VRANCEA SEISMIC ZONE – A NEW GEOPHYSICAL MODEL BASED ON WRENCH TECTONICS, VOLCANISM AND REGIONAL GEODYNAMICS

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The study dedicated to the Vrancea seismic zone is based on the interpretation of relevant geophysical data for regional, crustal and lithospheric geological structures: gravity, magnetics, refraction seismics, heat flow, and especially seismic tomography.

New tectonic interpretations are offered at various scales, starting with the tectonic vortex determined by the three subduction zones in the Mediterranean Sea, Adriatic Sea and the East Carpathians, continuing with the wrench tectonics system developed between the Adriatic Sea and the Dniester river, and ending with the presence of the Romanian Trough, continuation of the Polish Trough along the western margin of the East European Platform.

Reinterpretation of regional geophysical data, in the context of the newly proposed wrench tectonics system, and the tectonic events determined by horizontal displacement of large geological structures along the transcurrent faults, suggested that there is no need of another platform, such as the Scythian Platform, between the East European Platform and the Tisza–Dacia tectonic block, or of the Wallachian tectonic phase, postulated as being active during the Quaternary.

Volcanism in Vrancea seismic zone is probably the most unexpected topic in an area long time considered to be devoid of magmatic processes – subduction related andesitic eruptions, followed by the intrusion of a large dioritic batholith, being interpreted on aeromagnetic, refraction seismics, seismic tomography and heat flow data, as well as on geological indirect evidences.

The Vrancea zone high seismicity is interpreted to be associated at crustal levels with active normal faulting within the graben-like structure, in an extensional regime determined by the south-eastward regional drag, and to the strike-slip movements of the wrench tectonics southern transcurrent fault at lithospheric depths, in a transtensional regime.

Key words: regional geodynamics, active tectonics, wrench tectonics, volcanism, crustal seismicity, lithospheric seismicity, Vrancea tectonic model.

1. INTRODUCTION

Fifty years have passed since the first scientific paper discussing the Vrancea zone deep structure and associated high seismicity, using the novel Plate Tectonics concept structured during the late 60's, was presented in an international journal by C. Roman (1970). Constantin Roman, a graduated geophysicist in Bucharest (Romania), obtained a Ph.D. degree at the Cambridge University (UK) in Paleomagnetism at the time when this domain of Geophysics was able to scientifically prove the validity of the Plate Tectonics concept, interpreting the alternating normal and reverse magnetic polarity of oceanic lithosphere stripes during geological time.

A large number of scientific studies have been published ever since, presenting tectonic and geodynamic models which tried to explain the Vrancea high magnitude earthquakes "nest", a seismogenic structure situated within the East Carpathians Bend area (Fig. 1).

During the last decade the authors of this paper devoted an important part of their researches to the active tectonics, neotectonics, fault systems and associated seismicity in the Vrancea zone and its neighboring areas, by interpreting both regional and local geological, geophysical and geodetic data.

Geophysical data, considered relevant for revealing regional, crustal and lithospheric geological structures, have been interpreted within this study: gravity, magnetics, refraction seismics, heat flow and especially, seismic tomography.

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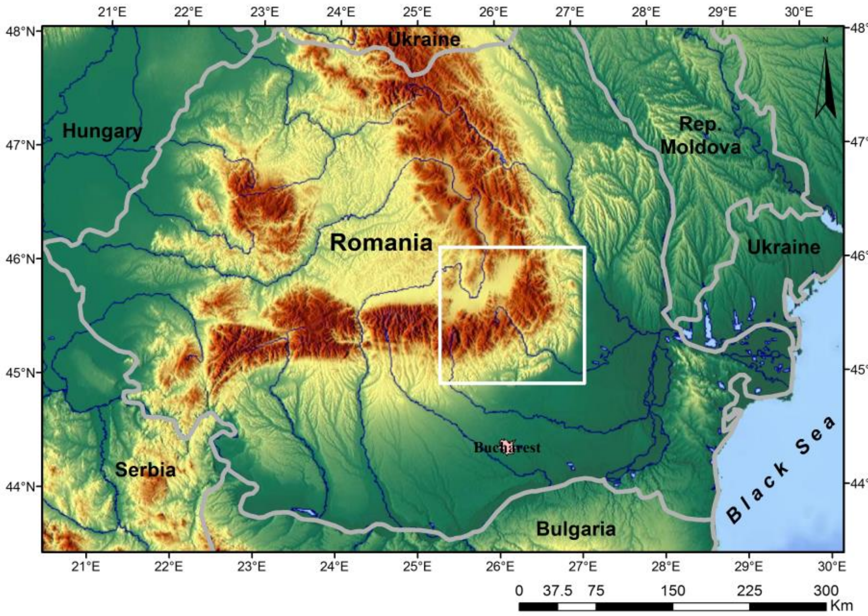


Fig. 1 – Location of the Vrancea seismic zone (Romania) – white rectangle.
Relief map: H. Braxmeier (2017), https://maps-for-free.com/ accessed 2021.

New tectonic models are offered at various scales: a) the regional tectonic vortex determined by the three subduction zones in the Mediterranean Sea, Adriatic Sea and the East Carpathians; b) the wrench tectonics system, developed between the Adriatic Sea and the Dniester River; c) the Romanian Trough, continuation of the Polish Trough along the western margin of the East European Platform.

Reinterpretation of regional geophysical data suggested that there is no need of a platform, such as the Scythian Platform, between the East European Platform and the Tisza-Dacia tectonic block, or of the Wallachian tectonic phase, considered as being active during the Quaternary.

Volcanism in Vrancea seismic zone is an unexpected topic in an area long time considered to be devoid of magmatic processes. Subduction related andesitic eruptions, followed by the intrusion of a large dioritic batholith, are interpreted on aeromagnetic, refraction seismics, seismic tomography and heat flow data, as well as on geological indirect evidences.

The Vrancea zone high seismicity is here interpreted to be associated at crustal levels with active normal faulting within the graben-like structure, in an extensional regime determined by the south-eastward regional drag, and to the strike-slip movements of the wrench tectonics southern transcurrent fault at lithospheric depths, in a transtensional regime.

2. GEOPHYSICAL STUDIES

The greatest interest for the Vrancea seismic zone derived from the strong earthquakes that occurred during history at a rate of several high magnitude seismic events per century, determining human casualties, buildings and infrastructure destruction. Since the geological structure associated with the highly destructive seismicity turned out to be deep, much deeper to be studied by geological mapping aided with observations on borehole cores, geophysical projects using methods and methodologies able to provide valuable information on the crust, lithosphere and upper mantle prevailed.

During the last 70 years a large number of geophysical projects have been carried out by Romanian scientists or research teams, at the scale of the Romanian territory, or focused on the Vrancea seismic zone. During the last 30 years the Romanian territory has been included in regional and continental-scale geophysical international projects, with significant scientific benefit for both the Romanian territory and the Vrancea seismic zone.

Important geological and tectonic features at crustal or lithospheric depths were revealed each time when newly acquired geophysical data have been carefully analysed, processed using up to date software and properly interpreted.

2.1. Bouguer gravity map of Romania, edited and printed in three editions by Airinei & Socolescu (1962, δ = 2.20 g/cc), Nicolescu & Roșca (1991, δ = 2.67 g/cc) and Ioane & Ion (1992, δ = 2.67 g/cc, gridded 7.5’ × 5.0’ mean values), was the first regional geophysical source for deep geological structures interpretation.

Even if between mid-sixties and early nineties such kind of geophysical data was treated as confidential, important studies on regional tectonics and geodynamics have been published based on Bouguer gravity anomalies during the last six decades:

– ***Airinei & Socolescu, 1962***: Bouguer gravity map of Romania (δ = 2.20 g/cc), excepting the mountainous areas, not covered with measurements at that time;
– ***Gavăt, Airinei, Botezatu, Socolescu & Stoenescu, 1963***: Geophysical model of Romania at the crystalline basement depths and detection of regional faults;
– ***Airinei, 1977***: Tectonic plates boundaries and Geodynamic model for the Romanian territory, based on the Bouguer gravity anomalies;
– ***Calotă, Ioane & Ion, 1991***: 3D modelling of gravity anomalies associated to magmatic intrusions in the Gurghiu Mts, East Carpathians;
– ***Nicolescu & Roșca, 1991***: Bouguer gravity map of Romania (δ = 2.67 g/cc);
– ***Ioane & Ion, 1992***: Bouguer gravity map of Romania (δ = 2.67 g/cc, gridded mean values 7.5’ × 5.0’), included in the Bouguer gravity map of Europe;
– ***Visarion, 1998***: Geological interpretation of the Bouguer gravity map of Romania;
– ***Ioane & Atanasiu, 2000***: Bouguer regional, residual and horizontal gradient maps of Romania;
– ***Hackney, Martin, Ismail-Zadeh, Sperner & Ioane, 2002***: 3D gravity modelling of the lithospheric and upper mantle structure in the Vrancea seismic zone;
– ***Sperner, Ioane & Lillie, 2004***: 2D gravity modeling across the Vrancea seismic zone;
– ***Ioane & Ion, 2005***: 3D gravity stripping map of Romania, computed at the Moho depth;
– ***Ioane & Caragea, 2015***: Western boundary of the East European Platform interpreted on the stripped gravity map of Romania.

2.2. Gravimetric geoid – the advent of high precision positioning technology (GPS) during early ’90 required high quality gravimetric geoids, which included satellite and terrestrial observations. A long time just a geodetic matter, the gravimetric geoid offered new possibilities of using the gravity field for interpreting deeper and larger density contrasting geological structures. Scientific works dedicated to using the gravimetric geoid in geophysical and geological studies based on gravimetric geoid solutions, such as the OSU91A (1991 – Ohio State University Model), EGM96 (1996 – Earth Geopotential Model) and EGG97 (1997 – European Gravimetric Geoid) have been carried out for the Romanian territory (Ioane *et al.*, 1993; Hackney *et al.*, 2002; Ioane, Stanciu, 2018).

Selected published studies are mentioned in the following:

– ***Ioane, Olliver, Radu & Atanasiu, 1993***: Possibilities of geophysically interpreting the geoidal anomalies (undulations), with application to the Romanian territory using the OSU91A geopotential model;
– ***Ioane & Atanasiu, 1998***: Analysis and geophysical interpretation of local gravimetric geoid and EGM96 gravity geopotential model in Romania;
– ***Hackney, Martin, Ismail-Zadeh, Sperner & Ioane, 2002***: Use of EGM96 gravity geopotential model for 3D modeling the lithospheric and upper mantle structure in the Vrancea seismic zone;
– ***Ioane & Stanciu, 2018; 2019***: Interpretation on the EGG97 European geoid in Romania

– lateral displacements induced by a wrench tectonics system to the East European Platform western boundary in the East Carpathians Bend Zone.

2.3. Magnetic regional anomalies have been also used for interpreting deeply situated geological structures, either at the scale of the Romanian territory or particularly in the Vrancea seismic zone. The ΔZ vertical component of the magnetic field map (1983) had Airinei and Beşuţiu as main promoters, while Cristescu and Ştefănciuc have been main organizers of the airborne magnetic surveys during 1962–1968. The aeromagnetic map was assembled by Sprânceană and Beşuţiu (2006), by compiling the flight panels surveyed at different altitudes and building the ΔT total field map of Romania. Recently, satellite magnetic anomalies have been used by Ioane and Caragea (2015) for interpretation of deeply located regional geological structures across the Romanian territory.

Significant studies for the Romanian territory and the Vrancea seismic zone have been selected as follows:

– ***Gavăt, Airinei, Botezatu, Socolescu & Stoenescu, 1963***: Geophysical model of Romania at the crystalline basement depths, correlating regional ΔZ magnetic regimes with areas affected by geotectonic events of different geological ages;
– ***Airinei, Stoenescu, Velcescu, Romanescu, Visarion, Rădan, Roth, Beşuţiu & Beşuţiu, 1983***: Vertical component (ΔZ) and vertical component anomaly (ΔZa) magnetic maps of Romania, scale 1: 1.000.000;
– ***Beşuţiu, 1984***, The effect of the crustal basaltic layer in the regional anomaly of the geomagnetic field on the Romanian territory;
– ***Calotă, Ioane, & Ion, 1991***: 3D modelling of aeromagnetic anomalies associated to magmatic intrusions in the Gurghiu Mts, East Carpathians;
– ***Sprânceană, Beşuţiu & Dordea, 2006***: ΔT total field aeromagnetic map of Romania upward continuated at 2,600 m altitude;
– ***Ioane & Caragea, 2015***: Interpretation of MagSat satellite magnetic anomalies aiming at locating the deeply buried western boundary of the East European Platform in Romania.

2.4. Seismic refraction studies did not cover the entire Romanian territory with transects, but in each area where they have been carried out, the results represented important milestones for understanding the crustal structures across Romania (Constantinescu & Rădulescu, 1967–1976), or when investigating the Vrancea seismic zone (Hauser *et al.*, 2001; Hauser *et al.*, 2007).

As important results of such seismic refraction projects are here selected the following studies, performed by Romanian, or by Romanian and German geophysicists:

– ***Rădulescu, 1988***: Crustal models in Romania, illustrated in structural maps at Conrad and Moho seismic velocity discontinuities;
– ***Rădulescu & Diaconescu, 1998***: An updated version of refraction seismic profiles, completed with reflectivity information of crustal components in Romania;
– ***Hauser, Răileanu, Fielitz, Bălă, Prodehl, Polonic & Schulze, 2001***: Refraction seismic profile Vrancea'99, carried out between Zimnicea and Bacău, tangent to the East Carpathians Bend Zone and investigating the Vrancea zone crustal structure;
– ***Hauser, Răileanu, Fielitz, Dinu, Landes, Bălă & Prodehl, 2007***: Refraction seismic profile Vrancea 2001, carried out between Tulcea and Aiud, crossing the East Carpathians Bend Zone / Vrancea seismic zone and building a detailed seismic velocity model.

2.5. Magnetotelluric (MT) soundings, carried out on regional profiles, investigated the main crustal and lithospheric structures of the Romanian territory, especially where refraction seismic information was lacking: the East Carpathians. Such studies devoted a particular interest to crustal and lithospheric depth boundaries in Romania, to the Carpathian High Conductivity Anomaly and to the Vrancea seismic zone (Stănică, 1981–2016).

Selected published studies on these topics:

– ***Stănică & Stănică, 1981***: Structural model across the East Carpathians Bend based on recordings on a MT transect;

– ***Stănică & Stănică, 1998***: In the Vrancea zone (Tulnici area), a high conductivity anomaly developed in-depth up to 50 km, was interpreted as representing a sector of the regional Carpathian High Conductivity anomaly, situated beneath faulted sedimentary formations;
– ***Stănică, Stănică & Zugrăvescu, 1999***: Three magnetotelluric profiles crossing the Vrancea zone have been processed to derive resistivity maps at 100 and 150 and 200 km depths. A high resistivity body contoured at 100 and 150 km depths, located between Brașov and Buzău cities, has been interpreted as a sunken slab into the asthenosphere;
– ***Stănică, Stănică, Piccardi, Tondi & Cello, 2004***: Magnetotelluric anomalies interpreted as evidences for a geodynamic torsion of lithospheric structures in the Vrancea zone (East Carpathians).

2.6. Heat flow studies contributed, at the Romanian territory scale (Veliciu, 1987; Demetrescu, 1993) or focusing at the East Carpathians Bend Zone (Andreescu, Demetrescu, 2001), to a better understanding of deep geothermal effects due to geotectonic processes.

Significant published results are mentioned in the following:
– ***Veliciu & Visarion, 1984***: Geothermal models for the East Carpathians area based on boreholes heat flow measurements;
– ***Veliciu, 1987***: Geothermal regime of the Carpathian area presented as heat flow map, with details on the Carpathians, Moldavian Platform and the Moesian Platform;
– ***Demetrescu, Andreescu, Polonic & Ene, 1993***: Maps illustrating the variability of heat flow and geothermic gradient; geothermal crustal models are also presented;
– ***Demetrescu & Andreescu, 1994***: Maps presenting the measured heat flow in Romania, the computed heat flow at 20 km depth and a thermal model of a subducted slab in the East Carpathians Bend zone;
– ***Andreescu & Demetrescu, 2000***: Thermal structure of the lithosphere in the convergence zone of the East Carpathians;
– ***Demetrescu, Wilhelm, Ene, Andreescu, Polonic, Baumann, Dobrică & Șerban, 2005***: Geothermal gradients in boreholes are discussed and interpreted as effects of sedimentation, palaeoclimate changes and fluid flow.

2.7. Seismic tomography studies proved to represent since the mid-90’s the main geophysical tool in studying large lithospheric and mantelic structures situated at depths up to 1,000 km (*e.g.*, Zielhuis, Nollet, 1994; Piromallo, Morelli, 1997; Geyko *et al.*, 2001), as well as past and present tectonic processes, subductions being the most spectacular since the very beginning of this geophysical method (*e.g.*, Wortel, Spakman, 2000). A number of seismic tomography studies have been devoted to the Vrancea lithospheric and upper mantle structure (*e.g.*, Lorentz, 1997; Martin, Wenzel, 2006).

We consider the following as most valuable seismic tomography studies for Romania and the Vrancea seismic zone:
– ***Piromallo & Morelli, 1997***: Spectacular signatures of past or actual subductions in southern Africa and northern Europe, related to the collision between African and Eurasian plates;
– ***Lorentz, Wenzel & Popa, 1997***: Study dedicated to the Vrancea zone, the main result being the interpreted torsion of the lithospheric structures from NE–SW to N–S between two lithospheric slices computed at ca 100 and 200 km, respectively;
– ***Fan, Wallace & Zhao, 1998***: Study dedicated to the territory of Romania, the main results being two NW–SE sections and two NE–SW sections, all sections crossing the Vrancea seismic zone;
– ***Wortel & Spakman, 2000***: Study dedicated to Europe and the Mediterranean area, the velocity anomalies map at 200 km showing lithospheric slabs of past subductions (Calabrian Arc, East Carpathians) or actual subduction (Hellenic Arc);

- ***Martin & Wenzel, 2006:*** Study dedicated to Vrancea zone, showing that the lithospheric slab is developed between Trotuș river and the Intramoesian Fault; the slab is interpreted to be partially detached;
- ***van der Meer, Hinsbergen & Spakman, 2018***: High quality regional velocity anomalies cross-sections, that have been computed across Europe and the neighboring regions, using the HADES software. Of high geotectonic significance for Romania and Vrancea zone are sectors of the seismic tomography sections computed across the Alpine, Carpathian, Aegean and Anatolian areas.

