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Seismic Experiments Target Earthquake-prone Region in Romania

Several major earthquakes struck Romania in the last century, and all of them occurred in the Vrancea zone in the southeast Carpathian Mountains (Figure 1). These earthquakes claimed many lives and caused extensive damage. In the 1977 earthquake alone, 1,570 people died and more than 11,300 were injured, 32,900 apartments were completely destroyed or severely damaged, and economic loss was estimated at more than $2 billion.

To study the crustal and uppermost mantle structure beneath this seismic high-risk area, two major active-source seismic experiments were carried out in 1999 and 2001, nearly 30 years after the last seismic investigations across the eastern Carpathians in the 1970s. The joint seismic refraction and reflection field effort conducted in August and September 2001 (Figure 1), which used almost 800 stand-alone recorders, is one example of the productive interaction forged during the 1999 experiment [*Hauser et al.*, 2001].

The two seismic refraction projects are a contribution to the joint German-Romanian research program, Strong Earthquakes—A Challenge for Geosciences and Civil Engineering. This program was initiated by the Collaborative Research Centre 461 (CRC 461) at the University of Karlsruhe, Germany, and the Romanian Group for Vrancea Strong Earthquakes (RGVE) at the Romanian Academy in Bucharest.

The joint geoscientific and civil engineering research activities [e.g., *Wenzel et al.*, 2001] seek to better understand the tectonic processes that are responsible for the strong intermediate-depth seismicity in the Vrancea area; reduce the risk by applying appropriate techniques from civil engineering; develop realistic models and predictions of ground motion; estimate the potential damage in case of a strong earthquake; and develop a disaster management tool to help rescue groups and governmental institutions make decisions.

Initial results from the analysis of first arrivals indicate strongly variable sediment thickness along the line, the strongest of which is associated with the Carpathian Orogen and the Focsani Basin. Future addition of reflected phases to the analysis should improve the detail and robustness of our velocity model.

Seismotectonic Overview

The Eastern Carpathians are part of the Alpine-Carpathian orogenic belt and the result of the collision of several microplates with the European margin, which closed the former Tethys Ocean. The Tertiary tectonic evolution of the Carpathians is characterized by southwest- to west-dipping subduction. In Cretaceous times, this subduction was active along the whole of the Alpine-Carpathian arc. However, after Eocene continental collision in the Alps, subduction continued further east in an embayment of the European Continental Margin [e.g., *Sperner et al.*, 2001]. This embayment was bordered by the European Platform to the north and east and by the Moesian Platform to the south. Continental collision started about 14 Ma ago in the northernmost part of the Carpathians and shifted toward the southeast and south, leading to a corresponding shift of foreland basin depocenters [*Meulenkamp et al.*, 1996]. Finally, in the middle Pannonian, at ~10 Ma, continental collision also occurred in the southeastern Carpathians.

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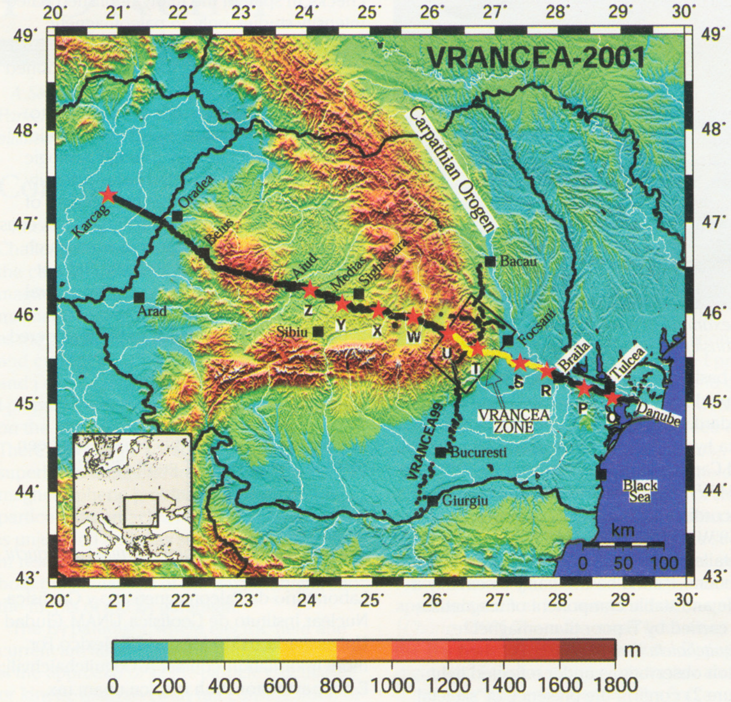

