Romanian Reports in Physics, Vol. 61, No. 2, P. 325–334, 2009

EARTH PHYSICS

SEISMOTECTONICS OF VRANCEA (ROMANIA) ZONE: THE CASE OF CRUSTAL SEISMICITY IN THE FOREDEEP AREA*

A.ȚUGUI, M. CRAIU, M. ROGOZEA, M. POPA, M. RADULIAN

National Institute for Earth Physics, P.O.Box MG-2, Calugareni 12, Bucharest-Magurele, 077125, Romania, atugui@infp.ro, www.infp.ro

(Received July 30, 2008)

Abstract. Vrancea seismic zone is located in Romania at the South-Easter Carpathians bend, where at least three major tectonic units are in contact: East Europen Plate, Intra-Alpine Plate and Moesian Plate. The seismicity of the Vrancea zone consist of both crustal and intermediate-depth earthquakes. The crustal events are moderate ($M_w \leq 5.5$) and generally occur in clusters in space (the subzones Râmnicu Sărat and Vrâncioaia, situated in the Vrancea epicentral area and adjacent to it) and in time (main shocks accompanied by aftershocks and sometimes by foreshocks or swarms). Seismic activity in Râmnicu Sărat zone consist of shallow earthquakes with moderate magnitudes $M_s \leq 5.2$ (Radu, 1979), wich frequently occur in clusters. The hypocenters are generally situated at focal depths between 15 and 30 km within the foredeep region lying in front of the major bending of the Carpatian Arc. The sequence of 29 November–03 December, 2007 consist of 37 events with $1.8 \leq M_D \leq 3.9$. The earthquakes hypocenters are grouped in a parallel direction with the Carpathian Bend, and the fault plane solution (of the main shock) is reverse. The seismic sequence from Râmnicu Sărat, 2007 was compared with the previous sequences knowing the regional seismotectonics.

Key words: seismic sequence, Râmnicu Sărat zone.

1. INTRODUCTION

The seismic activity on the Romanian territory is clustered at the Eastern Carpathians Arc bend where frequent and strong shocks are generated at intermediate depths in the Vrancea region. The extreme concentration of seismic activity in the Vrancea region in contrast with the lack of earthquakes elsewhere along the Carpathians belt suggests that this is a last and isolated segment of the Eurasian Plate in some manner decoupled in the upper mantle where final processes of the lithospheric subduction are still active.

---

* Paper presented at the Annual Scientific Conference, June 6, 2008, Faculty of Physics, Bucharest University, Romania.