2.8. The **Vertical Electric Sounding (VES)** geophysical technique has been recently employed aiming to detect traces of active regional faults, covered by soil and/or shallow geological formations, in the Vrancea seismic zone (Ioane *et al.*, 2018).

Studies to be mentioned:

- ***Ioane, Nuțu-Dragomir, Diacopolos, Stochici & Stanciu, 2018***: VES profiles have been measured across the southern transcurrent fault in the Vrancea seismic zone;
- ***Nuțu-Dragomir, Ioane, Diacopolos, Chitea & Stochici, 2018***: VES profiles have been measured across the Cașin–Bisoca Fault, at the junction with a NE–SW trending regional fault, the geophysical results illustrating the strike-slip character of the latter one.

2.9. Seismology and seismicity

The numerous scientific studies dedicated to seismological features of the Romanian territory and especially to the Vrancea seismic zone followed specific methodological techniques and data processing software and have a multitude of end-users. That is why the seismological scientific results are not entirely used by geophysicists and geologists in their studies, when relating seismicity to geophysical anomalies and geological structures.

Information continuously updated on the Romanian territory seismicity, or particularly to the Vrancea seismic zone, are to be found in the seismological catalogue built at the National Institute of Earth Physics, known as the ROMPLUS Catalogue (Oncescu *et al.*, 1999 – updated).

Valuable scientific works in Seismology and Geodynamics have been published during the last 60 years in monographs or books, most of them dedicated to the high magnitude seismicity in the Vrancea zone:

- ***Atanasiu, 1961***: First book dedicated to the earthquakes monitoring, including maps with regional intensity of seismic events based on interviews over the Romanian territory. Main seismogenic areas have been analyzed and lineaments with high seismicity have been interpreted;
- ***Cornea, Radu (Eds.), 1979***: An important geodynamic and seismological volume dedicated to the high magnitude March 4th, 1977 earthquake, discussing the earthquake focal mechanism, parameters of the earthquake hypocenter, description of the seismic source, regional distribution of infrastructure and buildings damages, associated light and biological phenomena;
- ***Bălan, Cristescu, Cornea (Eds.), 1982***: A comprehensive seismological, geophysical and geological monograph analyzing the March 4th earthquake in Romania as major seismic event, its precursors and consequences;
- ***Constantinescu, Enescu, 1985***: A book dedicated to seismological analyses of seismic events occurred in Vrancea, prediction possibilities of strong earthquakes, structure of lithosphere and geodynamical interpretation;
- ***Zugrăvescu, Șuțeanu (Eds.), 2005***: A monograph describing Vrancea as a natural laboratory, including contributions on neotectonics, seismic precursors, thermal, rheological features and clustering properties of intermediate-depth seismicity.

3. TECTONIC AND GEODYNAMIC MODELS

Geodynamic and tectonic models have been built for the Vrancea crustal and lithospheric structures during the last five decades using the plate tectonics concept, starting with the “sinking lithosphere” model published by C. Roman (1970).

A large number of tectonic models have been published ever since by Romanian scientists, by foreign researchers or by mixed research teams, based on geological, tectonic, geophysical and geodynamical data.

A small number of previously built geodynamic and tectonic models have been selected and briefly presented in the following, aiming at illustrating the evolution and diversity of envisaged tectonic solutions during time.

3.1. SINKING OCEANIC LITHOSPHERE (Roman, 1970)

First tectonic model for the Vrancea seismic zone, using the newly Plate Tectonics concept at that time, was built by C. Roman, fifty years ago! It was presented during 1970 at the Assemblée Générale de la Commission Séismologique Européenne in Luxembourg, published in Nature, a prestigious scientific journal, and quoted by important papers on regional and continental tectonics (*e.g.*, Dewey *et al.*, 1973).

Considering seismological observations regarding the Vrancea zone recorded before 1970, a 160 km vertical body was interpreted as part of the Black Sea microplate, sinking under the East Carpathians due to the African Plate movements toward the Eurasian Plate.

The cold lithosphere going down into the mantle determined a convective cell and high heat flow. The beginning of the underthrust was considered to be older than the East Carpathians andesitic volcanism, suggesting the geological time needed for the oceanic lithosphere consumption. It would mean that the beginning of the seismic activity in Vrancea is coeval with the Gura Haitei andesites (Lower Sarmatian). The geological and tectonic models presented in Fig. 2 shows stages of subduction of Black Sea oceanic lithosphere, accompanied by magma generation (volcanism and intrusives) and building of the accretionary wedge (sedimentary nappes) (Roman, 1970).

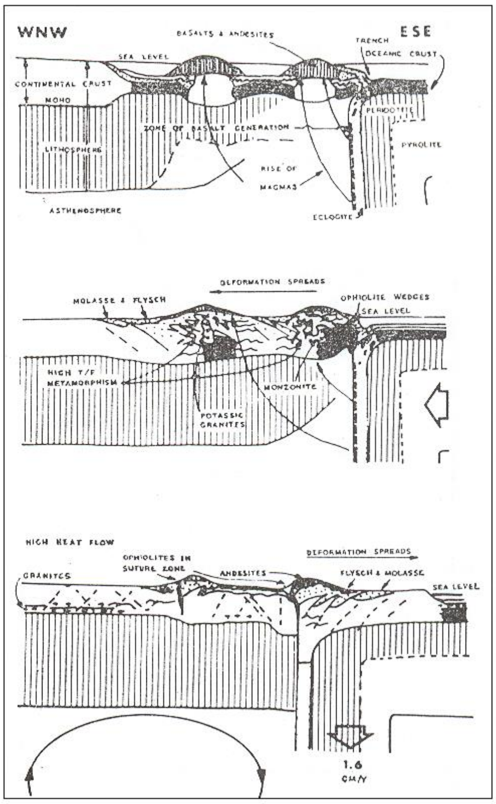


Fig. 2 – Geological and tectonic models illustrating relationships between the sinking oceanic lithosphere, volcanism and tectonics in the Vrancea zone (modified, after Roman, 1970a).

3.2. TRICONFINIUM OF PLATES/SUBPLATES BOUNDARIES (Constantinescu *et al.*, 1976)

This geotectonic model considers Vrancea zone as located at the triconfinium of tectonic plates/subplates: East European, Moesian and Intra-Alpine (Pannonian and Transylvanian blocks) (Fig. 3). The contact between the Moesian and Intra-Alpine subplates was considered to present clear subduction relationships in Vrancea. The active subduction beneath Vrancea was influenced by the Eurasian Plate, as suggested by the interpreted Benioff plane based on intermediate-depth hypocenters and fault plane solutions. The deep Sarmatian–Pliocene Depression (Focșani–Odobești Depression) was considered to represent an effect of subduction processes generated in the upper mantle. The subducted Benioff zone is shown in a cross-section to be affected by shearing processes and includes the deep earthquakes; other seismic events are occurring on faults developed between the Benioff zone and the Moho discontinuity.

Along the north-western part of the East European Plate contact, the subduction was considered “frozen”, while active subduction Benioff plane is situated beneath the Focșani Depression (Constantinescu *et al.*, 1976 – Fig. 3).

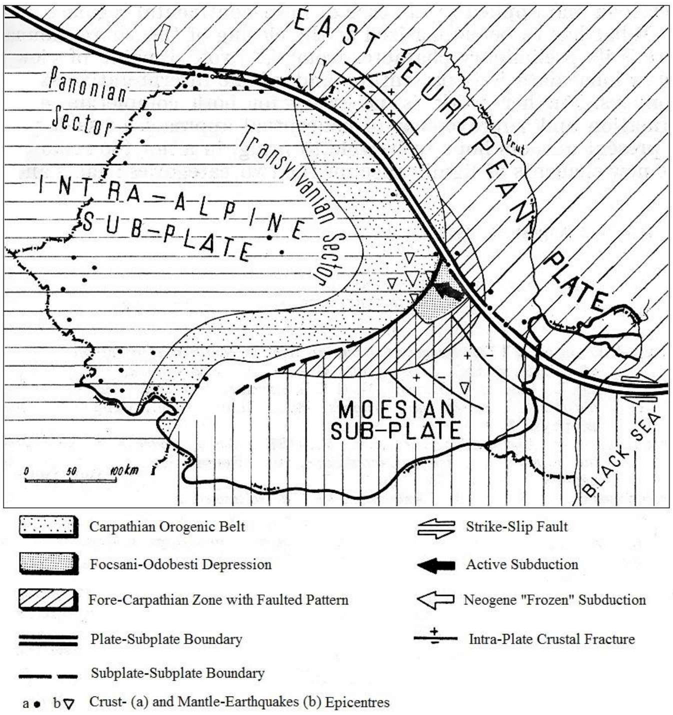


Fig. 3 – Triconfinium of plates/subplates and active subduction in Vrancea seismic zone (Constantinescu *et al.*, 1976).

3.3. GEODYNAMIC MODEL OF THE ROMANIAN TERRITORY (Airinei, 1977)

The geodynamic model presented in Fig. 4 was built by Airinei (1977) by considering the regional Bouguer low gravity anomalies as boundaries between plates and microplates on the territory of Romania. It represented a first interpretation at this scale of ideas and hypotheses generated at that time by Romanian and foreign geoscientists within the plate tectonics concept, including the Black Sea microplate as having an active role in subduction and collision processes (*e.g.*, Roman, 1970; McKenzie, 1972).

The arrows indicating the plates/microplates movements in Fig. 4 suggest convergence and subduction processes:

a) along the East Carpathians, between the East European Plate and the Intra-Alpine microplate;
b) between the Intra-Alpine microplate and the Black Sea microplate, at the East Carpathians Bend Zone.

This geodynamic model has been employed as state of the art for the Carpathians region in numerous regional geodynamics and geophysical international projects especially during the 90's, when the Romanian territory or the Vrancea zone has been involved.

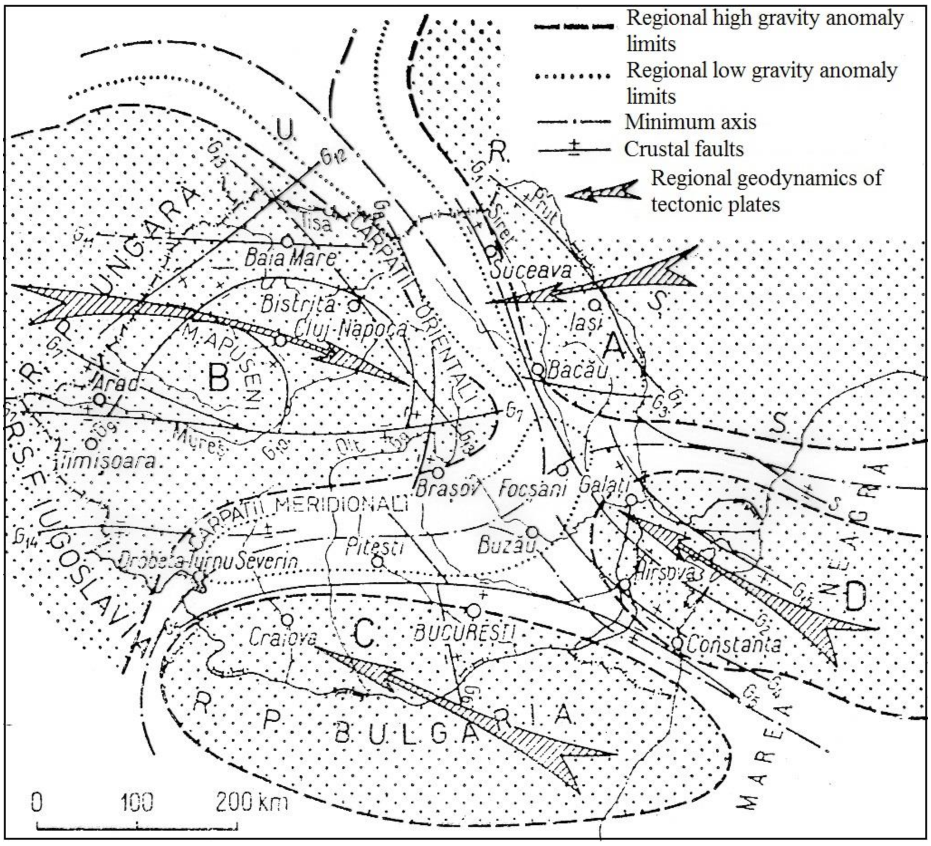


Fig. 4 – Geodynamic model for the Romanian territory based on Bouguer gravity anomalies (Airinei, 1977).

3.4. MODEL OF LITHOSPHERE DELAMINATION AND ASTHENOSPHERE UPWELLING
(*e.g.*, Gîrbacea, Frisch, 1998)

The model intended to reconstruct the geological and tectonic evolution since the Pliocene of the East Carpathians Bend Zone. Subduction related continental collision between the Tisza–Dacia microplate and the East European Plate was followed by break-off of the west-dipping slab, determining lithospheric delamination and finally, movement of the Vrancea slab in its actual location.

Delamination was followed by asthenospheric upwelling, magma generation and basaltic volcanism in the Perșani Mts. and calc-alkaline in Harghita Mts.

The vertical slab in Vrancea was illustrated in the tectonic models as a segment of the delaminated lithospheric mantle, seismically active due to the gravitational pull of the eclogitized subducted oceanic lithosphere (Fig. 5). The authors considered as a contradictory situation (slab in the wrong place!) the eastern position of the interpreted slab, with respect to the suture zone location (Gîrbacea & Frisch, 1998).

The source of the calc-alkaline magma generated in the subduction zone was displaced eastward by the delaminating slab and partly mixed with mafic magma.

The distance between the present time position of the slab and the initial location of slab break-off is ca 130 km. The present time intermediate-depth seismic activity suggests that the seismogenic slab is 130 km long – it was once delaminated and subsequently rotated to a vertical position (Girbacea & Frisch, 1998).

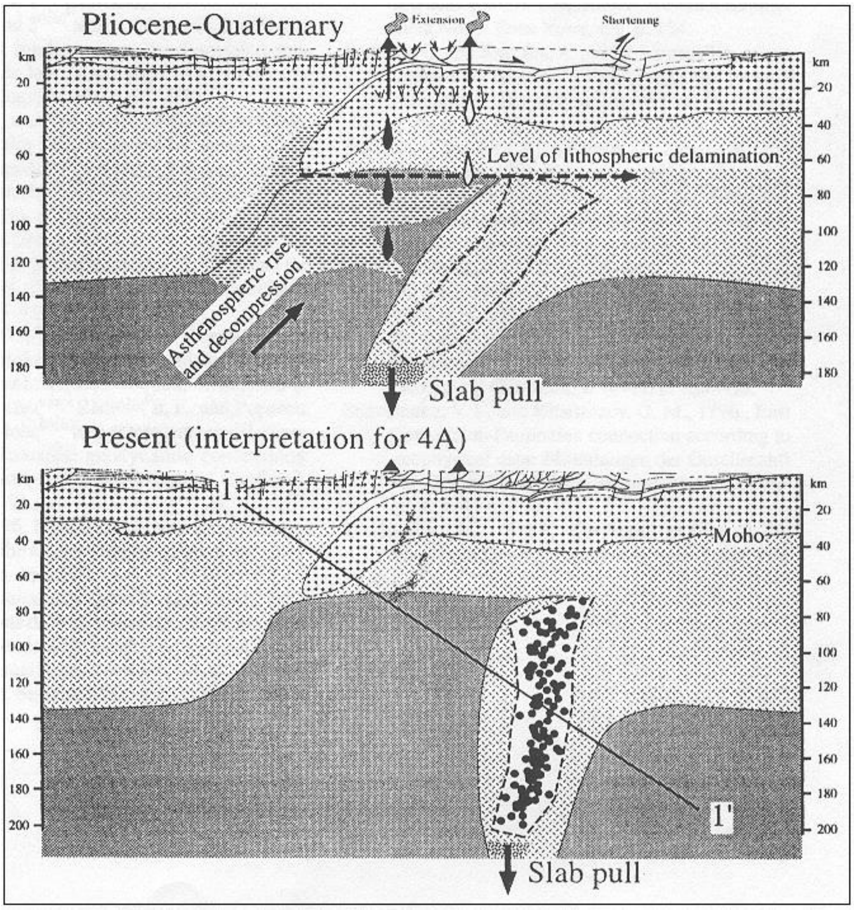


Fig. 5 – Model of lithosphere delamination and asthenosphere upwelling (modified, after Gîrbacea & Frisch, 1998).

3.5. ALTERNATIVE SUBDUCTION RELATED TECTONIC MODELS IN THE VRANCEA SEISMIC ZONE (Gîrbacea & Frisch, 1999, in Sperner *et al.*, 2004)

Several international scientific projects dedicated to the Vrancea strong seismicity, involving Romanian and foreign researchers, tried hardly to understand the present time deep tectonics and geodynamics of the East Carpathians Bend Zone and its clustered intermediate-depth seismicity.

Possible tectonic solutions for the Vrancea zone have been collected or imagined some twenty years ago by Gîrbacea & Frisch (1999), briefly illustrating results of geoscientist brain storming sessions and fruitful scientific debates of that time.

There were numerous Pro and Con arguments for each tectonic model presented in Fig. 6, but unfortunately, none of them could at that time, or can be considered nowadays, as the final Vrancea tectonic model, explaining everything and convincing everyone.