Fig. 1. This topographic map of Romania shows the seismic experiments VRANCEA99 and VRANCEA2001. Labeled red stars indicate the shot points, and grey dots are the recording sites for VRANCEA2001. The yellow segment between shot points U and R is DACIA PLAN's coincident seismic reflection line.

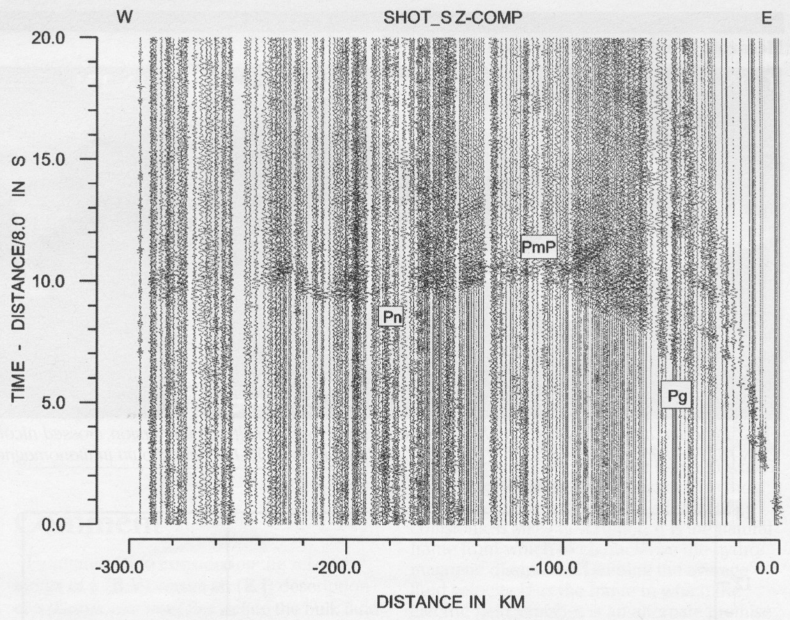

Fig. 2. Record section from shot point S in the Focsani Basin. The record section is displayed with a reduction velocity of 8 km/s so that refracted arrivals from the uppermost mantle (Pn) are nearly horizontal. PmP is the reflection from the crust-mantle boundary. Pg is the diving wave through the crust.

Then collision ceased and post-Pannonian deformation remained minor [*Matenco*, 1997].

Sperner et al. [2001] proposed that, corresponding to continental collision, lithospheric slab break-off also started in the north and propagated along the arc toward the south. Thus, today, the last fragment of the slab hangs beneath the southeastern bend of the Carpathian arc, the Vrancea zone, and is the cause for the strong seismicity in the area. The assumption that the seismogenic volume is part of the subducted lithosphere is supported by seismological data.

While the shallow seismic activity in Romania scatters widely and has moderate magnitudes ($M_w \le 5.6$), the epicentral region of the intermediate-depth seismicity is confined to an area of only about 40 x 80 km [*Oncescu et al.*, 1999]. These earthquakes have caused a high toll of casualties and extensive damage over the last few centuries, and they occur between 60 and 180 km depth within an almost vertical column and frequently have large magnitudes ($M_w \le 6.5$). Deeper events have also been recorded, but these show only small magnitudes. The depth interval of the strong events is separated from the crustal events by a zone of low seismicity located between about 40 and 70 km depth [*Oncescu et al.*, 1999]. Earthquakes with magnitudes in excess of 6.0 are well documented for the last century [*Radu*, 1991] and satisfy a Gutenberg-Richter relation with recurrence times of 10 years for $M_w > 6.5$, 25 years for $M_w > 7.0$, and 50 years for $M_w > 7.4$.