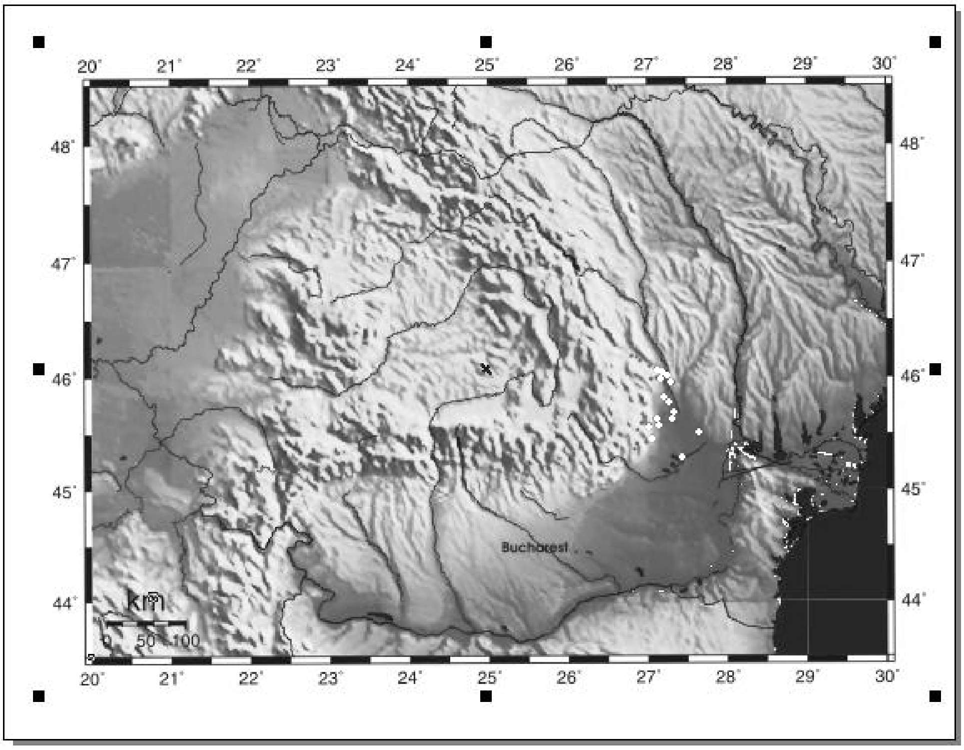

Fig. 1 – Representation of the seismic sequences recorded in Râmnicu Sărat zone in 2004 and 2007.

The spatial distribution of the shallow earthquakes shows a characteristic concentration of seismicity in the foreland of the South-Eastern Carpathians. The deep seismic refraction and reflection profiles show a significant lateral structural heterogeneity in this region which is made up of a complex puzzle of stable units, with different geometries and mechanical characteristics (e.g., Matenco et al., 2003; Cloetingh et al., 2004). The contacts are seismically active especially in front of the Carpathians Arc bend, most probably induced in response to the geodynamic process in the subcrustal domain.

Partly, the shallow seismicity follows the alignments at the contact between the major plates colliding in the South-Eastern Carpathians area: the system of major faults oriented NW-SE, separating the Eastern European Plate from Moesian Subplate and the eastern sector from the western sector of the Moesian SupPlate (Trotuş fault, Peceneaga-Camena fault, Intramoesian fault).

At the same time, the complex colliding process accompanied by specific detachment and roll-back processes in the upper mantle (Linzer et al., 1998; Wenzel et al., 1998; Wortel şi Spakman, 2000; Sperner et al., 2001) resulted in a very deep sedimentary basin located just in front of the major bending of the Carpathians Arc, between the Peceneaga-Camena and Intramoesian faults (Fig. 2).

Here a thick Miocene Quaternary sedimentary package has being developed in the Focşani Basin which is the thickest sedimentary basin over the whole Carpathian Arc system (more than 10 km).