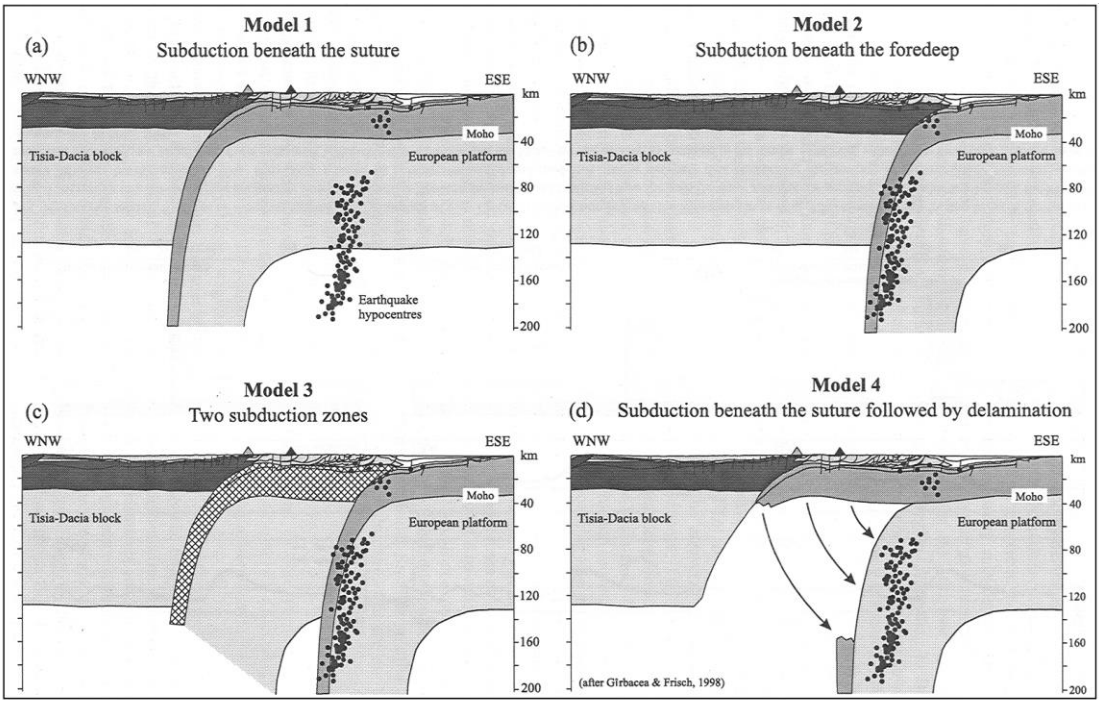


Fig. 6 – Alternative tectonic models involving subduction, collision and seismicity in the Vrancea zone (Gîrbacea & Frisch, 1999, in Sperner *et al.*, 2004).

4. WRENCH TECTONICS SYSTEM

A wrench tectonics system has been recently interpreted crossing the Romanian territory, the two transcurrent faults trending NE–SW, at least between Prut and Danube rivers. The wrench tectonics system was suggested at the regional scale by the EGG 97 geoidal anomalies along TESZ in the region of the East Carpathians. The EGG 97 gravimetric geoid map, presented in Fig. 7 – Left, represents a smoothly filtered version, sampled in a 50 km squared grid to allow data processing. The straight NW–SE lineament observed across Poland and Ukraine, with rapid variations of the geoid heights, rapidly change while entering in Romania to a reversed ***S*** shaped letter, first displaced eastward and subsequently westward (Ioane & Stanciu, 2018).

Since geoidal anomalies are determined by deeper density inhomogeneities than the gravity anomalies (Ioane *et al.*, 1993), the rapid variations in geoid heights are interpreted as being determined by the western boundary contact of the East European Platform (EEP) with the European Palaeozoic Platform, the Panonnian Basin, the Tisza–Dacia tectonic block and the Moesian Platform western compartment. The thinner crust and lithosphere of the westerly located tectonic blocks, as compared to the East European Platform, determine the sudden increase of the geoidal values over short distances along TESZ, due to uplifted position of higher density upper mantle rocks.

A processing technique usually employed to detect fault systems and tectonic contacts (horizontal gradient of Bouguer gravity anomalies) was applied over the EGG 97 geoidal gridded values. The resulted map, presented in Fig. 7 – Right, illustrates by elongated high anomalies (colored in yellow and orange) deep tectonic contacts or regional fault lines with significant vertical displacements of compartments. The NW–SE trending anomalies are interpreted as being due to the western boundary of the East European Platform (TESZ), shifted south-westward at the East Carpathians Bend Zone, and continued with the same trend across the Moesian Platform and the eastern part of Bulgaria.

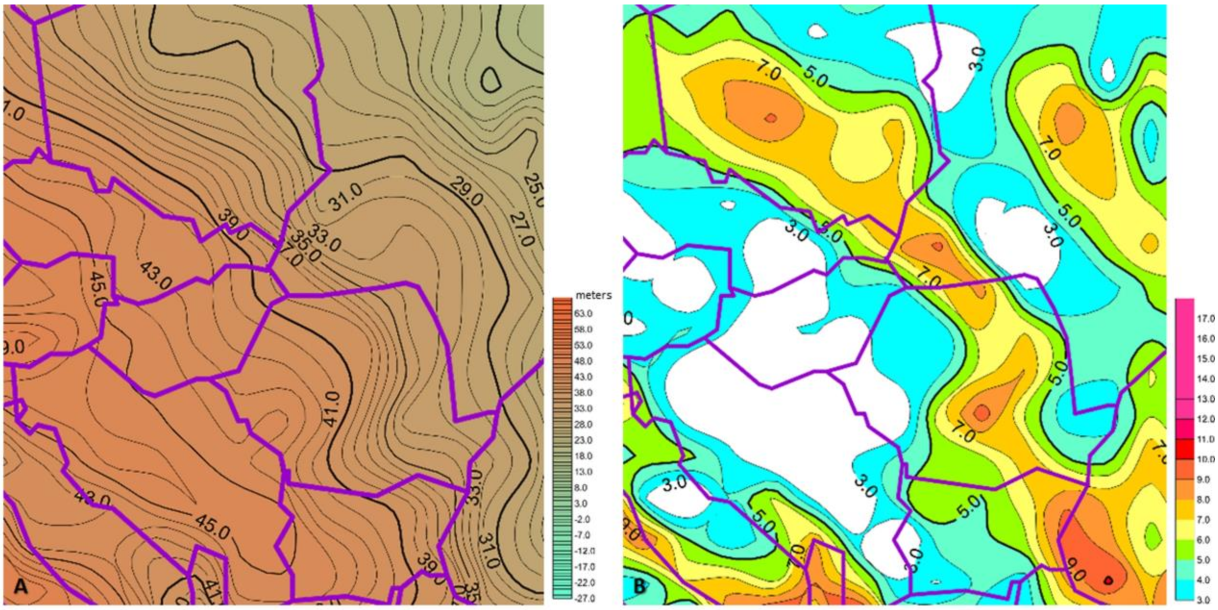


Fig. 7 – Left: EGG 97 geoidal anomalies along TESZ.
Right: Variability of geoidal heights with distance (Ioane & Stanciu, 2018).

The NE–SW trending anomaly, shifting TESZ within the Vrancea zone, is interpreted as being due to a wrench tectonics (WT) system with two regionally developed parallel transcurrent faults: WT Northern Fault and WT Southern Fault (Fig. 8).

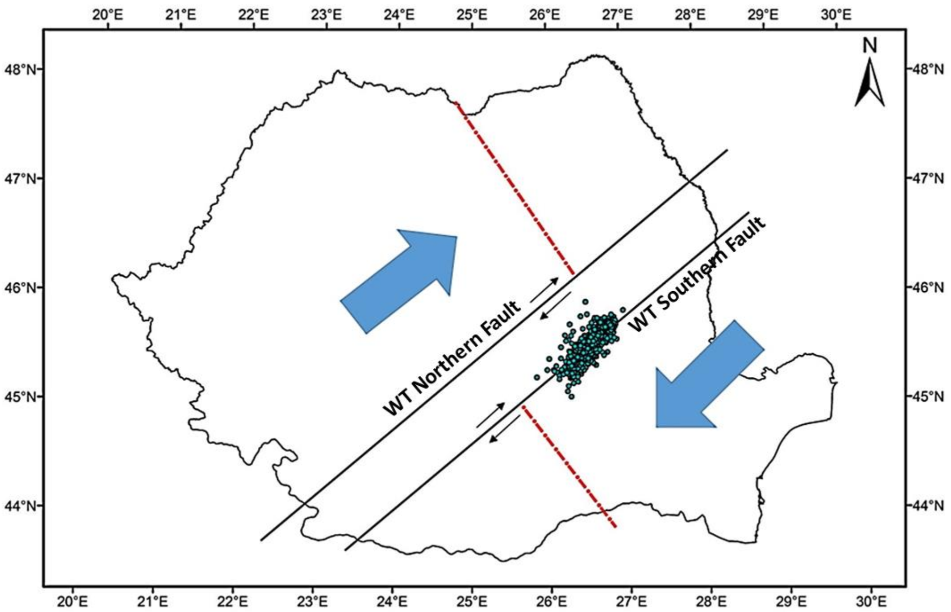


Fig. 8 – Regional geodynamic model and wrench tectonics system across Romania.
Black lines: trancurrent faults; Red dotted lines: western EEP boundary; Green circles: subcrustal Vrancea seismicity; Black arrows: strike-slip displacements; Blue arrows: regional geodynamic movements
(modified, after Ioane & Stanciu, 2018)

When analyzing regional tectonics and seismicity in Albania and Romania it turned out that there are geological, remote sensing and seismological observations sustaining the south-westward continuation of the transcurrent faults, and hence of the wrench tectonics system, till the Adriatic Sea (Ioane & Stanciu, 2020).

Considering the NE–SW trending and elongated shape of the regional distribution of seismic energy provided by the Vrancea strong earthquakes, the wrench tectonics transcurrent faults may be continued north-eastward till the Dniester river.

The entire transcurrent faults transect is developed on ca 1 000 km, between the Adriatic Sea in Albania and the Dniester river in Republic of Moldova.

Since the editorial format of the previous papers dealing with this topic was too tight (Ioane & Stanciu, 2018; Ioane & Stanciu, 2019), there will be given in the following several examples using magnetic anomalies and geomorphological features as “markers” when interpreting the transcurrent faults transects in Romania.

4.A. MAGNETIC ANOMALIES AS WRENCH TECTONICS MARKERS

A1. Thin and elongated ΔT aeromagnetic anomaly following the NNW–SSE Caşin–Bisoca tectonic contact, due to andesitic tuff layers included within Lower Sarmatian–Upper Meotian sediments (Dumitrescu *et al.*, 1970), which changes to NE–SW direction toward Bisoca, after crossing the wrench tectonics system (WTS) southern transcurrent fault (Fig. 9).

Considering this interpretation, the onset of the wrench tectonics systems should be earlier than Lower Sarmatian–Upper Meotian, in case of coeval andesitic volcanism and sin-sedimentary tectonic horizontal movements.

A2. Large and W–E elongated ΔT magnetic anomaly in the Moesian Platform, possibly due to granodioritic intrusions within the upper crust crystalline formations, which abruptly changes direction toward NE–SW, following the fault strike-slip southwestward movement (Fig. 10).

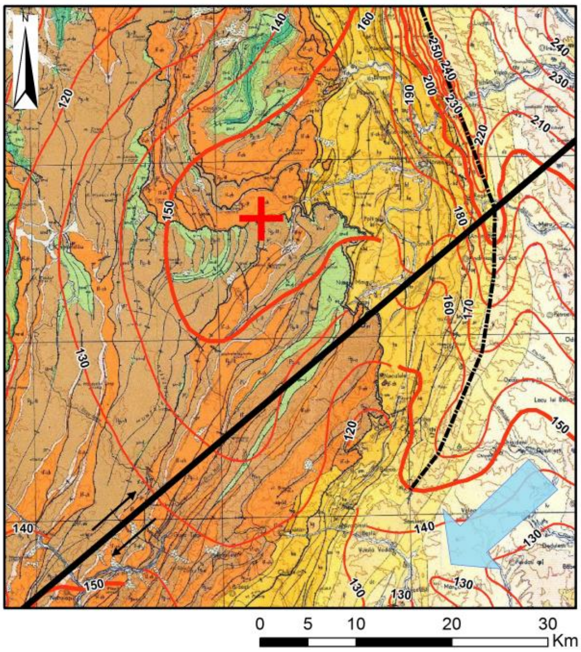


Fig. 9 – Aeromagnetic anomalies in the Vrancea seismic zone (Cristescu & Ştefănciuc, 1962-1968).
Red lines: aeromagnetic anomalies; Dotted black line: axial trend modification due to WT; Black line: WT Southern Fault;
Black arrows: strike-slip fault; Blue arrow: regional WT geodynamic movement;
Geological data: Dumitrescu *et al.*, 1970.

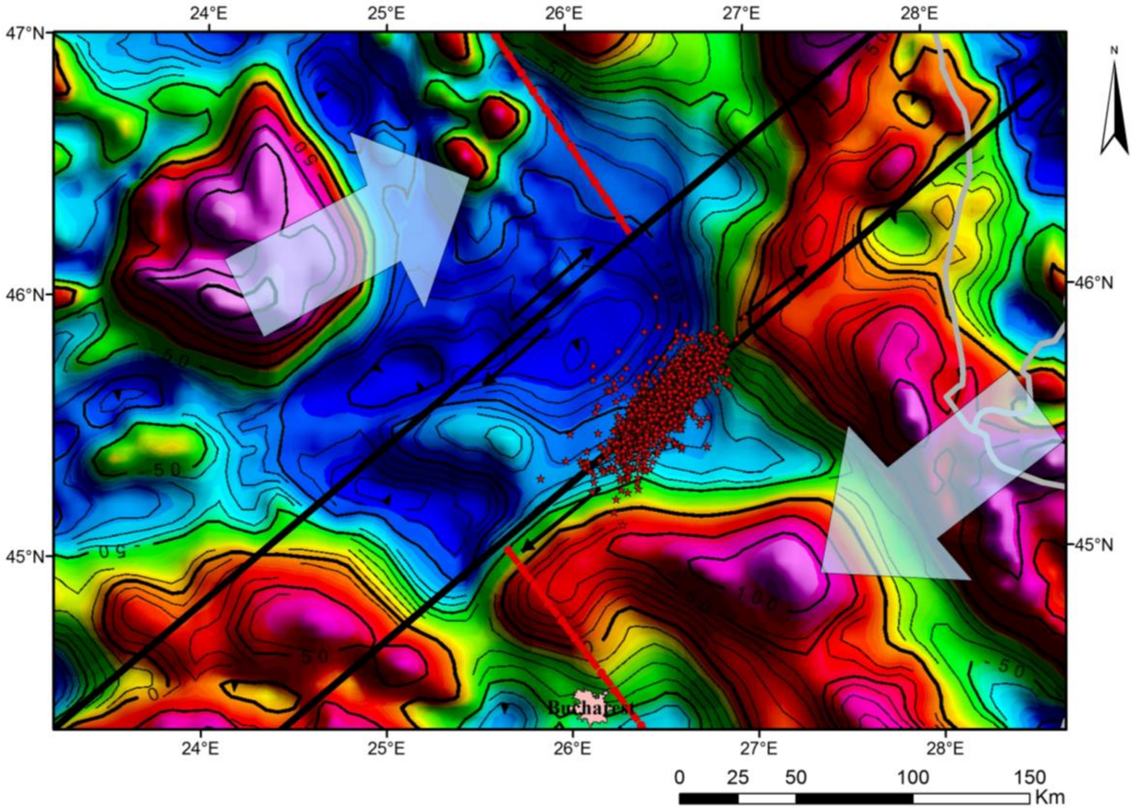


Fig. 10 – Horizontal movements along the WT trascurrent faults illustrated by ΔT magnetic anomalies. Red: high magnetic anomalies; Blue: low magnetic anomalies; Black lines: WT transcurrent faults; Red dotted lines: western EEP shifted boundary; Red stars: subcrustal Vrancea seismicity (Magnetic data – WDMAM 2.0, http://wdmam.org/, accessed 2018).

A3. Elongated NW–SE ΔT magnetic anomaly associated to the North Dobrogean Promontory due to magmatic intrusions and high magnetic metamorphic formations, developed till the WT Southern Fault, rapidly changes direction toward ENE–WSW after crossing the southern transcurrent fault, due to the fault strike-slip north-eastward movement (Fig. 10).

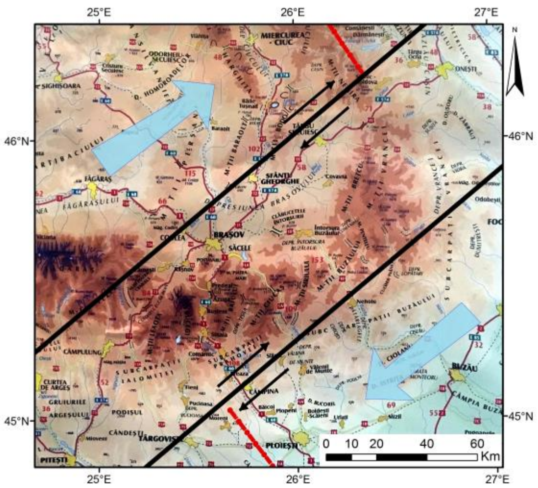
A4. The elongated aeromagnetic ΔT anomaly, trending NNW–SSE along the East Carpathians from the Ukrainian border till Piatra Neamț city, has been displaced north-eastward along the Prut river, due to the fault strike-slip north-eastward movement (Fig. 14).

4.B. GEOMORPHOLOGICAL AND GEOLOGICAL FEATURES AS WRENCH TECTONICS MARKERS

B1. Specific WT diagonal trending modification of structures situated between wrench tectonics transcurrent faults (Zolnai, 2000), applied to the Carpathian mountainous ranges situated between the WT Northern and Southern faults: Iezer Mts, Leaota Mts., Bucegi Mts., Ciucaș Mts., Siriu Mts., Buzău Mts., Vrancea Mts. The mountainous ranges look like diagonal NNE–SSW trending stripes, as compared to W–E trending in the South Carpathians and NNW–SSE in the East Carpathians, respectively (Fig. 11).