During the last 20 years, the results of several seismic tomography studies in southeastern Romania have confirmed that high seismic velocities characterize the intermediate-depth seismogenic volume. For example, *Wenzel et al.* [1998] imaged a compact, high-velocity body with a maximum positive velocity perturbation of about 5% with respect to the reference model. The high-velocity feature extends from a sub-crustal depth of about 70 km down to at least 200 km. Due to the spatial resolution of the available data sets, the detailed structure of the uppermost mantle could not be imaged. Therefore, a large-scale passive seismological experiment (CALIXTO) was undertaken in 1999 [e.g., *Wenzel et al.*, 1998] to generate high-resolution images of the depth range 40–80 km, which are essential for understanding and testing geodynamic models.

Project Description

The two seismic refraction investigations from 1999 and 2001 consisted of three profiles (Figure 1). The first was a 300-km-long line from the Danube River, southwest of the city of Giurgiu, across Bucharest, and to the city of Bacau, traversing the Vrancea epicentral region in a south-southwest/north-northeast direction. The second was a 70-km-long, east-west-directed fan line along the Putna valley north of the Vrancea epicentral region. The third was a 460-km-long, west-northwest/east-southeast-directed profile from the Black Sea to the Transylvanian Basin (shot points O-Z in Figure 1). To take full advantage of the recording equipment and human resources, data acquisition during VRANCEA2001 took place within an integrated refraction/reflection seismic field program coordinated by the University of Karlsruhe.

The main objective of the seismic refraction investigation is to understand the propagation properties of seismic waves between the Vrancea zone and Bucharest. Furthermore, determination of the crustal velocity structure and its thickness provides important boundary conditions needed for seismic mantle tomography. A detailed crustal model is also needed to test and develop geodynamic models for the southeast Carpathians [e.g., *Sperner et al.*, 2001].

In addition, the availability of several hundred small and lightweight recording units allowed the recording of a coincident seismic reflection experiment called Danube and Carpathian Integrated Action on Processes in the Lithosphere and Neotectonics (DACIA PLAN). It forms one component of a new multidisciplinary initiative of the Netherlands Centre for Integrated Solid Earth Sciences and the University of Bucharest. DACIA PLAN will investigate the architecture of the Tertiary/Quaternary basins developed within and adjacent to the Vrancea zone, including the foreland basin; the presence and geometry of structural detachments in relation to foreland basin development, including constraints for balanced cross-sections and geodynamic modeling of basin origin and evolution; the relationship between crustal structure and basin evolution, especially deep-seated neotectonic structures; and integration with complementary studies in the Carpathian-Transylvanian region for evaluating and validating competing geodynamic models for the present-day situation.

The new seismic refraction profile VRANCEA2001 comprises a 460-km-long, west-northwest/east-southeast-striking profile. In its central part, the profile traverses the Vrancea seismic zone and at the same time crosses the profile VRANCEA99 (Figure 1). The line begins at the western margin of the Transylvanian Basin near the town of Aiud, crosses the Carpathian Mountains, the adjacent Focsani Basin, and ends in the Dobrogea, which is south of the Danube delta and close to the Black Sea (Figure 1). The study area comprises many hills and mountains with difficult access to about 50% of the land. Along the refraction line, 10 borehole shots (Figure 1, O-Z) were fired. The charge sizes of the shots varied between 300 kg and 1500 kg, and the shot points were separated from each other by about 40 km on average. The drilling and loading of the shot points was done immediately before the start of the experiment.

On this profile, 460 recording units were installed with a mean station spacing of 1 km. Of those, 150 instruments were three-

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Romania

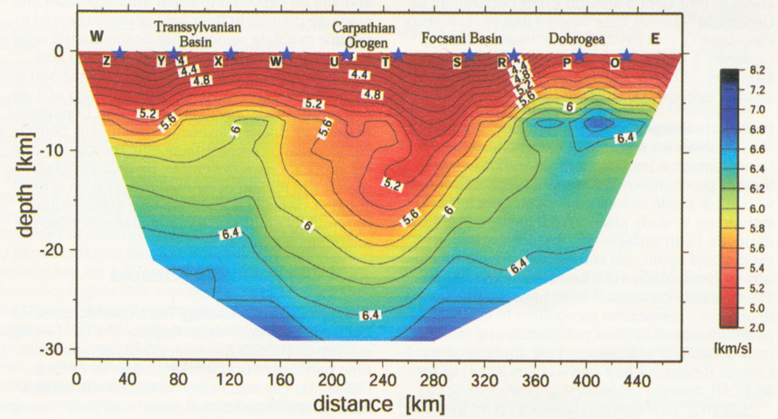

Fig. 3. In this preliminary, two-dimensional tomographic velocity model for the upper crust, blue stars indicate shot points O to Z. Numbers are the P-wave velocity in kilometers per second. This model is based on first arrivals only.