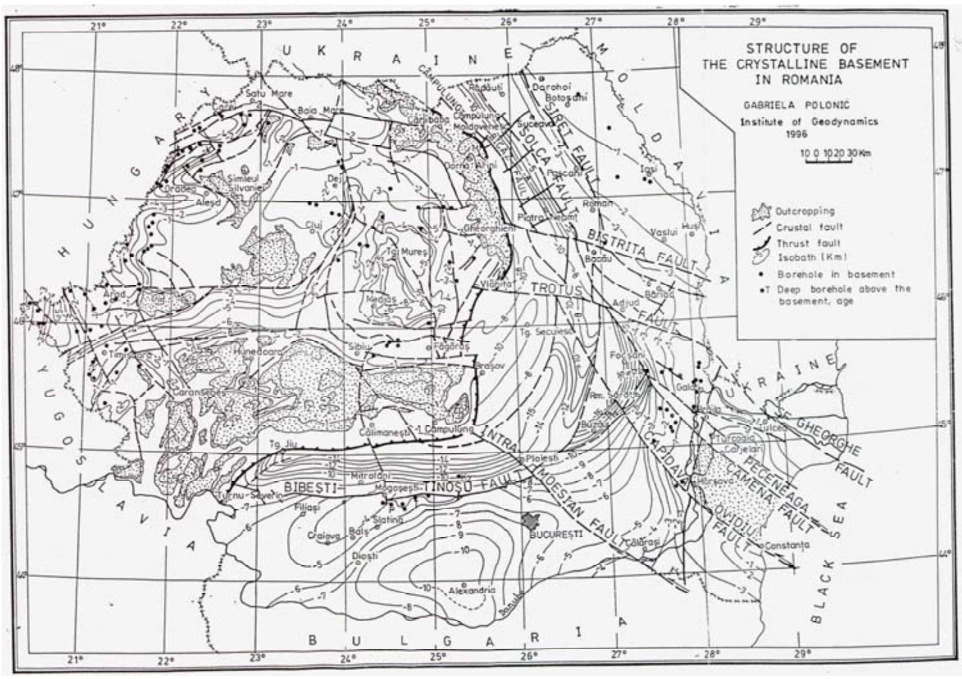

Fig. 2 – Seismotectonic map of Romania (Polonic et. al, 1996).

Deformation in the lower crust is characterized by normal faults of 14-15 Ma age (Tărăpoancă et al., 2004) with a well-defined active line oriented parallel to the Carpathians Arc bend. This particular seismic segment is known as Râmnicu Sărat seismic zone (e.g., Radulian et al., 2000) and represents a highest interest for understanding the geotectonics and coupling processes in the SE Carpathians region.

The seismic activity in the Râmnicu Sărat zone (RSZ) consists of moderate-magnitude earthquakes with $M_w \leq 5.2$ (Radu, 1979), which frequently occur in clusters. The earthquake sequences which frequently occur at the contact between Focşani Basin and orogen are following the same trend of thrust faults paralleling the orogenic front (Tărăpoancă et al., 2004), as expression of coupling between the shortening and collision of orogen with East European/Scythian block and foreland (Ziegler et al., 1995).

The velocity modelling suggests that basement material (characterized by velocities greater than 5.5 km/s) is likely involved in Carpathian thrusting (e.g., Bocin et al., 2005). The back-thrusting is particularly important along the western flank of the Focşani Basin, at the contact with the orogen structure, along a NE-SW alignment (parallel to the bending of the Carpathian Arc). The hypocenters of the earthquakes in the RSZ are generally situated at focal depths between 15 and 30 km, clearly shaping this contact (Popescu et al., 2000).

Coherent seismicity patterns observed in the RSZ outline well-defined structures in the stress field which characterizes the area in front of the Carpathians Arc bend. As shown by previous studies (Popescu, 2000; Popescu and Radulian, 2001) the fault plane solutions combine normal with reverse faulting. Note that the reverse faulting, predominantly recorded in the subcrustal Vrancea subducting lithosphere, is practically absent in the crustal domain all over the foreland region except RSZ. This observation, together with the tendency of the focal depth of the crustal events to increase as approaching the Carpathians orogen, made Radulian et al. (2000) to consider RSZ as a sort of transition zone between the compression stress regime in the downgoing lithosphere at intermediate depths and the extension regime specific for the entire foreland region, as well as for the entire Moesian Platform extending toward south in Bulgaria and Greece.

Frequent earthquake sequences are recorded in the Ramnicu Sarat Zone tentatively associated with the occurrence of the Vrancea intermediate-depth major shocks (Mârza, 1991). The last sequence was recorded between 29 November and 3 December 2007. The main goal of the present study is to analyze this sequence and to investigate the possible similarities with the previous sequences characteristic for the Ramnicu Sarat Zone.

2. EARTHQUAKE SEQUENCES IN THE RÂMNICU SĂRAT ZONE

In the last forty years twelve significant sequences were instrumentally recorded in the Râmnicu Sărat Zone. A synthesis of these data can be fined in Popescu (2000):

– on 21 December 1969 a main shock of magnitude $M_w = 3.5$ was followed by 70 aftershocks at depth around 40 km (Iosif and Iosif, 1977);

– on 8 February 1975 a sequence of 13 events was triggered by a shock of $M_w = 3.5$ in the area of Băicoi city. The estimated focal depth was around 55 km. After about one month, on 2 March 1975 another shock of magnitude $M_w = 3.2$ was followed by 10 aftershocks close to Focşani city; (ROMPLUS catalogue, Oncescu et al., 1999).