B2. Change of the N–S and NNW–SSE directions in the Gurghiu Mts. into NW–SE in the Harghita Mts., after the onset of the regional Wrench Tectonics system. As a consequence, the Harghita Mts., the youngest segment of the Neogene magmatic belt, crossed the sedimentary nappes of the East Carpathians due to changes of the subduction geometry. Considering this interpretation as a time marker for the onset of the wrench tectonics horizontal displacements in that region determined by the WT Northern Fault, the resulted age is the Pontian.

B3. The presence of isolated hills in the close vicinity of the WTS transcurrent faults: Măgura Codlea (1292 m), associated with the WT Northern Fault, and Măgura Odobești (1,001 m), associated with the WT Southern Fault. It is likely that these geomorphological features have been built by the most intense horizontal terrain movements close to the transcurrent faults, locally stopped and delayed by NW–SE trending faults or accumulations of unconsolidated geological formations. That could be the case of Măgura Odobești, where Quaternary Cândești gravel has been mapped on top of it, at 1,000 m altitude. In case this hypothesis is correct, wrench tectonics processes could explain folding and uplifting of Quaternary geological formations in this region, instead of the postulated Wallachian tectonic phase (Săndulescu, 1984).



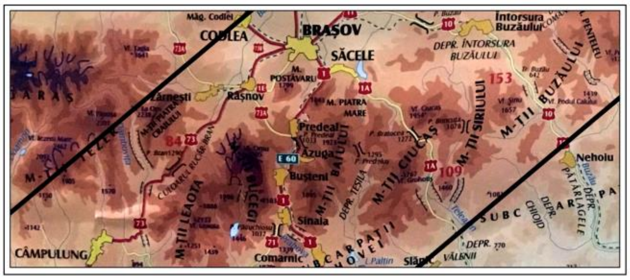


Fig. 11 – Geomorphological diagonal features determined by Wrench Tectonics at the Carpathian Mts Bend Zone. Black lines: transcurrent faults; Black arrows: strike-slip faults; Blue arrows: geodynamic movements (Geographical data – Physical map of Romania, Ielenicz, 2000).

As significant geological consequences of tectonic processes determined by a wrench tectonics system (Zolnai, 2000), several interpreted tectonic uplifts are to be mentioned in this stage of our research, all included between the transcurrent faults:

a) Vrancea tectonic half-window of the Tarcău sedimentary nappe (Săndulescu, 1984), uplifted by subjacent geological structures vertical movement and exposed to active erosion processes;

b) the Craiova–Balș structural uplift located in the western part of the Moesian Platform including crystalline basement, Palaeozoic sediments and magmatic intrusions (*e.g.*, Paraschiv, 1979; Mutihac, 1990, Ioane *et al.*, 2005). Geophysical data showed that the bimodal magmatic intrusions, pierced here by boreholes, represent the upper part of a deeply enrooted intrusion (Fig. 18: CBU – Craiova – Balș Uplift), clearly illustrated by seismic tomography velocity anomalies till 175 km depth (Geyko, 2001).

c) ophiolitic structures in Albania, as contoured by high intensity aeromagnetic anomalies.

5. REGIONAL GEODYNAMICS

5.1. REGIONAL TECTONIC VORTEX

Romania and the Vrancea seismic zone are situated in a region characterized by active geodynamics determined since the Miocene (*e.g.*, Dewey *et al.*, 1973), by the collision between the African and Eurasian plates, leading to subduction processes in three areas situated in a triangular area:

– ***Adriatic Sea (Albania):*** ended subduction determined by lateral escape of the Adriatic microplate, WSW–ENE directed compression, continental collision, high seismicity in the Durres–Shkoder zone;
– ***East Carpathians (Romania):*** ended subduction determined by lateral escape of the Adriatic microplate and compressional regime determined by the Tisza–Dacia tectonic block towards the East European Platform, subduction directed SW–NE, W–E and finally NW–SE, volcanism in the Călimani–Gurghiu–Harghita magmatic belt, high seismicity in the Vrancea zone;
– ***Hellenic Arc (Mediterranean Sea),*** active subduction determined by the S–N movement of the African Plate toward the Eurasian Plate beneath the Aegean Sea, active volcanism in the Aegean islands (*e.g.*, Santorini), moderate to high seismicity associated to subduction processes.

Geodynamics projects based on satellite geodesy carried out in this region, showed horizontal displacements of continental blocks characterized by variable trending and intensity (*e.g.*, Hefty, 2004; Munteanu, 2009; Jouanne *et al.*, 2012).

When considering the S–N compressional tectonic regime determined by the African and Arabian plates, the field velocity vectors display a sort of ***clockwise regional tectonic vortex***: SW–NE in Italy toward Albania and Croatia, NW–SE in SE Romania and Bulgaria, E–W in Turkey, NE–SW in the Aegean Sea and S–N in Egypt toward Greece.

5.2. NEWS ON THE REGIONAL GEOLOGY AND GEODYNAMICS IN ROMANIA

The East European Platform (EEP), which will be used in the following instead of the Eurasian Plate, is located in Romania east of the East Carpathians, till the Prut river. It will be further discussed in this paper on a larger area, being continued southward to include the North Dobrogean Orogen (NDO), the North Dobrogean Promontory (NDP) and the Moesian Platform (MP) eastern compartment. There are geophysical data to sustain this new regional tectonic model, such as the 3D stripped gravity map (Fig. 12 – Ioane & Caragea, 2015), seismic tomography maps at different depths (*e.g.*, Piromallo & Morelli, 1997) or cross-sections (*e.g.*, van der Meer *et al.*, 2018), already discussed and interpreted in some of our recent scientific works (*e.g.*, Ioane & Caragea, 2015; Stanciu, 2020).

Regional geological information which may be in favor of unifying EEP, NDO and NDP as the western margin of the East European Platform in Romania is the map of the pre-Vraconian geological formations, where Silurian, Devonian, Carboniferous and Triassic sediments are equally present north and south of the Bârlad Depression (BD); they are also present in BD, but at deeper levels beneath Jurassic formations (Săndulescu & Popescu, 1969).

The North Dobrogean Orogen (NDO) represents the south-western crustal margin of the East European Platform, as it is geophysically depicted by the high aeromagnetic regional anomalies in the eastern part of Romania (Fig. 14). The interruption of the aeromagnetic and magnetic anomalies regional continuity, as observed in Figs. 14 and 15, was determined by the high compressional regime associated with the Adriatic microplate lateral escape.

Successive extensional and compressional processes created the North Dobrogea Orogen and its concealed north-western continuation, the North Dobrogean Promontory.

The graben-like structure interpreted on the refraction seismics velocity model (Fig. 25 – Hauser *et al.*, 2007) is considered in this study to represent the prolongation of the Polish Trough along the EEP western margin; it continues south-westward as the Romanian Trough (Ioane *et al.*, 2019), along the western EEP limit toward the Alexandria Depression. As mentioned above, we interpret the EEP western boundary within the Moesian Platform either the Intramoesian Fault, or the High Seismicity Boundary (Stanciu, 2020). The continuity of the Polish Trough into the Romanian Trough along the East European Platform western margin may be preserved till the Alexandria Depression (southern Romania), only if the Moesian Platform eastern compartment is part of EEP.

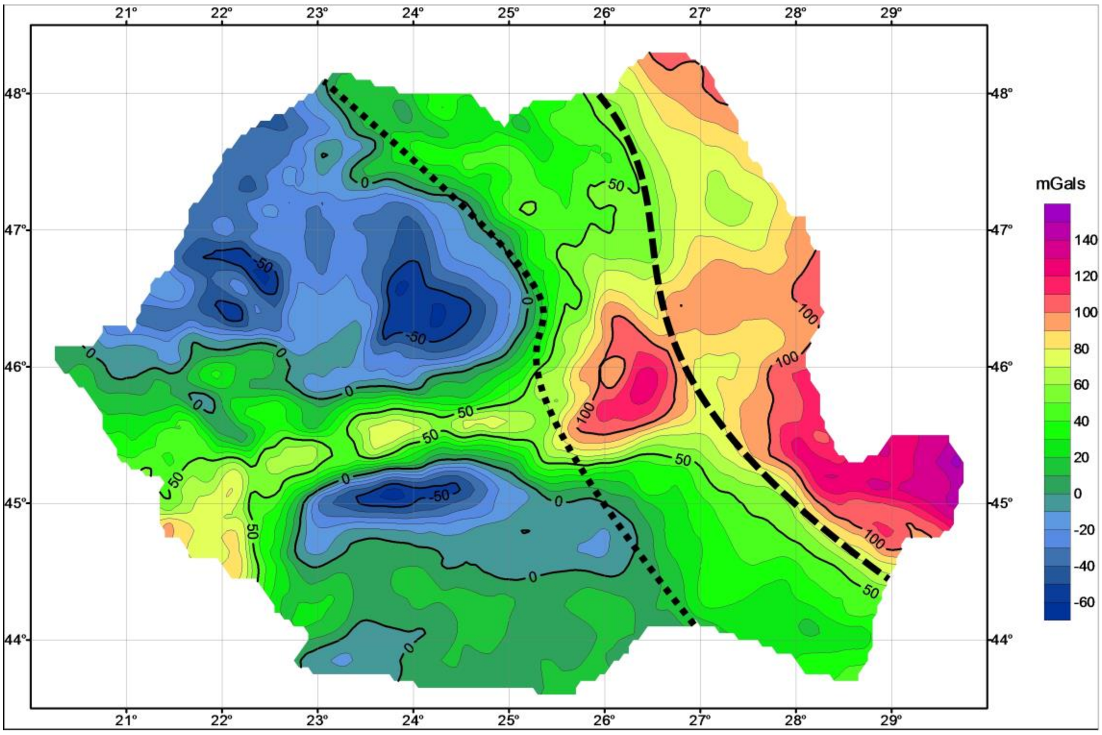


Fig. 12 – Gravity stripped map of Romania.
Black dashed line: EEP western boundary at the crystalline basement depths;
Black dotted line: EEP south-western boundary at deeper depths
(Ioane & Caragea, 2015, modified after Ioane & Ion, 2005).

There was a similar interpretation provided by Săndulescu (1984), which continued the Miechow Depression from Poland, through the Focșani Depression and finally into the Alexandria Depression, but not considering the Moesian Platform eastern compartment as part of the East European Platform. It was a valuable hypothesis on the development of regional geological structures, but for reasons presented above it was not tectonically possible.

The regional wrench tectonics system, as it was recently interpreted (Ioane & Stanciu, 2018; Ioane & Stanciu, 2020), was probably initiated during the Pannonian, considering the Central Paratethys stratigraphic chart, as a consequence of the compressional tectonic regime climax determined by the Adriatic microplate lateral escape, suite of post-subduction collision and docking processes in the East Carpathians. It was considered that the actual position of wrench tectonics transcurrent faults, which develop NE–SW on ca 1,000 km through orogenes (Albanides, Balkans and East Carpathians), platforms (Moesian, East European) and a depressionary area (Transylvanian), was conditioned by the northward limit of the Hellenic Arc subduction zone, presently advanced till southern Bulgaria at ca 100 km depth. It is likely that the cold massive subducted structure was more difficult to break and displaced as compared to the more viscous asthenosphere and younger, thinner and "warmer" lithosphere (Ioane & Stanciu, 2000).

5.3. BREAK OF THE EAST EUROPEAN PLATFORM FOREFRONT

We consider that one of the most important tectonic events, generated during the Miocene (Pannonian) in this region by the Adriatic microplate lateral escape, due to intense W–E directed compressional regime, was the break of a block of the East European lithosphere western margin of ca 200 km long and 250 km thick, as illustrated by the seismic tomography section presented in Fig. 13.

The seismic tomography section presented in Fig. 13 illustrates the East European Platform (Eurasian Plate) rupture by a vertical thin red "channel" at about 22 degrees (van der Meer *et al.*, 2018). The EEP broken block includes southern East Carpathians and the East Carpathians Bend Zone; the rolled-back oceanic slab, attached to the EEP broken margin, was backward displaced due to deep compressional tectonic regime determined by the Hellenic active subduction and its oceanic slab dynamics, the latter attached to the African Plate at depths below 400 km (Fig. 13).

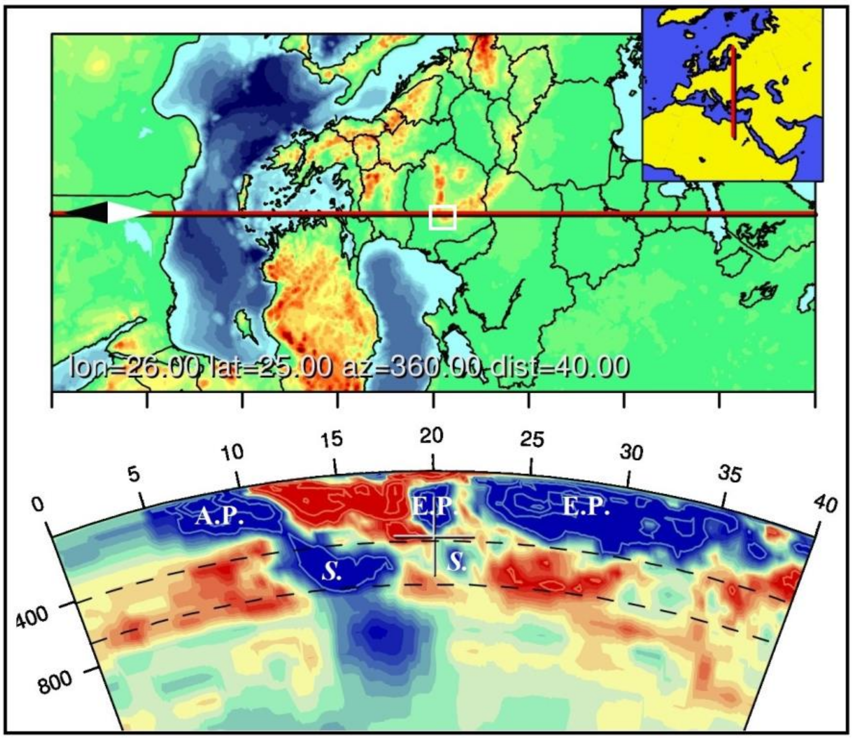


Fig. 13 – Seismic tomography section crossing the East Carpathians Bend Zone.
Blue (0–300 km): Eurasian (E.P.) and African (A.P.) plates; Blue (300–700 km) oceanic subducted slabs (S);
South: Hellenic Arc active subduction; North: slab break-off and continental collision
(modified, after van der Meer *et al.*, 2018).

The aeromagnetic map shows the area where upper crustal Tisza–Dacia metamorphic structures, characterized by low magnetic anomalies, have been displaced eastward and replaced the East European Platform highly magnetic ones. It determined an interruption in the area of present-day Piatra Neamț and N Bacău cities of the trans-continental elongated high magnetic anomalies, stretching between the Baltic Sea and the Black Sea (Fig. 15).

Significant tectonic consequences, suite of tectonic regional compression and onset of the wrench tectonics system, possible to be interpreted on the aeromagnetic/magnetic maps:

a) the north-western continuation of the North Dobrogean Promontory was abruptly diverted toward ENE, between the WT transcurrent faults;
b) the broken sector of the EEP western boundary was pushed eastward and then north-eastward, the latter suite of horizontal displacements along a regional NNW–SSE strike-slip fault (Figs. 14 and 15).

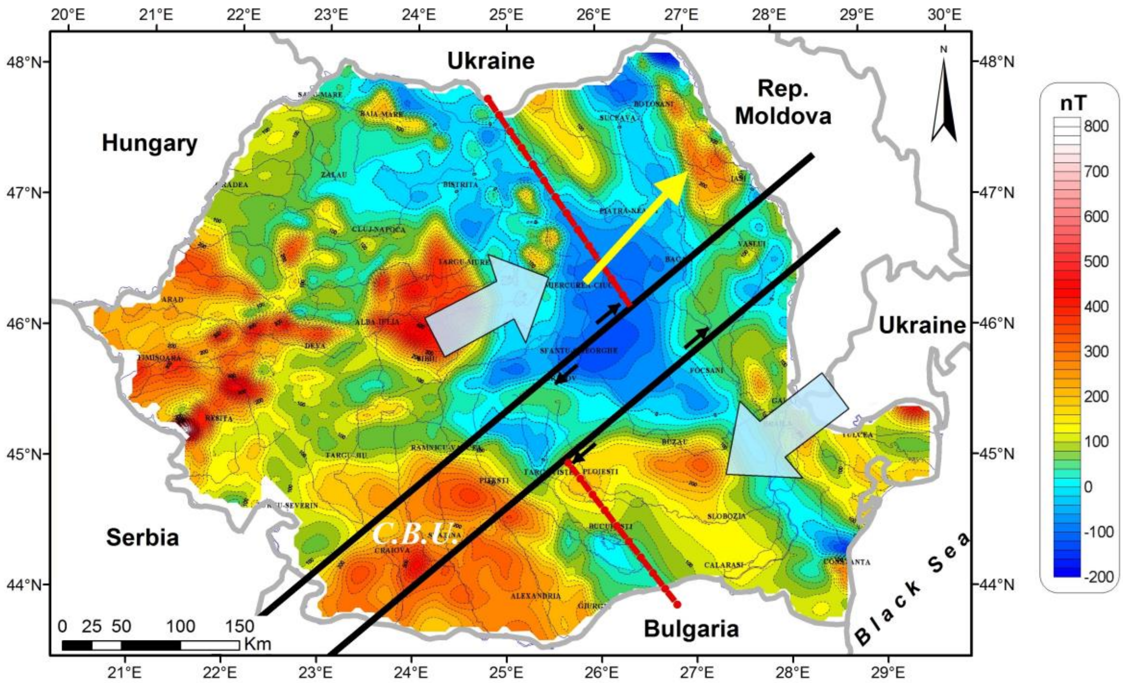


Fig. 14 – The aeromagnetic anomaly map of the Romanian territory at 2,600 m altitude
(modified, after Sprânceană *et al.*, 2006).
Black lines: WT transcurrent faults; Black arrows: strike-slip fault; Red lines: EEP western boundary;
Blue arrows: geodynamic regional movements; Yellow arrow: EEP margin north-eastward displacement.