component recording stations equipped with 1-Hz seismometers from the GeoForschungs-Zentrum (GFZ) in Potsdam, Germany. Each recording crew handling these instruments consisted of two people in a van, and they were responsible for 10–12 stations. The other instruments were small, one-component units equipped with 4.5-Hz geophones, which were made available and serviced by the University of Texas at El Paso (UTEP) and the IRIS/PASSCAL equipment pool. One "Texan crew" had to deploy between 20 and 50 stations, depending on terrain conditions and station spacing. The majority of these one-component stations were buried in the open countryside. For security reasons, all three-component instruments had to be installed in cellars or in gardens near houses.

Additional funding from Hungarian colleagues extended the profile to the west of shot point Z by another 250 km (Figure 1). This segment runs through the Apuseni Mountains and into the Pannonian Basin in Hungary. It was occupied with 30 recording units from UTEP and 30 from Warsaw, Poland. This resulted in an average station spacing of 3–5 km. The Hungarian colleagues reactivated one of the CELEBRATION2000 [*Guterch et al.*, 2001] shot points near the town of Karcag to extend the line and tie the two projects together.

The deep seismic reflection component of DACIA PLAN comprised an approximately 140-km-long profile across the Vrancea Zone and Focsani Basin, coinciding with this segment of the refraction line (Figure 1). Data acquisition took place in three segments utilizing 640 independently deployed "Texan" recorders provided by UTEP and IRIS/PASSCAL. Station spacing was about 100 m with shots every 1 km. These data are to be integrated with industry seismic data, as well as new, medium high-resolution seismic reflection profiles across neo-tectonically active key structures in the Focsani Basin.

Initial Results

The seismic field set-up and instrumentation used in the VRANCEA2001 and DACIA PLAN profiles worked very well and over 95% of the recorders deployed returned useful data. In general, the efficiency of the seismic sources varied and data quality, therefore, depends highly on local conditions like structure and physical properties of the shot and recording sites. This variability in data quality was also experienced during the VRANCEA99 experiment.

It will take 1 to 2 years to fully model and interpret the data set produced by this experiment. Until now, the data from the one-component "Texan" recorders have been processed, compiled into shot records, and plotted (Figure 2). The processing and integration of the remaining data is underway.

Although we are at a very early stage in the data analysis, some initial observations can already be presented. Data from shot points in the Dobrogea indicate a thin sedimentary cover in this area with surface P-wave velocities of 5.5 km/s or higher. Moving further to the west into the Focsani Basin, first arrivals with very low apparent velocities extend to distances of about 100 km, indicating the presence of a thick pile of sediments. A strong reflection from the crust-mantle boundary (PmP) suggests a crustal thickness of more than 40 km under the Carpathian Mountains. Seismic waves are severely attenuated by the sedimentary strata of the Carpathian Mountains, which reduce the observational distance to less than 100 km. Further to the west, across the Transylvanian Basin, seismic wave propagation becomes more efficient again. Here, initial results of the PmP reflections from those shot points indicate a decrease of the crustal thickness toward the Pannonian Basin.

Picking first arrival times only and inverting them using the non-linear tomographic technique of *Hole* [1992] produced the preliminary two-dimensional velocity model shown in Figure 3. It confirms the variable thickness of the sediments along the line. The most dominant feature is seen in the center of the model and is associated with the Carpathian Orogen and the Focsani Basin. This massive structure extends between shot points R and W over some 80 km. Since reflections from the crust-mantle boundary and from an intracrustal layer are visible on most sections, the inclusion of those phases will certainly improve the resolution of the model further.

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