– on 26 May 1975 a swarm of 17 earthquakes (maximum magnitude $M_w = 2.8$) was recorded in the Focşani area at about 60 km depth;

– between 6 and 13 June 1979 a swarm of 14 events with duration magnitudes from 2.3 and 4.1 were recorded in the lower crust (30–50 km depth); (ROMPLUS catalogue, Oncescu et al., 1999).

– on 21–22 February 1983 a main shock of M_w = 3.5 was followed by 11 aftershocks (estimated depth of 14–19 km); (ROMPLUS catalogue, Oncescu et al., 1999).

– a swarm of 36 events with magnitudes from 1.3 to 2.6 were recorded between 1 and 7 August 1984 at depth around 10 km; (ROMPLUS catalogue, Oncescu et al., 1999).

– on 27–29 April 1986 a sequence of 74 earthquakes was recorded. The magnitude of the main shock was M_w = 3.7 with the focal depth of 26 km; (ROMPLUS catalogue, Oncescu et al., 1999).

– a sequence of 50 earthquakes occurred between 31 August and 1 September 1991. The main shock of magnitude M_w = 3.6 was generated at 32 km depth. It was preceded by 3 foreshocks (M_w = 3.1, 2.2, 2.3). The largest aftershock had a magnitude of M_w = 3.4. The aftershocks were generated at 30–35 km depth and migrated along a SW-NE direction; (ROMPLUS catalogue, Oncescu et al., 1999).

– on 6 to 8 December 1997 a sequence of 23 events was identified (14 of them were located as well) in the RSZ. The main shock had M_w = 3.2 magnitude, while the largest aftershock magnitude was M_w = 3.3. The focal depth domain was 10-15 km; (ROMPLUS catalogue, Oncescu et al., 1999).

– a swarm of 15 events with magnitudes M_w between 2.1 and 2.8 was generated on 30 April 2004 at 15–20 km depth; (ROMPLUS catalogue, Oncescu et al., 1999).

– a swarm of 11 events with magnitudes M_w between 2.1 and 2.9 was generated on 10 September 2005 at 1–11 km depth;

– a sequence of 37 earthquakes with magnitudes between 2.0 and 3.1 occurred on 29 November–3 December 2007.

3. EARTHQUAKE SEQUENCE OF 30 APRIL 2004

The burst of seismicity at the contact between the Focşani Basin and the Carpathians orogen is an expression of the complex collision process that takes place at the South-Eastern Carpathians Arc bending zone. It is difficult to explain at present how the coupling between deformation at depth and deformation in the crust generates earthquake sequences and how these sequences can be related to the generation of major Vrancea subcrustal shocks.

The presence of an unusual thick sedimentary basin in front of Vrancea region cannot be associated with a Beniof's plane, since the subducting lithosphere is placed in front of the mountain belt and is dipping almost vertically (85^{o} toward NW). A possible explanation of this configuration is a roll-back phenomenon in the south-eastern part of the Carpathians, which was accelerated when a segment of lithosphere was taken apart from the crust (Linzer et al., 1998; Wenzel et al., 1998; Wortel şi Spakman, 2000; Sperner et al., 2001). According to this hypothesis, the break-off process was completed along the South-Eastern Carpathians, except the Vrancea area, where is still active.

The epicenter distribution for all the sequences in the RSZ shows a permanent active alignment oriented NE-SW, parallel to the elongation observed for the hypocenters in the Vrancea subcrustal domain (Popescu, 2000; Popescu and Radulian, 2001). It is worth to mention that in all cases the main shock is located toward the south-western edge of the epicenter distribution and the aftershock migration is mainly unilateral toward NE.