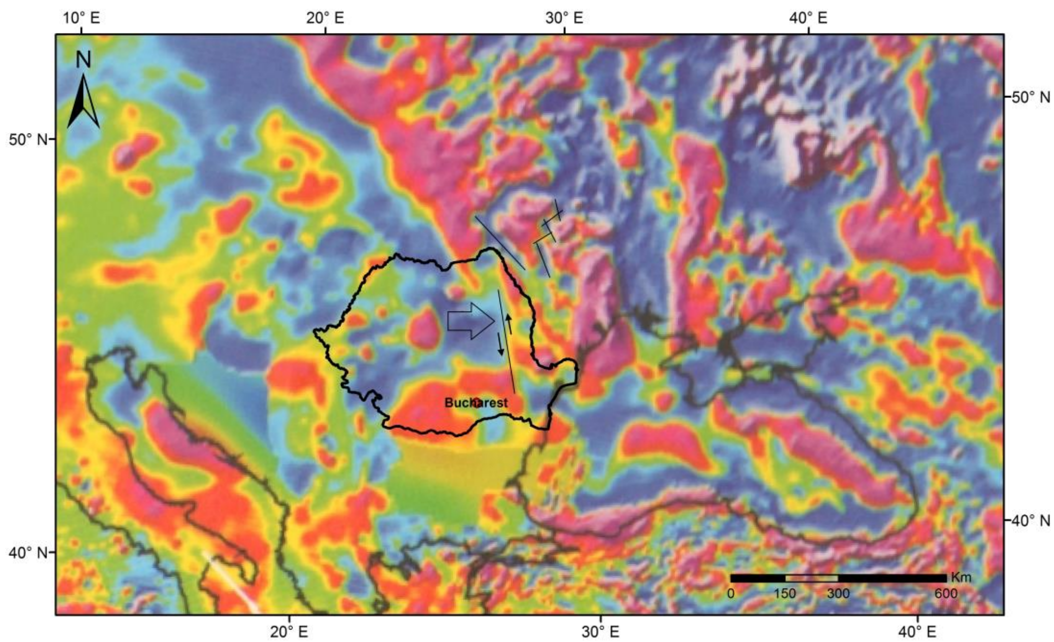


Fig. 15 – Magnetic anomalies in Central and Eastern Europe.
Hollow arrow: eastward displacement of the EEP boundary; Black line: strike-slip fault (Ioane & Caragea, 2015)
(Magnetic data, modified after Korhonen *et al.*, 2007).

The regional magnetic map illustrates the continuation of the high magnetic East European Platform western margin in Poland and Ukraine, its interruption in NE Romania and the eastward displacement along the Prut river of the crustal ruptured margin (Fig. 15).

The EEP lithospheric ruptured margin may be interpreted on seismic tomography sections (van der Meer *et al.*, 2018) as trending NW–SE toward Adjud, partly parallel to the Trotuş river, and then toward N Galaţi, till the Prut river.

Present-day data show that toward SE the EEP lithosphere rupture, interpreted in Fig. 13, gradually changes to thinned lithosphere, as it may be observed in Fig. 16, between 20 and 25 degrees, which may turn again to broken lithosphere with deepening of the EEP ruptured block, as it may be interpreted in Fig. 18.

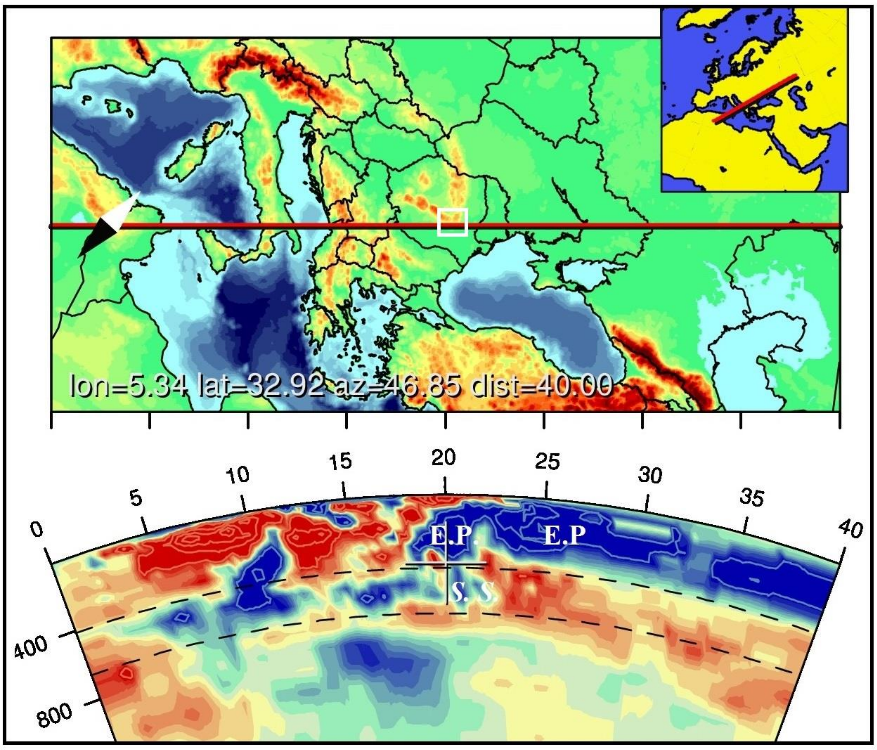


Fig. 16 – Seismic tomography section tangent to the East Carpathians Bend Zone.
Blue (0–400 km): Eurasian Plate (E.P.); Blue (400–700 km): oceanic subducted slab (S)
(modified, after van der Meer *et al.*, 2018).

The strong compressional tectonic regime generated by the Adriatic microplate lateral escape during the Pannonian, determining the onset of the NE–SW regional wrench tectonics system between the Adriatic Sea and the Dniester river, had important tectono-magmatic consequences:

– after the eastward “invasion” of Tisza–Dacia crustal structures into the East European Platform realm the subduction plane became oblique, meaning NW–SE, as considering the N–S trending of the East Carpathians geological structures;

– due to the replacement of high magnetic EEP metamorphic basement with lower magnetic Tisza–Dacia one in the area situated between Siret river and the East Carpathians sedimentary nappes, a Caledono–Hercynian platform was geophysically interpreted and geologically located between the East European Platform and the Carpathian Orogene, aiming to explain the large low magnetic anomaly (*e.g.*, Săndulescu & Visarion, 1988). Considering the geodynamic and tectonic aspects interpreted and described to have happened during the Pannonian, there is no longer need of another platform, such as the Scythian Platform, between the East European Platform and the Tisza–Dacia tectonic block;

– when the western margin of the East European Platform was broken and Tisza–Dacia crustal structures moved eastward for tens of km into the EEP realm, volcanism in the East Carpathians magmatic belt changed direction. The Neogene–Quaternary volcanism migration along the arc in S Gurghiu and Harghita Mts. changed direction from NW–SE (12 Saca to 13 Borzonț volcanic structures) to W–E (14 Șumuleu to 15 Ciumani–Fierăstrae and possibly, 16 Răchitiș volcanic structures) and then NW–SE (17 Ostoros to 24 Ciomadul volcanic structures) (Fig. 17). Most probably, the W–E migrating volcanism took place during the EEP crustal rupturing.

– after the time interval requested by the new arrangement of the East European Platform western margin, oblique to the East Carpathians chain, the volcanism resumed with NW–SE trending in the Harghita Mts. by crossing the Carpathian structures (Szakàcs *et al.*, 1993);

– the oblique subduction that continued in the southern part of East Carpathians generated a NE–SW directed oceanic slab, preserved beneath the Moesian Platform western compartment (Fig. 18).

The unconsumed oceanic slab preserved beneath the Moesian Platform may be explained by the lack of an oceanic lithosphere accumulation zone (oceanic lithosphere “graveyard”) between depths of 400 to 700 km in that region, where the oceanic slab should have continuously outpoured during subduction; it was probably displaced by the deep compressional regime and upper mantle dynamics induced by active subduction along the Hellenic Arc (Figs. 13 and 16).

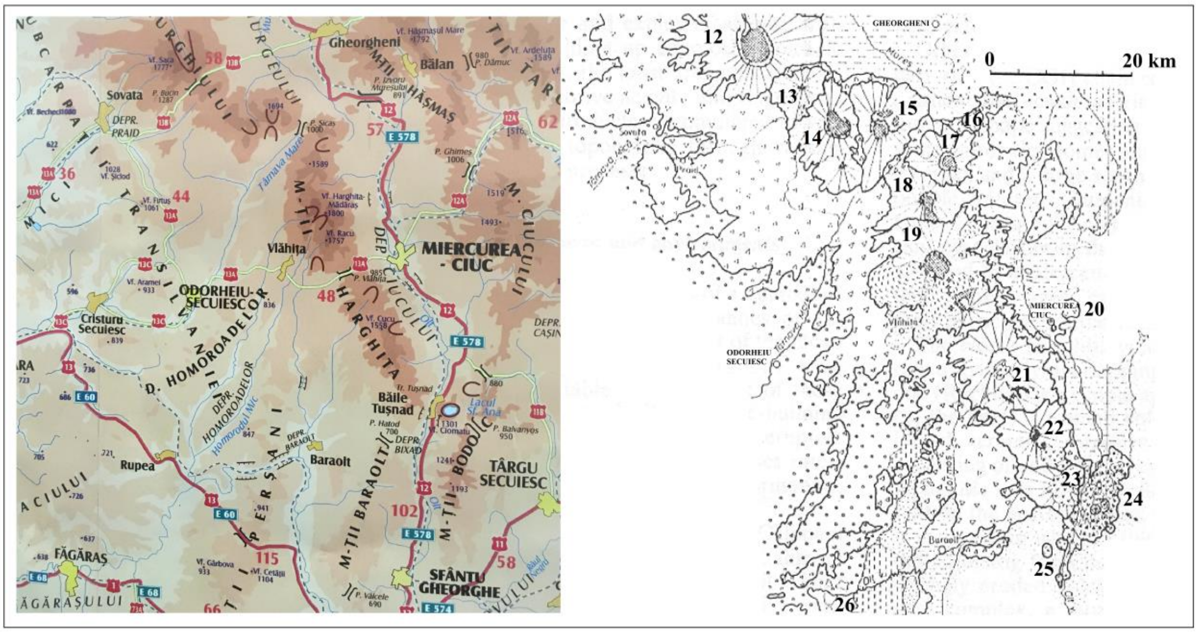


Fig. 17 – Trend changes of volcanic structures in the Gurghiu and Harghita Mts.
(Left: Detail from the Physical map of Romania, Ielenicz, 2000;
Right: detail from the volcanological map, Szakàcs & Seghedi, 1995).

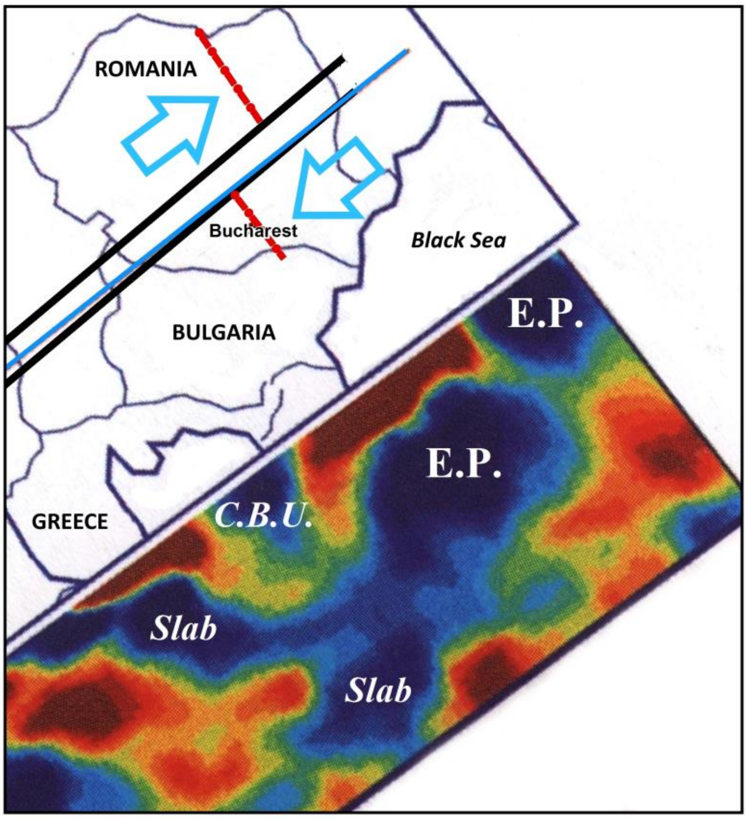


Fig. 18 – Seismic tomography section between the Dniester and Adriatic Sea (Piromallo & Morelli, 1997).
Blue, E.P.: East European Platform/Eurasian Plate; Blue, C.B.U.: Craiova–Balș Uplift; Blue, Slab: subducted oceanic slabs; Black lines: WT transcurrent faults; Dashed red lines: EEP western boundary; light blue arrows: regional geodynamics.

6. TECTONICS, VOLCANISM AND SEISMICITY IN THE VRANCEA ZONE

6.1. ACTIVE TECTONICS IN AND AROUND THE VRANCEA ZONE

When discussing the Vrancea zone and its high seismicity in terms of past subductions, an important question is "which platform was involved in subduction processes"?

There were two main answers during the last 50 years:

a) Moesian Platform, because its geological boundary with the North Dobrogean Promontory is considered to be along the Trotuș river and includes this way the Vrancea zone;

b) East European Platform, with geological boundaries along the Siret and Bistrița rivers. There are geological maps including the Scythian Platform between the East European Platform and East Carpathians (*e.g.*, Săndulescu & Visarion, 1988), but most scientific projects and papers dealing with subduction and collision in the Vrancea zone considered that East European Platform was involved in its past tectonic processes, as it was all along the East Carpathians.

We consider that the East European Platform, in fact the Eurasian Plate, was involved in subduction and collision processes in the Vrancea zone, the overriding microplate being represented by the Tisza–Dacia tectonic block.

Considering geophysical relevant data regarding this matter, the gravity stripped map of Romania (Ioane & Ion, 2005) was analyzed aiming at locating the East European Platform western boundary (Ioane & Caragea, 2015). Two boundaries have been interpreted when considering crustal and lithospheric depths (Fig. 12);

a) at crystalline basement depths, in the easternmost area of Romania (between Siret, Prut and Danube rivers);
b) at deeper levels, crossing diagonally the Romanian territory, following the western limit of the East Carpathians and the contact between the two compartments of the Moesian Platform.

The south-western continuation of the East European Platform, which incorporates the eastern compartment of the Moesian Platform, as it was interpreted on the gravity stripped map (Ioane & Caragea, 2015), offers a good opportunity to consider EEP at the right place to have had interacted with Tisza–Dacia in subduction and post-subduction collision.

The Vrancea zone is situated at the north-eastern part of the clockwise Tectonic Vortex interpreted in this paper, with almost circular displacements of the continental tectonic blocks and three subduction/collision zones on an imaginary circumference: Adriatic Sea, Eastern Carpathians and Hellenic Arc.

This tectonic vortex is constituted by the following continental blocks movements: N–S and NW–SE, determined by the active subduction beneath the Hellenic Arc, SW–NE in Italy and Central Europe, determined by post-subduction collision of Adriatic microplate and its tectonic lateral escape, W–E and SW–NE due to the latter processes and the regional Wrench Tectonics System in Tisza–Dacia, past SE–NW in Vrancea, present-time NW–SE outer of the East Carpathians Bend, and E–W in Turkey and NE–SW in the Aegean Sea. The main regional "engines" of this tectonic vortex are the active subduction and post-subduction collisions between the Eurasian Plate with the African and Arabian plates.

During subduction in the East Carpathians area the Tisza–Dacia tectonic block was the active, overriding plate, pushed by the Adriatic microplate, part of the African Plate promontory.

The W–E compressional regime during the Moldavian tectonic phase, which generated sedimentary nappes in the East Carpathians, has been determined by the African and Eurasian plates collision during the Sarmatian. Suite of this high compressional regime the Wrench Tectonics system has been initiated during the Lower Pannonian.

The Wallachian tectonic phase, whose tectonic mechanism was not clearly described in the past, represents in fact intense folding, faulting and uplifting of Quaternary sediments generated by horizontal movements along the WT Southern Fault. That is why Quaternary Cândeşti gravel has been mapped on top of Măgura Odobeşti, at 1000 m altitude.

Along the East Carpathians several stages of post-subduction collision may be interpreted on seismic tomography cross-sections (*e.g.*, Piromallo & Morelli, 1997; Wortel & Spakman, 2000; van der Meer *et al.*, 2018):

– NW of the Trotuș river (broken and eastward displaced EEP western boundary zone): post-subduction collision, detached oceanic slab, detached EEP "leading edge" beneath the Călimani-Gurghiu area and platform rebound from the subduction inclined position;
– the NW–SE trending sector of the EEP oblique western boundary: unconsumed and undetached oceanic slab, "frozen" slab beneath the Moesian Platform, but still preserving subduction angle, EEP rebound;
– past SE–NW subduction in Vrancea: partly tectonized EEP "leading edge" by WT Southern Fault, bent EEP forefront, undetached vertical oceanic slab, EEP deepening beneath Tisza–Dacia at lithospheric depths.

The oceanic lithosphere slab was detached and consumed along the East Carpathians during NE–SW and E–W directed subduction stages.

While subduction became oblique, a small part of the oceanic slab was transformed into magma, feeding the Harghita NW–SE migrating Neogene–Quaternary eruptions, with decrease in magma volumes and modifying its petrographic characteristics. Most of the "oblique" subducted oceanic slab is still preserved beneath the Moesian Platform, undetached and having no access in a deep mantle accumulation zone (Figs. 13, 16 and 18).

The south-westward displacements determined by the WT Southern Fault since the Pannonian moved the EEP ruptured block toward SW up to the Intramoesian Fault, or the High Seismicity Boundary (Stanciu, 2020), as present-day eastern compartment of the Moesian Platform. This south-westward position of the East European Platform western margin offered good possibilities for subduction and collision processes directed SE–NW, EEP being actively involved.

