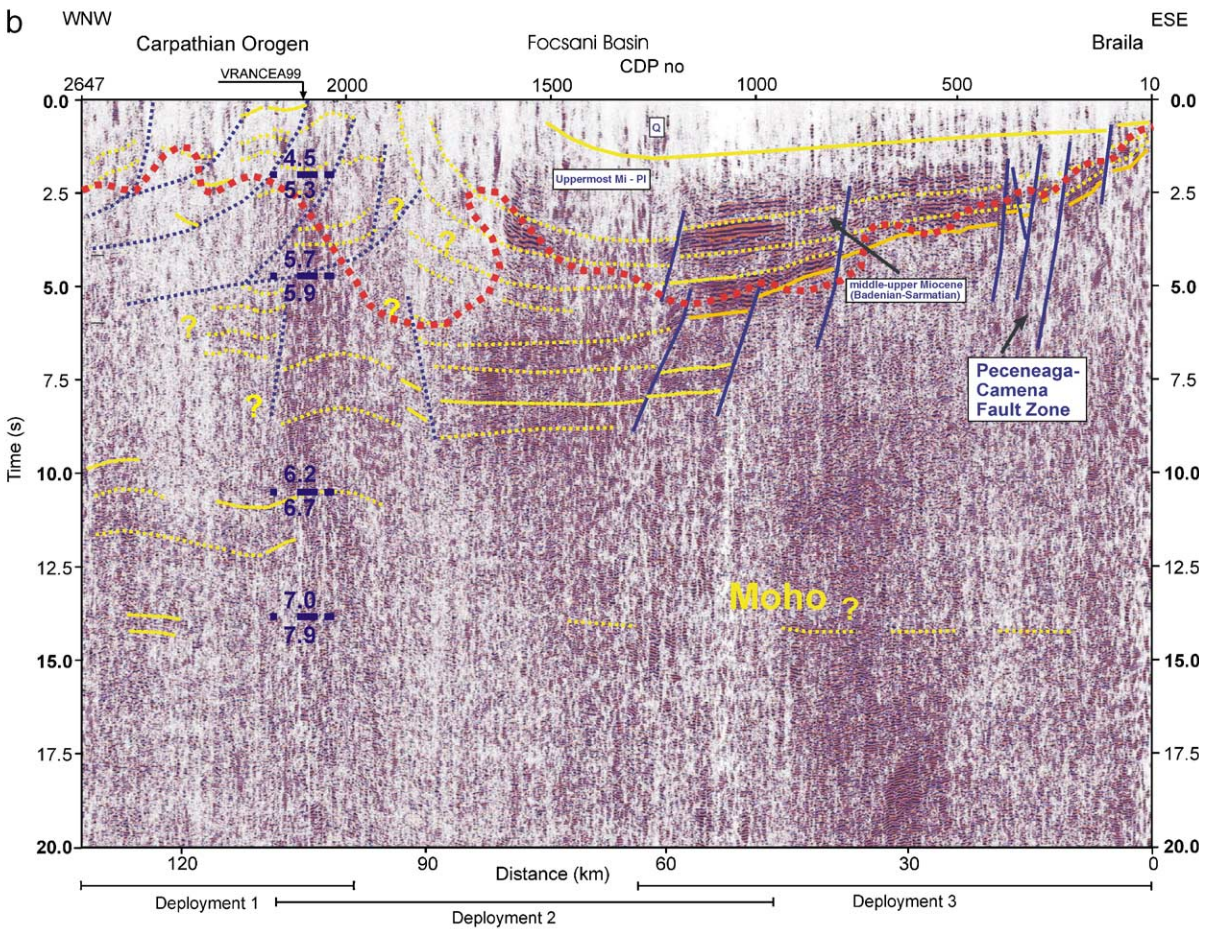

Fig. 10 (*continued*).

seismicity in this area. The inferred extensional basin is likely two-dimensional (i.e., has a clear structural trend in plan view), which cannot be determined from the seismic profile, however, whereas the seismicity with which it is associated is laterally constrained. This implies that the source of the stresses giving rise to earthquakes is confined to this particular area, in the bending zone of the south-eastern Carpathians, and, therefore, probably related to whatever the sources of the deeper Vrancea earthquakes are.