If we refer to earthquakes sequences recorded in the Râmnicu Sărat area, the principal characteristic of them is the systematic orientation of rupture direction parallel to the orientation of the Carpathians arc (Popescu, 2000; Popescu and Radulian, 2001). For example, the hypocentral distribution for 30 April 2004 sequence (Fig. 3) and the fault plane solution (Fig. 4) emphasize the NE-SW preferential rupture propagation.

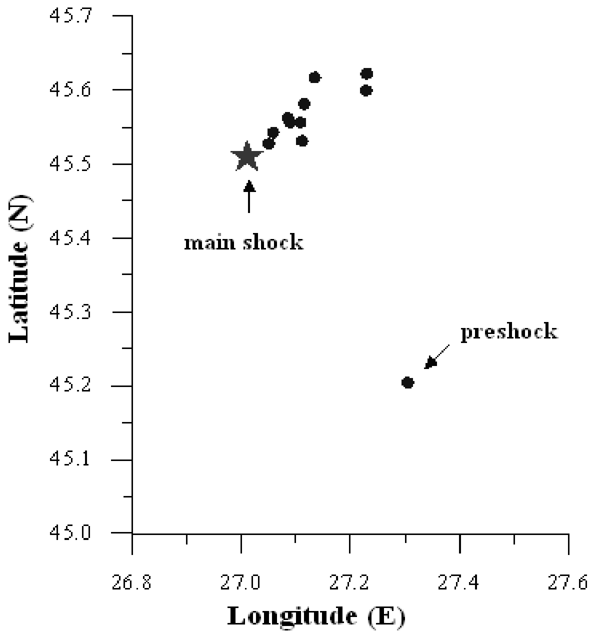

Fig. 3 – Epicenters distribution of earthquakes sequence of 30 April, 2004.

The characteristic geometrical configuration of the epicenters correlates with the fault plane solutions available for the largest events.

If we compare the fault plane solution obtained for the April 2004 shock with previous available fault plane solutions of earthquakes sequences generated in the Râmnicu Sărat area, we observe some similarities suggesting a persistent stress field with the principal axis of compression orientated SE-NW. Also the rupture plan seems to be always parallel to the Carpathian Arc, accordingly with the aftershocks orientation on the same direction.

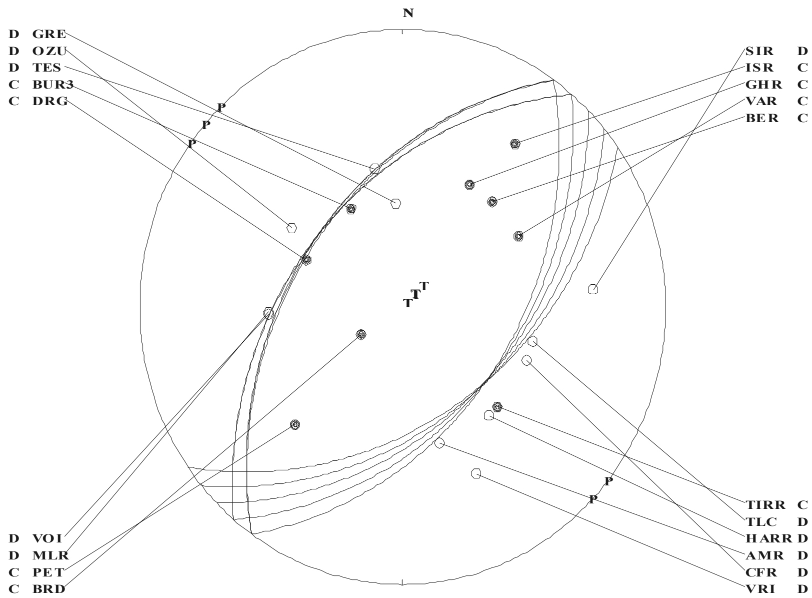

Fig. 4 – Fault plane solutions of earthquakes sequence from 30 April 2004.