Considering the regional geodynamic displacements of Tisza–Dacia and East European Platform western boundary during time, several stages of subduction along the East Carpathians may be interpreted, as suggested by the elongated low residual gravity anomalies, colored in bleu in Fig. 19 (Ioane & Atanasiu, 2000), interpreted as former trenches filled with low density sedimentary formations.

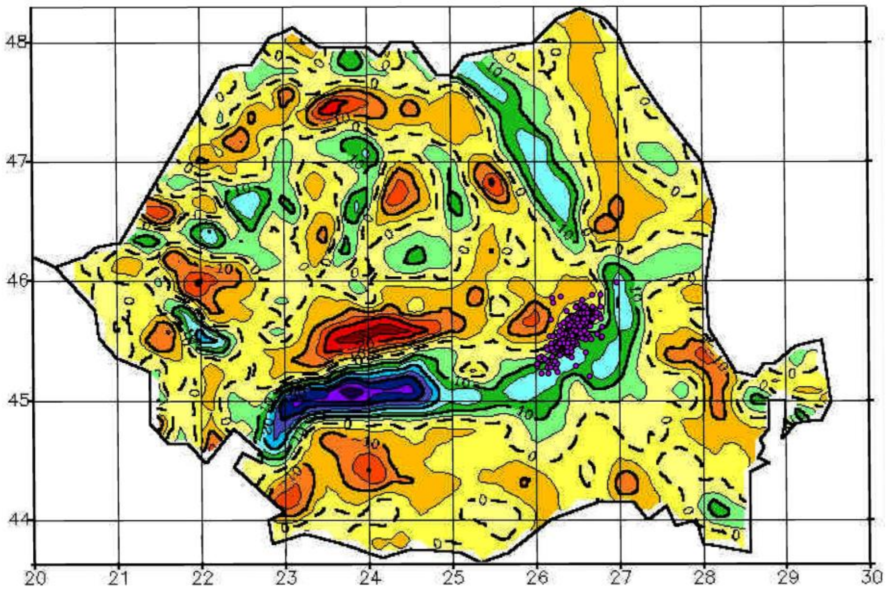


Fig. 19 – Residual Bouguer gravity anomalies in Romania (Ioane & Atanasiu, 2000). Red and orange: high gravity anomalies; Green and blue: low gravity anomalies. Purple circles: Vrancea subcrustal seismicity.

Evaluation of geological ages of the tectonic collisions, suite of subduction processes in the region of East Carpathians, was aided by seismic tomography data (Piromallo & Morelli, 1997; Wortel & Spakman, 2000; van der Meer *et al.*, 2018) interpretation and dating of Neogene–Quaternary volcanic products (Seghedi & Szakàcs, 1998):

– **Collision in Pannonian:** present day, detached slab, detached EEP leading edge beneath the Călimani–Gurghiu area;
– **Collision in Pontian:** present day, detached slab, undetached EEP leading edge beneath the Gurghiu area;
– **Collision in Pontian:** present day, undetached NE–SW developed slab, suite of oblique subduction, beneath the Moesian Platform;
– **Collision in Dacian:** present day, undetached slab, beneath the Northern Harghita and the Vrancea zones.

Considering the post-subduction collision in the Vrancea zone, highly illustrative data have been offered by seismic tomography section computed on the same transect at 18 years time interval (Fig. 20 – Left: Wortel & Spakman, 2000; Right: van der Meer *et al.*, 2018). It is rather instructive to interpret the East European Platform (blue) deepening, at the eastern part of both sections, beneath the East Carpathians Bend and the Tisza–Dacia block (red), and preserving its straight ahead undetached “leading edge”.

What was previously considered in numerous papers interpreting seismic tomography data as the vertical oceanic slab generating the Vrancea high seismicity, is here interpreted as the bended EEP forefront due to intense continent-continent collision processes. The oceanic slab resulted from subduction in Vrancea is better observed in recent seismic tomography data (van der Meer *et al.*, 2018) as a vertical blue thinner feature, attached to the bended EEP lithosphere and engulfed in the upper mantle between 350 and 660 km.

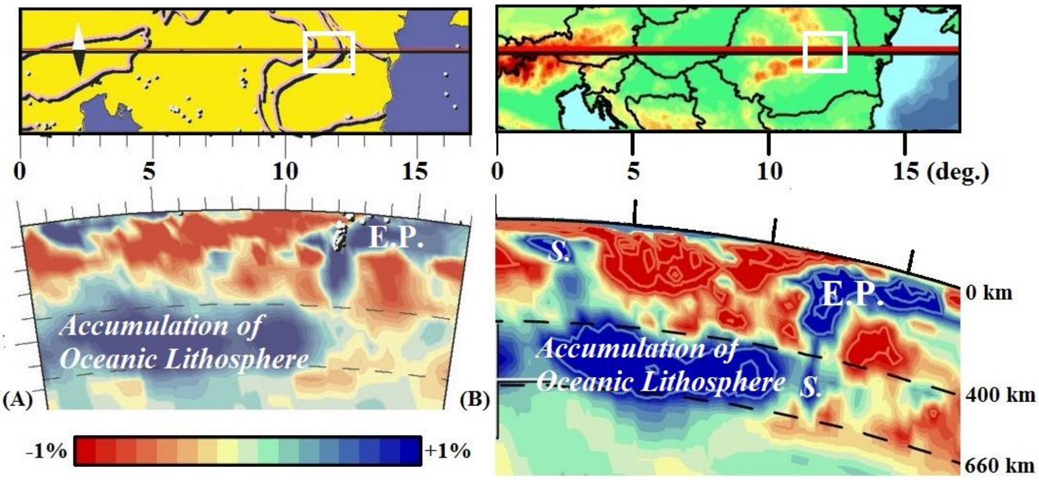


Fig. 20 – Seismic tomography sections across the Vrancea zone.
Left: Blue horizontal feature on top/right: East European Platform/Eurasian Plate (EP); Blue vertical feature beneath EP: attached oceanic slab; White dots crossing EP: Vrancea intermediate-depth seismicity (Wortel & Spakman, 2000).
Right: East European Platform (EP, blue) beneath Tisza–Dacia (red), attached vertical slab (blue), interrupted access to oceanic lithosphere accumulation zone (light blue) (van der Meer *et al.*, 2018).

The high gravity anomaly contoured in Vrancea (East Carpathians Bend Zone) on the gravity stripped map (Fig. 12), situated at the East European Platform south-westward “promontory”, is most probably generated by the vertical high density EEP forefront, bended to vertical as interpreted above (Fig. 20), and shown beneath Vrancea by seismic tomography studies to develop at depths between 200 and 350 km (Wortel & Spakman, 2000; van der Meer *et al.*, 2018).

A seismic tomography study investigating the Romanian territory and dedicated to the Vrancea seismic zone (Fan *et al.*, 1998) interpreted a continent–continent collision suite of subduction processes, better shown in Fig. 21, on a transect crossing Vrancea from NW to SE. Such intense tectonic compression, determined by the Adriatic microplate lateral escape, was able to bend the EEP forefront on one side, and to progressively deepen Tisza–Dacia crustal geological structures inner of the East Carpathians Bend on the other side.

The present-time result is a 200 km deep lithospheric zone with buried Tisza–Dacia crustal and lithospheric structures, probably including the “missing” crystalline formations overthrusted nappes, due to the Tisza–Dacia change of role during the collision stage, from overriding block to a confronting and subsiding one (Fig. 21).

Discussing **fault systems** as components of active tectonics in Vrancea, active faults were not generally considered to be of interest when trying to explain its clustered high seismicity in most tectonic models. This was probably due to the high depth of strong subcrustal earthquakes and to the fact that tectonic models describing subduction, collision, oceanic slabs and lithosphere delamination have been much more attractive.

Deep active faults have been previously considered to exist above the Benioff-type plane (Constantinescu *et al.*, 1976; Cornea & Lăzărescu, 1982), while regional faults have been employed in a tectonic model interpreting in Vrancea an unstable continental triple junction, but only as plate / microplates boundaries (Beşuţiu, 2001).

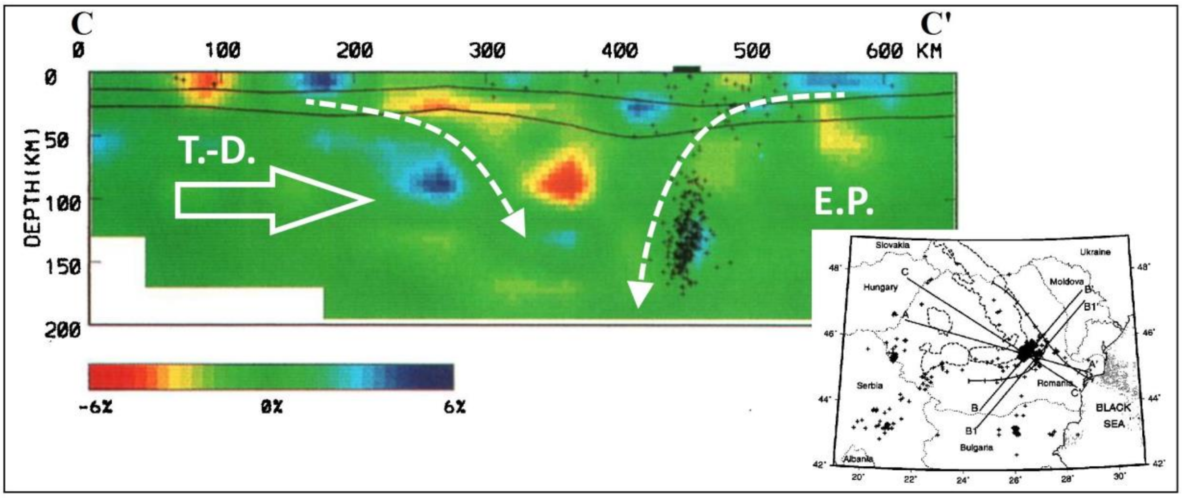


Fig. 21 – Seismic tomography section across Romania (modified after Fan *et al.*, 1998).
White dotted arrows: deepward displacements of tectonic blocks forefronts;
White arrow: direction of compressional regime; T.-D.: Tisza–Dacia tectonic block;
E.P.: East European Platform/Eurasian Plate; Black dots: earthquake hypocenters.

The wrench tectonics system recently interpreted in Romania (Ioane & Stanciu, 2018) opened new possibilities for involving active faults in explaining Vrancea zone seismicity, the transcurrent faults affecting in a strike-slip sense the entire crust and subjacent lithosphere. The tectonic models discussing ever since the Vrancea seismic zone by our research team, associated the WT Southern Fault with the subcrustal seismicity in a transtensive regime (Ioane & Stanciu, 2019, Ioane & Stanciu, 2020).

We consider that active tectonics in Vrancea seismic zone is first represented by the two transcurrent faults and their satellite fault systems, all having strike-slip characteristics and determining SW–NE and NE–SW regional horizontal displacements. There are also several regional NW–SE trending fault systems, two of them crossing Vrancea and hence, the transcurrent faults and their satellite ones.

Vertical electric soundings have been employed to geophysically detect the WT Southern Fault in the Vrancea zone, in the vicinity of the area covered by East Carpathians overthrusted sedimentary nappes. The thick unconsolidated Cândești gravel deposits, largely developed in the Clipicești area, close to river Putna, contributed to illustrate by elongated low resistivity anomalies the transcurrent fault location and sediments structure deformations by associated horizontal displacements (Fig. 22 – Ioane *et al.*, 2018).

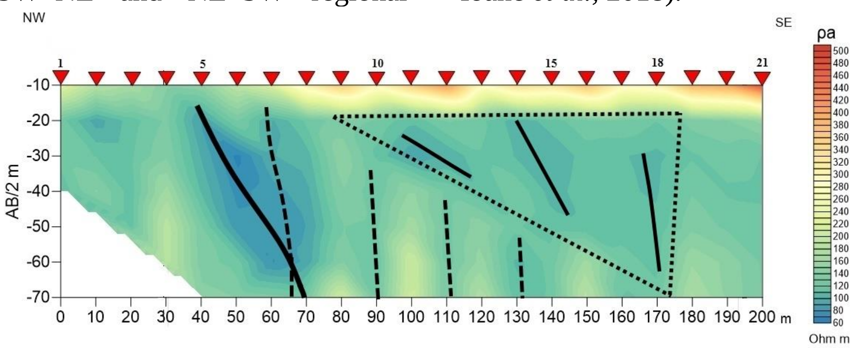


Fig. 22 – Tectonic interpretation of the resistivity section in the Clipicești (Putna river) area.
Thick black line: subcropping upper part of WT Southern Fault; Dotted black line: satellite faults;
Thin black lines: dislocated upper parts of satellite faults; Black dotted triangle: zone affected by horizontal displacements along the WT Southern Fault (Ioane *et al.*, 2018).

6.2. VOLCANISM IN THE VRANCEA ZONE

Almost all geological and geophysical studies dedicated to Vrancea, interpreting geological and geophysical data and building tectonic models, considered or stated that volcanism or magmatism is absent in that area, since it does not outcrop.

However, a few Romanian studies published during the 70's, theoretically considered as plate tectonics concept originally stated (*e.g.*, Le Pichon *et al.*, 1973; Kearey *et al.*, 2009), that subduction of oceanic lithosphere should generate magmatism in the overriding plate, and included volcanism or deep magmatic intrusions in their models built for the Vrancea zone.

C. Roman (1970), who pioneered plate tectonics in Vrancea, included in the development stages of his tectonic model andesitic eruptions and emplacement of monzonitic intrusions (Fig. 2), while Cornea & Lăzărescu (1982) emplaced a large andesitic intrusion in their tectonic model crossing the Vrancea zone (Fig. 23).

Two geophysical and geological data interpretations determined us to investigate traces of past volcanic processes, suite of oceanic lithosphere subduction beneath the Vrancea zone, and to look for concealed magmatic products covered by overthrusted sedimentary nappes or Quaternary formations: a) the large aeromagnetic anomaly in the Vrancea zone; b) the inferred metallogenical genesis for the Jitia metallic sulphides occurrences mapped in Vrancea.

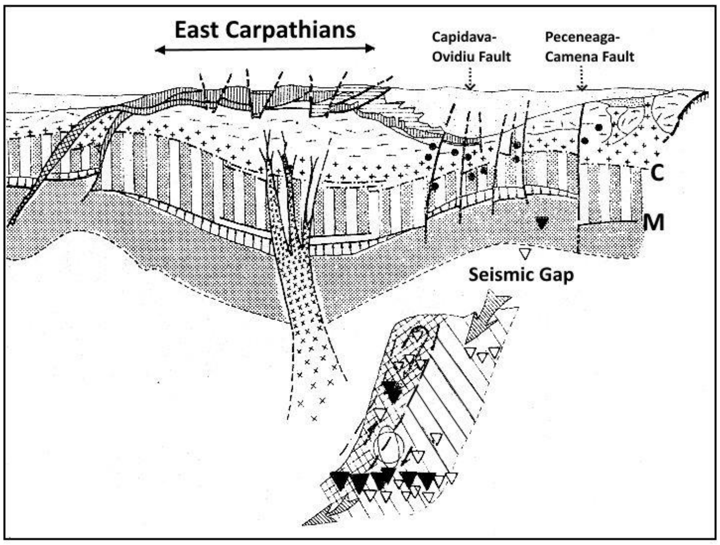


Fig. 23 – Tectonic model across the Vrancea seismic zone (modified, after Cornea & Lăzărescu, 1982). C: Conrad discontinuity; M: Moho discontinuity; Black dots: crustal earthquakes; White & black triangles: subcrustal earthquakes; Black dashed line: Benioff plane; Black crosses: magmatic intrusion.

A. *The aeromagnetic anomaly over the Vrancea zone*, elongated NE–SW in between the wrench tectonics transcurrent faults (Fig. 24 – Cristescu & Ștefănciuc, 1962–1968), suggest the presence of deeply located magmatic structures.

The large high aeromagnetic anomaly has been mapped in the Vrancea seismic zone using flight lines that followed at 200 m altitude the mountainous topography of the region, the detailed airborne geophysical survey being planned to detect mineral ore deposits.

The anomaly cannot be found on aeromagnetic maps edited at the scale of the territory of Romania, due to applied upward continuation techniques which eliminate local anomalies from the surveyed geomagnetic field. A good example is the aeromagnetic map edited by Sprânceană *et al.* (2006), upward continuated at 2600 m, where this magnetic anomaly is absent (Fig. 14).

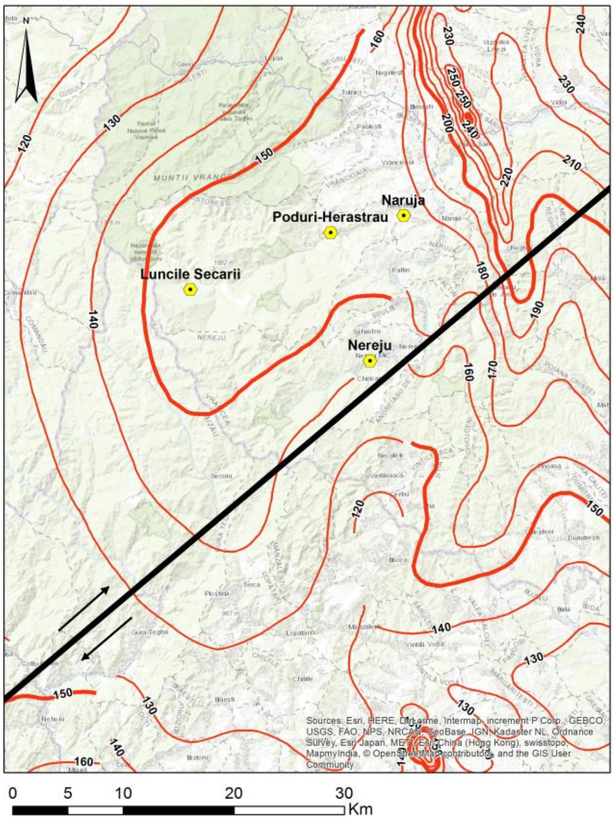


Fig. 24 – Aeromagnetic anomalies surveyed in the Vrancea seismic zone (Cristescu & Ştefănciuc, 1962–1968). Black line: WT Southern Fault; Black arrows: strike-slip fault; Red contours: aeromagnetic anomalies; Yellow dots: sulphurous springs (Crasu *et al.*, 1948).