Few laterally coherent events are discernible on the north-westernmost part of the DACIA-PLAN stack, beneath the south-eastern Carpathians external nappes. There are hints of sub-horizontal, gently folded, horizons in the uppermost 2.5 s and the thrust faults that are shown on Fig. 10b are inferred from these horizons accordingly. However, it is clear that the existence of such structures is supported more by the geological interpretation of this area—from surface exposures and nearby shallow subsurface—than from the seismic section (cf. the geological cross-section—Fig. 7—of this area published in Bocin et al., 2005—this volume). The tomography velocity model indicates velocities greater than 4.5 km/s below about 2–2.5 s suggesting that the materials involved in thrusting beneath this depth consist of sediments older than Tertiary, previously more deeply buried than at present and representing "basement" in the context of Carpathian thrusting. It is also important to note that the thrusting in this area, on the inferred thrust faults, predated the flexural couple (or "buckle") proposed to explain the rapid uplift of the overlying Vrancea zone (e.g., Sanders et al., 1999) contemporaneous with the rapid Neogene subsidence of the Focsani Basin (cf. Bertotti et al., 2003; Tărăpoancă et al., 2003).

The VRANCEA99 crustal refraction profile crosses the DACIA-PLAN profile at approximately CDP 2100. The main velocity discontinuities inferred in the VRANCEA99 model (Hauser et al., 2001) have been converted to two-way travel-times and plotted on Fig.

10b as short dashed blue line. Associated velocities (in km/s) above and below each discontinuity are also shown. The shallowest horizon conforms to the DACIA-PLAN tomography model in that high velocities greater than 5.0 km/s occur at relatively shallow depths beneath the Vrancea zone external nappes (thick red line in Fig. 10b; travel-time converted 5.0 km/s horizon from Bocin et al., 2005—this volume). The next horizon, which is not characterised by a large velocity contrast, occurs approximately at the inferred depth of nappe detachment. The crustal unit beneath this discontinuity, in the depth range 10–12 to about 30 km (10.5 s in Fig. 10b) and having velocities in the range 5.9–6.2 km/s (Hauser et al., 2001), shows evidence of sedimentary layering, possibly correlating with sediments within the buried rift-like basin to the east, as mentioned above.

The deeper layering structure underlying the western flank of the Focsani Basin and south-eastern Carpathian nappes (5–10 s in the CDP range 1300–2100) are flat-lying compared to the upwardly flexed Focsani margin. It follows that these units are detached from the overlying “buckle” structure involved in Neogene and recent uplift of the Vrancea zone and down warping of the adjacent Focsani Basin. Accordingly, it is clear that the Neogene Vrancea–Focsani “buckle” involves upper crustal units only and is not a crustal buckle as proposed by Bertotti et al. (2003). This is also in agreement with its wavelength. The implication is that material must be entering the section beneath the Vrancea zone at a depth of about 5 s (10–12 km) in order to drive and fill the volume beneath the uplift zone. Unfortunately nothing definitive can be said from the DACIA-PLAN image in this regard but the candidates are intracrustal thrust slices, either from the northwest or from out of the plane, or intruded igneous magmas. In the latter case, there is no supporting bright spot obvious in the seismic data. It is interesting to note, in this regard, the subsidiary antiformal structures beneath 5 s in the CDP range 1800–2200. However, it is not impossible that these are pull-ups related to higher velocities overlying them in the upper few seconds.