Fig. 5 – Fault plane solutions for main shocks of earthquakes sequences from Râmnicu Sărat Zone.

These features show a remarkable similarity with an assumed rupture plane following the same orientation as the sequence epicenters. We assume that this invariance feature outlines a specific deformation field in the foreland region just in front of the Vrancea area.

4. EARTHQUAKE SEQUENCE OF 29 NOVEMBER – 3 DECEMBER 2007

The last sequence occurred in the Râmnicu Sărat zone consisted of 37 locate events of relatively small magnitude (1.8 to 3.9). The epicenter distribution is given in Fig. 5. Locations were made using the JHD technique (Jordan, 1974). The distribution reproduces the typical NE-SW alignment observed for the previous sequences. The hypocenters are located in the lower crustal domain.

EPICENTER DISTRIBUTION OF THE SEQUENCE OF 29 NOVEMBER–3 DECEMBER 2007

The largest event was generated to the south-eastern edge of the distribution. It was preceded by two shocks located in its vicinity.

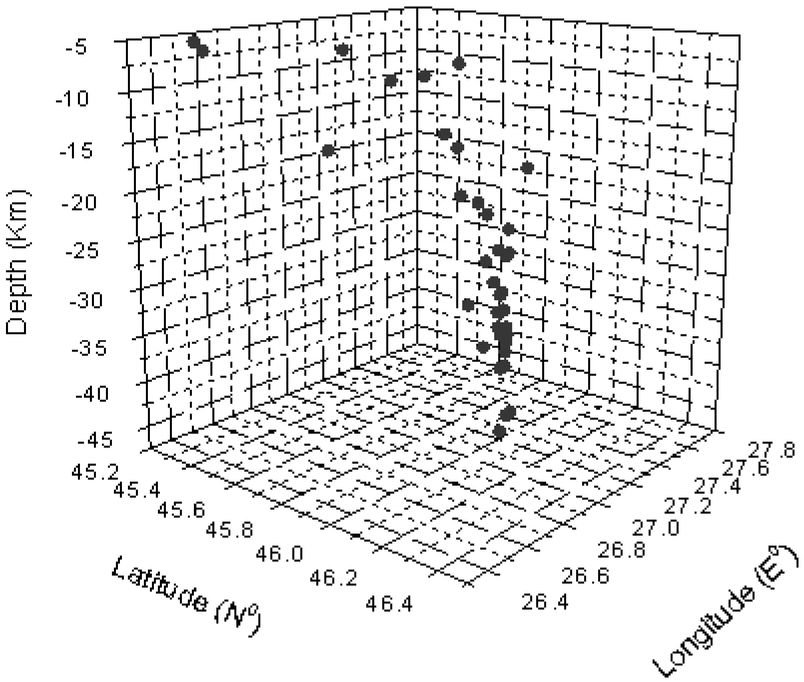

Fig. 6 – Hypocenters distribution for the sequence of 2007.

The hypocenters line up reproduces the configuration of the contact between the Focşani Basin and the Carpathians orogen which looks like a thrust fault paralleling the orogenic front (Tărăpoancă et al., 2003), as expression of coupling between the shortening and collision of orogen with East European/Scythian block and foreland (Ziegler et al., 1995). Note that the earthquakes of the sequence of 2007 occurred very close to the earthquakes generated during the sequences of 1986 and 2004 (and both these sequences were preceded by four and five months, respectively, the strong shocks of 30 August 1986 (M_w = 7.1) and 27 October 2004 (M_w = 6.0).

The focal mechanism of the largest shock (Fig. 7) shows a reverse faulting with a nodal plane nearly vertical and oriented NE-SW. We assume that this represents the rupture plane. The solution, obtained by inverting the P-wave polarities, is rather stable.