The Vrancea high aeromagnetic anomaly is interpreted, in this study, as being mostly determined by a large intrusive body (*e.g.*, Calotă *et al.*, 1991; Ioane, 1999; Berza & Ioane, 2001), probably of dioritic petrographical composition, emplaced suite of subduction processes in the Vrancea zone. This large magmatic intrusion possibly reached the crystalline basement palaeorelief, the depth evaluation to the intrusion upper part being ca 15 km, in good agreement with the thickness of the sedimentary cover.

The intrusive petrographic facies equivalent to the interpreted andesitic volcanic eruptions in Vrancea is diorite, a rock characterized by highest magnetic properties among magmatic intrusives. Considering the dimensions (ca 200 km^2) and intensity of the Vrancea aeromagnetic anomaly, it is likely that the large dioritic intrusion represents a deeply enrooted batholith.

It is likely that the interpreted dioritic batholith has been intruded beneath the Vrancea zone during the Late Pliocene, probably during the Romanian. The north-eastern end of the postulated Vrancea batholith is closely associated with the Caşin–Bisoca tectonic contact; the batholith area dynamics was determined by the SW–NE movements along the inner WT Southern Fault, contributing to the intense faulting and folding of the Subcarpathian Nappe and of the East European Platform sedimentary formations along the Caşin–Bisoca Fault.

In a lesser extent, the large high aeromagnetic anomaly may be generated by remnants of andesitic volcanic structures as suggested by local high magnetic ΔZ anomalies (Airinei *et al.*, 1983), sources of the mapped tuff layers, volcaniclastic deposits and andesitic sandstone. That is why the next stage of research was dedicated to finding traces of Vrancea past volcanic eruptions in the neighboring areas, meaning geological formations with volcanic debris, incorporated in Miocene and Pliocene sedimentary formations:

– in the area situated between Milcov and Șușița valleys the Upper Sarmatian sediments include andesitic sandstone, while the Meotian formations begin with andesitic sandstone and andesitic tuff. In Nutasca–Ruseni area the Meotian sediments begin with 10 to 80 m thick andesitic cinerites and tuffs, while in the Putna valley the Meotian formations begin with conglomerate rich in andesitic tuff (Dumitrescu *et al.*, 1970);
– andesitic cinerites and large fragments of andesites at Cleja (East European Platform) intercalated in Meotian sediments (Cosma & Mărunțeanu, 1988);
– the volcanic bombs noticed in the Nereju area (Vrancea) suggests local volcanism, or transport on small distances (Cosma & Mărunțeanu, 1988).

All these areas where layers of andesitic cinerites and tuff have been geologically mapped are situated in the Vrancea zone, or in areas situated at tens of km apart. More of that, the angular shape of crystals in tuffs and the volcanic bombs indicate very small aerial or fluvial transport (Cosma & Mărunțeanu, 1988), being most probably resulted from andesitic volcanic eruptions in the Vrancea zone.

Considering the geological observations presented above, the thin and elongated high aeromagnetic anomaly, following the Cașin–Bisoca Fault, is interpreted as being generated by layers of andesitic tuffs included in the Late Sarmatian - Lower Meotian folded sedimentary formations (Fig. 24).

B. *The metallogenical interpretation* provided by geologists T.P. Ghițulescu and M.G. Filipescu, who studied the Jitia zone during the ’40 and ’50, and stated that the genesis of the metallic Pb–Zn sulphides occurrences is hydrothermal. More recent mineralogical researches described that the epiclastics which host the metallic minerals include coarse-grained members, with clasts of volcanic feldspar and quartz-feldspar plutonite (Cioflică *et al.*, 1986).

Jitia area is located in the Vrancea zone, between the Bisoca–Cașin tectonic contact and the WT Southern Fault. The Jitia highly tectonized sector could have been easily penetrated by upward hydrothermal fluids from a magmatic source.

C. *Geological indirect evidences* for a concealed Pliocene magmatic structure in the Vrancea zone, still preserving high temperatures at crustal depths, may be represented by springs with geothermal groundwater. At Siriu, an area situated at the western limit of the Vrancea zone, emergences of thermal water with temperatures ranging between 30 and 60 degrees Celsius have been mapped and analysed (Bandrabur *et al.*, 1981), being employed as natural spa at Băile Siriu.

According to Crasu *et al.* (1948), sulphur occurrences, sulphurous and ferruginous springs have been observed by Mrazec in field works in Vrancea Mts. during 1889–1899, at Luncile Secării, Poduri–Herăstrău, Nereju and Năruja. High contents of sulphur and iron were noticed at Luncile Secării and Poduri–Herăstrău. As it may be observed in Fig. 24, such occurrences overlap the aeromagnetic anomaly (here interpreted as being determined by a dioritic batholith in Vrancea) and suggest the presence of a NE–SW tectonic line between Năruja and Luncile Secării.

We consider that the N-S trending geothermal anomaly, which develops at its southernmost sector in the Vrancea zone, indicates high heat flow beneath the overthrusted sedimentary nappes, determined by the Late Pliocene dioritic magmatic intrusion, the geothermal values being computed for a depth of 20 km (Demetrescu & Andreescu, 1994).

D. *Geophysical indirect evidences,* aiming at detecting concealed magmatic products in Vrancea, will be based in the following on contrasts of physical properties of rocks and geological formations, such as seismic velocity and density.

The refraction seismics project crossing Vrancea zone resulted in a seismic velocity model where a graben-like structure is concealed beneath the East Carpathians, while its south-eastern half includes the Focșani Depression (Fig. 25 – Hauser *et al.*, 2007). Beneath the Carpathian Orogene in Vrancea zone the Tisza–Dacia crust is represented to have a layered structure, interpreted as slices of Palaeozoic sedimentary formations embedded in metamorphic ones, to depths between 10 and 20 km.

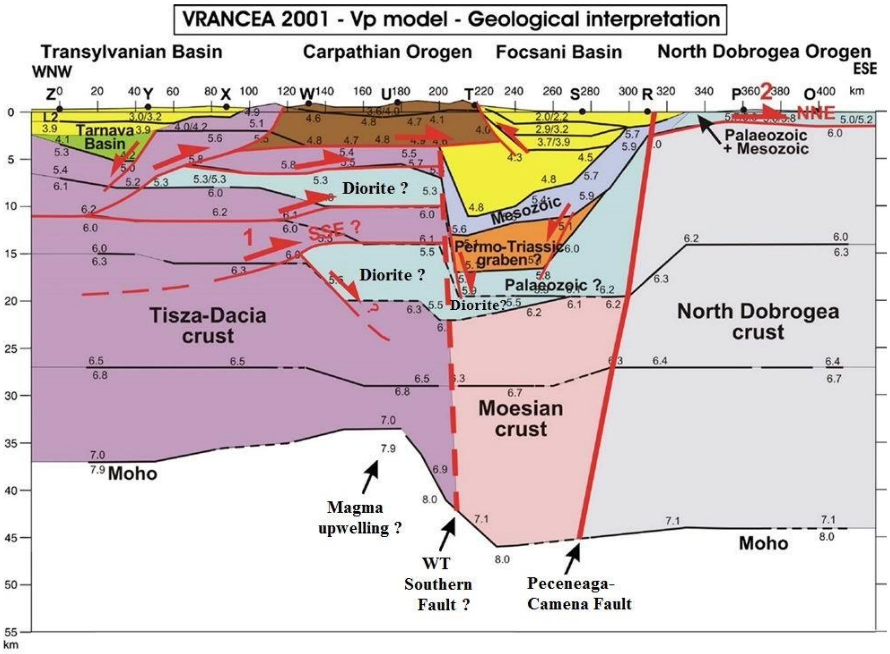


Fig. 25 – Refraction seismic section across the Vrancea zone (modified, after Hauser *et al.*, 2007).

The seismic velocity model gives for these slices values of 5.3 and 5.5 km/s, lower than the crystalline basement which is usually characterized by values of 5.8–6.2 km/s.

Since dioritic intrusions are characterized by a mean seismic velocity value of 5.6 km/s (Schön, 2004), we consider these low seismic velocity slices as marginal sectors of the large dioritic intrusion interpreted on aeromagnetic data, laterally developed at upper crustal discontinuities. The north-western vertical contact of the graben-like structure, which may here represent the WT Southern Fault, facilitated the magma upward ascent till its crustal emplacement.

Seismic tomography data, represented as maps of seismic velocity anomalies at a certain depth, may be also interpreted when looking for crustal or lithospheric geological structures.

The seismic velocity anomalies map represented at 27 km depth (Fig. 26 – Fan *et al.*, 1998) illustrates a NE–SW elongated high velocity anomaly in Vrancea zone (dark colors) situated between the wrench tectonics transcurrent faults, interpreted as the dioritic batholith contour at mid-crustal depth.

Even the Vrancea deep structure has been studied by means of 3D gravity modeling, it was only concentrated on the subducted oceanic slab (Hackney *et al.*, 2002).

Relevant gravity anomalies for our investigation are considered the residual gravity anomalies (Fig. 19 – Ioane & Atanasiu, 2000). A NE–SW elongated high gravity anomaly has been contoured in the Vrancea zone, interpreted as the upper part of the dioritic magmatic structure, the mean density of 2,82 g/cm^3 for diorite contrasting with less dense metamorphic rocks of crystalline basement, usually ranging between 2,70 and 2.75 g/cm^3 (*e.g.*, Ioane, 1993;

Ioane, 1999). Along the East Carpathians, the residual Bouguer gravity map of Romania depicted several couples of high and low anomalies: the high gravity anomalies correspond to Neogene volcanics and especially, to associated magmatic intrusions (Oaş–Gutâi, Ţibleş, Călimani–Gurghiu and Vrancea), while gravity lows correspond to the deeper parts of the foredeep sedimentary basins, remnants of former subduction trenches (Fig. 19).

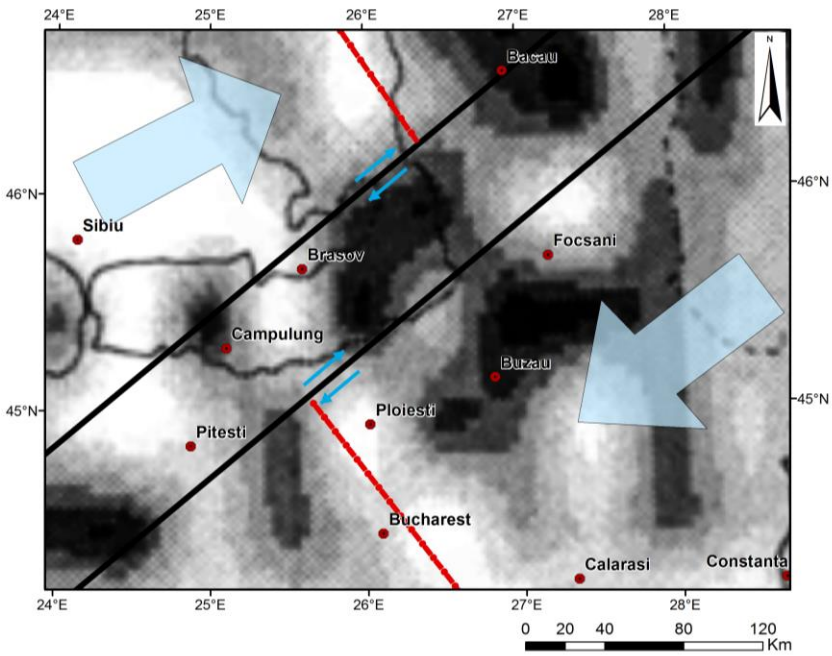


Fig. 26 – Seismic tomography map at 27 km depth (Fan *et al.*, 1998).
Dark areas: high velocity anomalies; Black lines: transcurrent faults;
Red lines: western boundaries of East European Platform; Blue arrows: geodynamic movements.

6.3. SEISMICITY OF THE VRANCEA ZONE

There are numerous studies analyzing and trying to understand the seismicity of the Vrancea zone, especially the subcrustal one that generates clustered high magnitude earthquakes.

Considering the seismotectonic approach of our study, an interesting way of addressing seismicity in the Vrancea zone has been published by C. Radu (1965); during several decades the map of Vrancea seismicity presented in Fig. 27 has been included in numerous scientific papers. By contouring areas with epicenters selected at several depth intervals, a westward inclined sector of seismic events has been illustrated, as well as a change of trend between crustal and subcrustal seismicity.

This already old interpretation of the Vrancea zone seismicity, with earthquakes epicenters geometrically situated in rectangles corners, was influenced by the low precision in seismic events positioning at that time.

Due to increased precision in positioning and depth determination, seismicity data recorded between January 2014 and December 2020 and included in the ROMPLUS Earthquake Catalogue of Romania (Oncescu *et al.*, 1999, updated) have been used to illustrate active faults, as main source of seismicity, at crustal and lithospheric depths in the Vrancea seismic zone.

N–S, W–E and NW–SE trending seismicity sections across the Vrancea area have been built using the technique described in Stanciu & Ioane (2017), as well as seismicity maps at various depths, or for depth intervals situated between 1 km and 160 km.

Aiming at separating the seismicity generated by active tectonic structures, situated at different depths in the Vrancea seismic zone, and considering the seismicity gap between 60 and

90 km described so far by most scientific studies, the seismicity data recorded between 2014 and 2020 have been splitted into three depth intervals: 0–60 km, 60–90 km and 90–200 km.

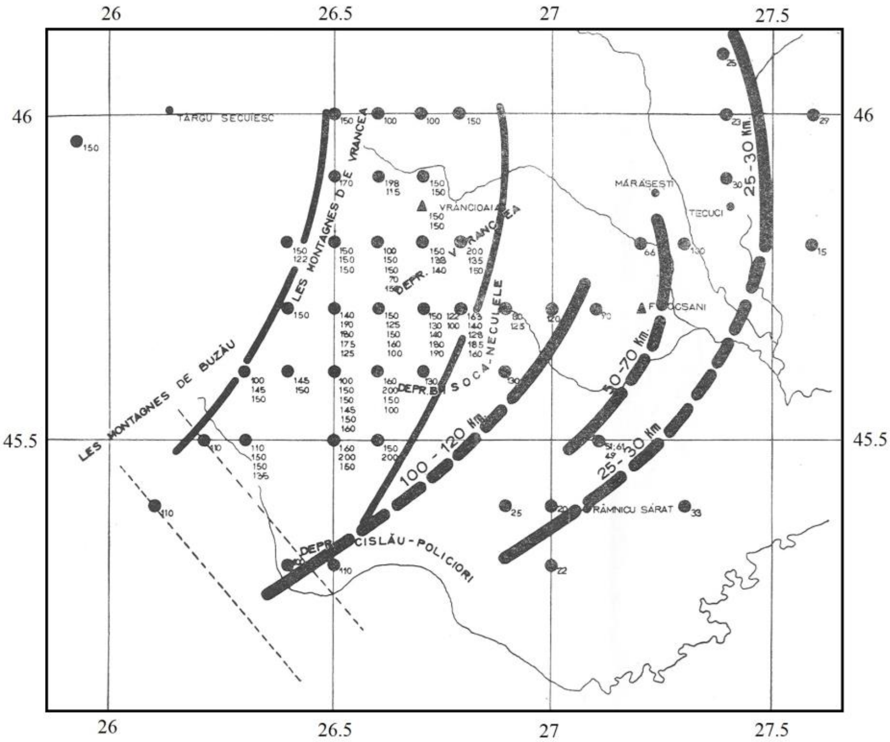


Fig. 27 – Seismicity map of Vrancea zone illustrating trend differences between crustal and subcrustal seismic areas (Radu, 1965).

The crustal seismicity recorded between 1 and 60 km reveals in the Vrancea zone two lineaments trending NNE–SSW and crossing the WT Southern Fault: the western one is located in the Vrancea Mts. and the eastern one is situated between Râmnicu Sărat and Mărășești cities (Fig. 28).

The two high seismicity lineaments have been recently interpreted as being determined by the re-activated tectonic contacts of the graben-like Permo-Triassic structure (Ioane *et al.*, 2019), illustrated till 50 km depth by refraction seismics (Fig. 25 – Hauser *et al.*, 2007), due to regional extensional processes.

The subcrustal seismicity, recorded between 60 and 90 km depicts a quite compact NE–SW seismic sector, elongated on ca 30 km along the inner part of the WT Southern Fault (Fig. 29), showing that the in-depth Vrancea seismicity is not totally interrupted at mid-lithospheric depths.

The clustered seismic sector overlaps the Vrancea high aeromagnetic anomaly, while the NE–SW active tectonic lineament described by epicenters of seismic events between Slănic and Prahova rivers, inner of the wrench tectonic system, may be correlated with sulphurous emergences (Fig. 24).

The deep lithospheric seismicity, recorded at depths ranging from 90 to 200 km, between the Putna and Buzău rivers, illustrates a compact, NE–SW trending clustered sector developed on both sides of the WT Southern Fault (Fig. 30). This close association between the transcurrent, regional strike-slip active fault and the deep seismic events gives information on two important aspects:

a) the transcurrent fault is cutting the geological structures from the surface (Ioane *et al.*, 2018) till the deepest lithospheric level;
b) the high magnitude Vrancea earthquakes are generated along the WT Southern Fault and its satellite faults system.