Several poorly displayed reflections occur at 13.5–14 s beneath the external nappe zone at the western end of the DACIA-PLAN profile, which may be an indication of the Moho, which lies at ~40 km (~13.5 s), above upper mantle with a moderately low velocity of 7.9 km/s, according to the refraction data (Hauser et al., 2001). Similarly, the Moho is poorly inferred from the DACIA-PLAN image to lie at about 14 s further to the east, where it is in part obliterated by a zone of artificial “ringiness” that extends through the crust and upper mantle in the CDP range 500–1000. It is thought that this may relate to laterally dispersed and reflected energy from the Peceneaga–Camena Fault. Răileanu and Diaconescu (1998) interpreted the Moho at 15 s, although also poorly displayed, on the nearby Râmnicu–Sarat seismic profile (Fig. 1). Preliminary analysis of the VRANCEA2001 refraction data (coincident with DACIA-PLAN) is also consistent with a Moho beneath the Carpathian foreland in this area at 14–15 s (42 km; Hauser et al., 2002, 2003).

Crystalline crust is evidently significantly thinned in the area beneath the buried extensional basin; it is represented by not more than 5 s, which, at a velocity of 6.5 km/s or more (Hauser et al., 2001), is considerably less than 20 km. Thin crust beneath a rift basin is not atypical, as a result of crustal stretching during extension, although the degree of thinning observed is fairly extreme. Other possible mechanisms include migration of the Moho to shallower levels as a result of (ultra)mafic intrusion in the lower crust, increasing its density and velocity to upper mantle levels, and delamination of the lower crust. With respect to the former, the upper mantle velocity recorded on VRANCEA99 is fairly low—7.9 km/s (Hauser et al., 2001)—and this could be seen as supporting evidence. With respect to the latter, crustal delamination is among a number of processes that have been proposed to be involved in providing the locus of the deeper seismicity recorded in the Vrancea Zone (cf. Wenzel et al., 2002; Cloetingh et al., 2004; Knapp et al., 2005—this volume). The main earthquake zone lies below the DACIA-PLAN image seen in Fig. 10 (i.e., deeper than 20 s, CDPs greater than 2000). Nothing notable was recorded from those depths in this area. However, it is likely significant that the crystalline crust along the DACIA-PLAN profile, directly above the earthquake zone and to the east, appears to be very thin, represented only by what is probably some kilometres of upper crust with overlying sedimentary successions.

5. Summary and conclusions

The DACIA-PLAN seismic profile is part of a multidisciplinary programme designed to study one of the most seismically active areas of Europe, namely the Vrancea zone. Its goal was to elucidate the deep structure of the external Carpathians nappes and the architecture of Tertiary/Quaternary basins developed within and adjacent to the Vrancea zone, including the Focsani Basin. Two seismic sections have been presented. The first, called the “partial-stack”, represents the results of shallow data processing and images the broad internal architecture of the sedimentary successions of the eastern Focsani Basin. The second stack, processed to 20 s along the entire line crossing the Vrancea zone as well as Focsani Basin and called the "full stack", shows the highly reflective sedimentary strata of the Focsani Basin, the geometry of the transition zone between the foreland basin and external nappes, as well as a number of intracrustal features.

In particular it reveals the presence of a thick rift-like sedimentary basin underlying this transition area, in the depth range 10–25 km. This sedimentary basin, which is of indeterminate age and could be as old as Early Palaeozoic or as young as Neogene, is approximately coincident with hypocentres that define the crustal depth segment of the earthquake prone Vrancea zone (as opposed to the seismically more intense upper mantle segment). The sedimentary successions within this basin and other horizons visible further to the west, beneath the Carpathian nappes, suggest that the geometry of the Neogene and Recent uplift observed in the Vrancea zone, likely coupled with contemporaneous rapid subsidence in the western Focsani Basin, is detached from deeper levels of the crust at about 10–12 km depth. The Moho lies at a depth of about 40 km along the profile, its poor expression in the reflection stack being supported by independent estimates from coincident refraction data. Given the apparent thickness of the (meta)sedimentary supracrustal units, the crystalline crust beneath this area is quite thin (<20 km). This may support the hypothesis of delamination of (lower) continental crust in this area involved in the evolution of the seismic Vrancea zone.

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