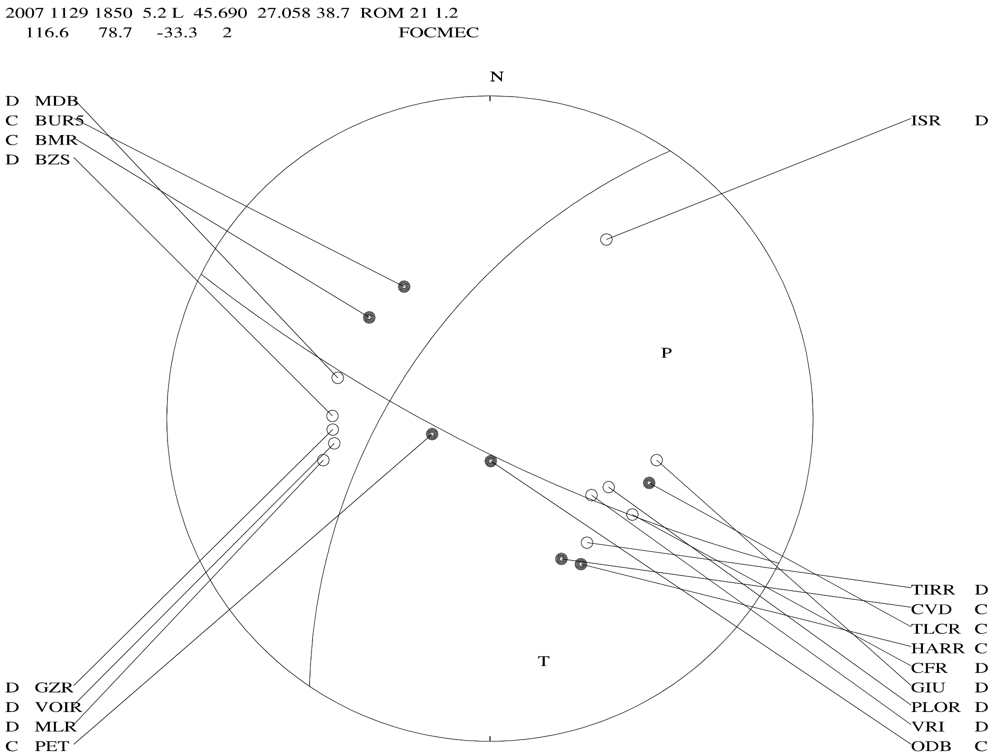

Fig. 7 – Fault plane solution for the largest event of the sequence in 2007.

6. DISCUSSION AND CONCLUSIONS

An interesting peculiarity of the Râmnicu Sărat zone is that moderate earthquakes ($M > 4.5$) are frequently accompanied by small earthquakes that appear very close in time with the main shock.

The seismicity in the Râmnicu Sărat zone seems to be in connection with the seismicity in the Vrancea intermediate-depth domain. Thus, after the occurrence of an important earthquake in Vrancea zone, we can observe a growth of the seismic activity in the Râmnicu Sărat zone, due to reactivation of the local faults by the depth seismic movement produced in Vrancea zone.

Also, in many cases, the sequences in Râmnicu Sărat preceed by a few months the occurrence of larger shocks in the Vrancea subcrustal focus.

The remarkable persistence of a NE-SW aligniament in the hypocentral distribution and focal mechanisms geometry outlines an active contrast between the western margin of the Focşani Basin and the Carpathians orogen. This is apparently compatible with the focal mechanism solutions.

However, the stress field is complex in the study area, showing a transition regime from the extensional regime in the Moesian Platform to the compressional regime in the Vrancea subcrustal zone.

REFERENCES

1. Bocin A., Stephenson R., Tryggvason A., Panea I., Mocanu V., Hauser F., and Matenco L., (2005), *2.5D seismic velocity modeling in the southeastern Romanian Carpathians Orogen and its foreland*, Tectonophysics, **410**, 273–291, doi:10.1016/j.tecto.2005.05.045.
2. Cloetingh S., Burov E., Matenco L., Toussaint G., Berotti G., Andriessen P.A.M., Wortel M.J.R., and Spakman W., *Thermo-mechanical controls on the mode of continental collision in the SE Carpathians (Romania)*, Earth Planet. Sci. Lett., **218**, *1–2*, 57–76 (2004), doi:10.1016/S0012-821X (03)00645-9.
3. Iosif S., and Iosif T., *Types of earthquakes sequences in the Vrancea region. Seismological Research on Vrancea earthquake of March 4, 1977.*
4. T.H. Jordan, *Some Comments on Tidal Drag as a Mechanism for Driving Plate Motions*, J. Geophys Res., **79**, *14*, 2141–2142 (1974).
5. Linzer H.-G., Frisch W., Zweigel P., Girbacea R., Hann H.-P., Moser F., *Kinematic evolution of the Romanian Carpathians*, Tectonophysics **297**, 133–156 (1998).
6. Matenco L., Bertotti G., Cloething S., and Dinu C., *Subsidence analysis and tectonic evolution of the external Carpathian-Moesian platform region during Tertiary times*, Sediment. Geol., **156**, 71–94 (2003).
7. Mârza V.I., *Precursory seismicity patterns in Vrancea (Romania) region: A General Account, International Conference on "Earthquake Prediction: State-of-the-Art",* 15–18 October 1991, Scientific-Technical Contributions (Preprints), CSEM/EMSC, Strasbourg, France, pp. 73–84, 1991.
8. Popescu E., *Complex study of the earthquake sequences on the Romanian territory* (in Romanian), PhD Thesis, Institute of Atomic Physics, September, 2000.
9. Popescu E., Radulian M., *Source characteristics of the seismic sequences in the Eastern Carpathians foredeep region* (Romania), Tectonophysics, **338**, 325–337 (2001).
10. Radu C., *The Catalogue of strong Earthquakes Occurred on the Territory of Romania. Part I-before 1901; Part II- 1901–1979* (in Romanian), *Seismological Studies on the March 4, 1977 Earthquakes* (eds. I. Cornea and C. Radu), pp. 723–752, Central Institute of Physiscs, Bucharest-Magurele, 1979.
11. Radulian M., Mandrescu N., Panza G.F., Popescu E., Utale A., *Characterization of seismogenic zones of Romania*, Pure appl. geophys., **157**, 57–77 (2000).
12. Polonic G., *Structure of the crystalline basement in Romania*, Rev. Roum. Geophys., 1996.
13. Sperner B., Lorenz F., Bonjer K.-P., Hettel S., Muller B., Wenzel F., *Slab break-off abrupt* cut or gradual detachment? New insights from the Vrancea Region (SE Carpathians, Romania), Terra Nova, **13**, 172–179 (2001).
14. Tărăpoancă M., Bertotti G., Mațenco L., Dinu C., Cloetingh S., *Architecture of the Focsani Depression: A 13 km deep basin in the Carpathians bend zone (Romania)*, Tectonics, **22**, 1074 (2003), doi:10.1029/2002TC001486.
15. Wenzel F., Lorentz F.P., Sperner B., Oncescu M.C., 1998. *Seismotectonics of Romanian Vrancea area*. In: Wenzel, F., Lungu, D.(Eds), *Vrancea Earthquakes*, Kluwer Academic Publishers, Dordrecht, Netherlands.
16. Wortel M.J.R., Spakman W., *Subduction and slab detachment in the Mediterranean-Carpathian region*, Science, **290**, 1910–1917 (2000).
17. Ziegler P.A., Cloetingh S., and van Wees J.D., *Dynamics of intra-plate compressional deformation: The Alpine foreland and other examples*, Tectonophysics, **252**, 7–59 (1995).