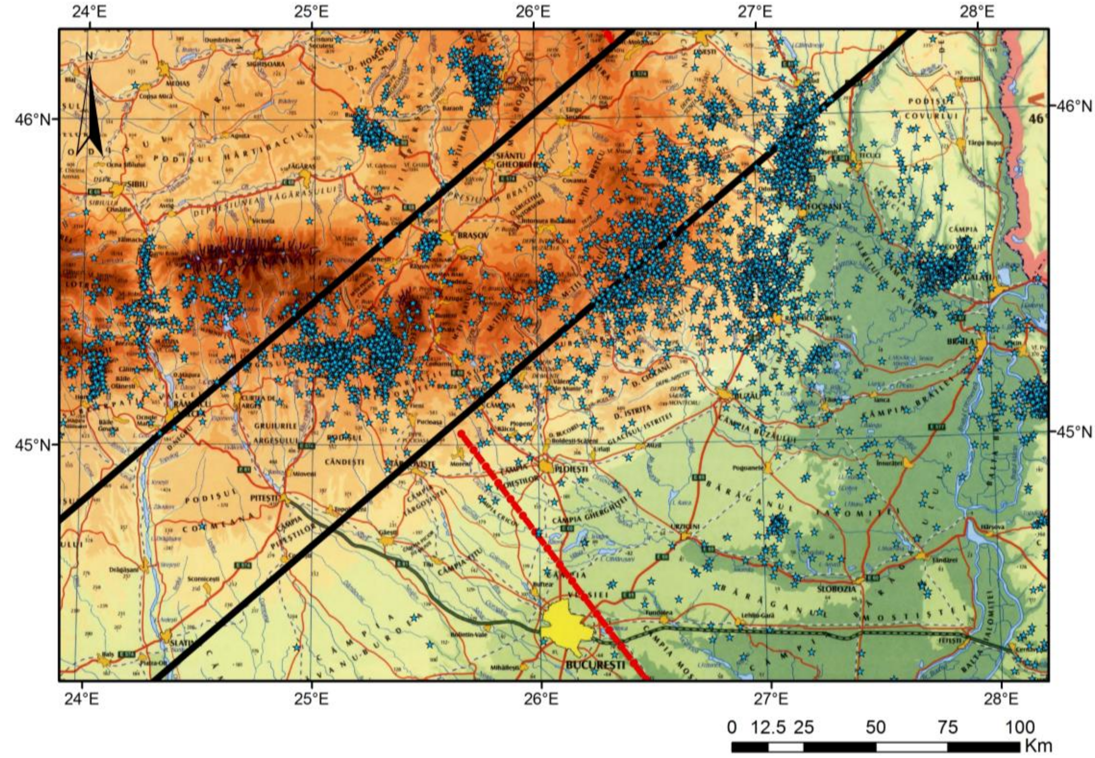


Fig. 28 – Vrancea seismicity recorded between 0 and 60 km depth (2014–2020).
Black lines: transcurrent faults; Red lines: interpreted western boundary of the East European Platform;
Blue stars: earthquake epicenters. Seismological data: Oncescu *et al.*, 1999, updated.

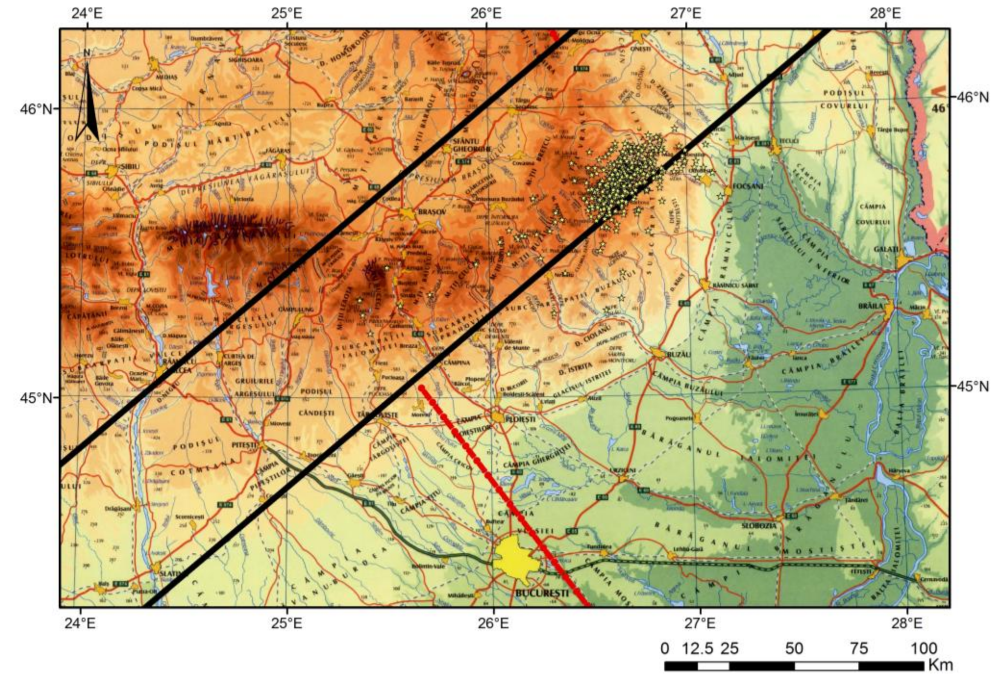


Fig. 29 – Vrancea seismicity recorded between 60 and 90 km depth (2014–2020).
Black lines: transcurrent faults; Red lines: interpreted western boundary of the East European Platform;
Yellow stars: earthquake epicenters. Seismological data: Oncescu *et al.*, 1999, updated.

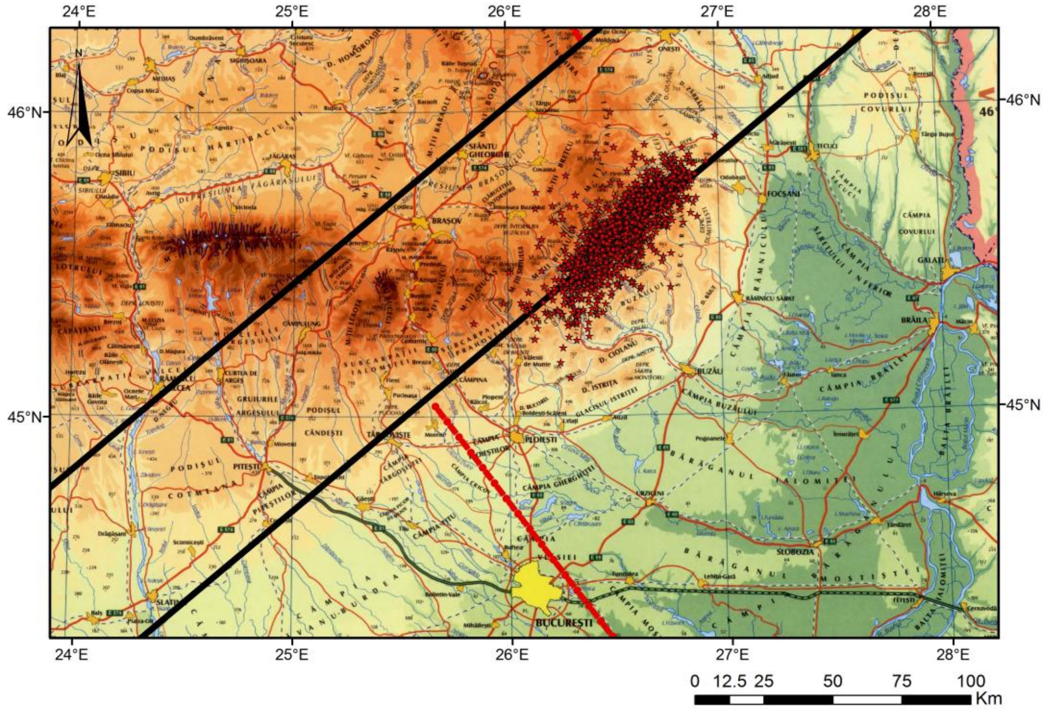


Fig. 30 – Vrancea seismicity recorded between 90 and 200 km depth (2014–2020).
Black lines: transcurrent faults; Red lines: interpreted western boundary of the East European Platform;
Red stars: earthquake epicenters. Seismological data: Oncescu *et al.*, 1999, updated.

The analysis of the recent crustal and lithospheric Vrancea seismicity (2014–2020) led to the following seismotectonic interpretations:

a) the most active seismicity, both at crustal and lithospheric depths, occurs at the junction area between the NE–SW trending WT Southern Fault and the NNW–SSE trending "Romanian Trough" (Ioane *et al.*, 2019), the graben-like structure detected by refraction seismics and illustrated by seismicity between 0 and 60 km (Figs. 25 and 28);

b) seismicity sections, built for depths between 1 km and 160 km across the Vrancea zone, illustrate active extensional tectonics, either due to the transtensional transcurrent fault at lithospheric depths, or to the SE geodynamic regional drag, especially at crustal depths.

The seismicity section built for latitude 45.4–45.5 illustrate the triangular shape of the seismogenic sector, with deep earthquakes generated by the transcurrent fault and shallower ones on normal faults on both sides of the graben-like tectonic structure (Fig. 31 Left).

The seismicity section built for latitude 45.7–45.8 illustrates a more consistent contribution to Vrancea seismicity by deep sectors situated along the transcurrent fault, between 60 and 160 km depth, its meandering shape suggesting effects of past compressional regimes exerted at lithospheric depths (Fig. 31 Right).

The seismicity gap between crustal and lithospheric depths in the Vrancea zone is well illustrated in Fig. 31 Left, but this study shows that it is not characterizing the entire Vrancea zone, as may be observed in Figs. 29 and 31R.

NW of the interpreted Vrancea batholith, emplaced in the WT Southern Fault vicinity, and of the East European Platform leading edge, uplifted ductile asthenosphere attenuates the seismic energy generated by the Vrancea earthquakes. Absence of EEP and presence of asthenosphere determine the lack of significant seismicity in Vrancea, along the WT Northern Fault.

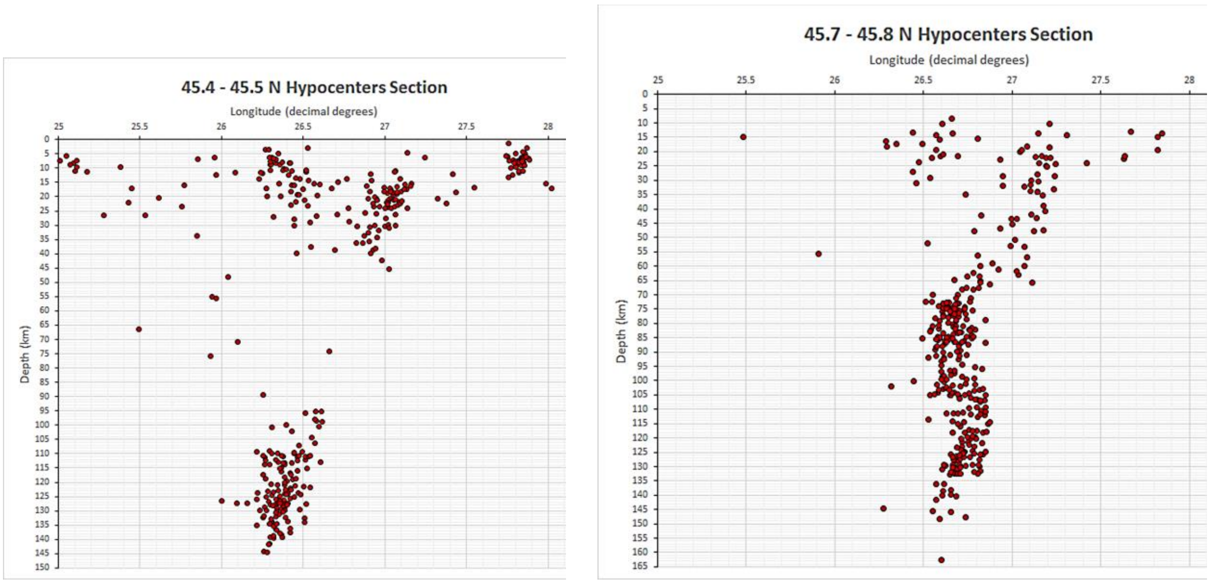


Fig. 31 – Seismicity sections in the Vrancea seismogenic zone (2014–2018).
Left: Vrancea zone crustal and lithospheric seismicity, separated by seismic gap;
Right: continuous crustal and lithospheric seismicity in Vrancea zone.
(Ioane & Stanciu, 2018).

7. TECTONIC MODEL OF THE VRANCEA SEISMIC ZONE

Numerous tectonic models already built for the Vrancea seismogenic zone neglected the differences in lithospheric thickness between the involved continental blocks in post-subduction collisional processes, due to lack of geophysical relevant information or simply ignoring its importance. Seismic tomography studies, carried out at regional or continental scales, have provided since the late 90's good quality data regarding lithospheric thickness of significant geotectonic structures.

In the Vrancea zone, we consider of highest importance the fact that the East European Platform, involved here in subduction processes, was illustrated by seismic tomography to have thickness ranging between 200 and 400 km. Since the Vrancea deep seismicity is usually recorded between 70 and 170 km, and the East European Platform is deepened at ca 100 km beneath Vrancea suite of both subduction and collision processes, it results that the intermediate-depth earthquakes occur within the East European Platform (*e.g.*, Wortel & Spakman, 2000).

We consider that the lithospheric structure, that was previously considered to be attached to the East European Platform in a vertical position due to break-off processes by many researchers, and develops between 200 and 400 km with thickness ranging between 150 and 200 km, does not represent the subducted oceanic slab, but the bended forefront of the platform, due to intense continent-continent tectonic collision, and cannot be directly involved in the Vrancea subcrustal seismicity. The oceanic slab is still attached to the EEP bended forefront in a vertical position between 400 and 700 km depth, and its thickness is of ca 50 km, as it should normally be considering the mean oceanic lithosphere thickness (Fig. 20 – Wortel & Spakman, 2000; van der Meer *et al.*, 2018).

Present day geodynamic processes, as illustrated by GPS monitoring results, show a south-eastward displacement of the East Carpathians Bend Zone and its foreland (*e.g.*, Hefty, 2004; Munteanu, 2009). A consistent displacement of this area towards SE may be also observed on remote sensing imagery data, while a crustal stretching of 10 to 15 km, due to extensional processes, was illustrated in the

Vrancea seismogenic zone by refraction seismic data (Hauser *et al.*, 2007).

A. The crustal high seismicity of the Vrancea zone is determined by active normal faults bordering or even crossing the Permo-Triassic graben-like structure, a continuation of the Polish Trough into the Romanian Trough (Ioane *et al.*, 2019), all along the western margin of the East European Platform (Fig. 32).

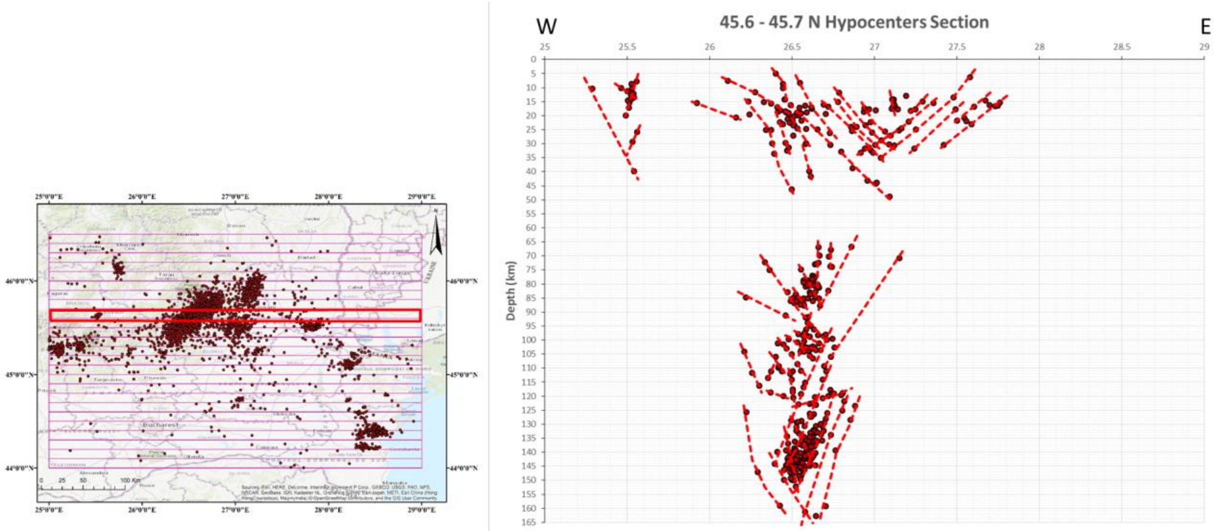


Fig. 32 – Normal faulting at crustal level and transtensional regime at lithospheric depths.

The crustal seismicity is enhanced by the regional geodynamic movement toward SE of the East Carpathians Bend and its outer area. The south-eastward geodynamic drag of this area may be considered to be determined by:

a) eastward displacement of the North Anatolian Fault northern compartment;

b) deep NNW compressional regime associated to the active subduction in the Hellenic Arc and reverse SSE movement of crustal structures, suite of a detachment at lithospheric depths. This detachment could be sustained by the self-contradictory situation of deep reverse faults, resulted on fault plane solutions, in a regional extensional regime.

The WT Southern Fault, characterized by strike-slip movements, determines ruptures in the adjacent dioritic batholith, contributing this way to the Vrancea crustal seismicity, as well as at upper subcrustal levels (Figs. 24 and 29).

B. The subcrustal high seismicity in Vrancea is determined by the strike-slip movements along the “trans-lithospheric” WT Southern Fault in a transtensional regime, while crushing and cutting the EEP north-westernmost margin, situated inside the transcurrent faults area, at depths between 100 and 200 km (Fig. 20). The mechanical and elastic properties of this frontal part of East European Platform have been enhanced by thermal metamorphism processes determined by magma upwelling and the dioritic batholith cooling, both in-depth and close lateral vicinity.

The meandering shape of the subcrustal seismicity, observed in some cross-sections, illustrates signatures of past compressional regimes developed at various depths, possibly acquired during the active Adriatic and Hellenic Arc subductions (Fig. 31R).

The subcrustal earthquake hypocenters depth variation, from shallower at the north-eastern extremity (90–110 km) to increasing depth south-westward (120–170 km), may be associated with variability of East European Platform rocks mechanical properties and hence, of strength to tectonic strike-slip and tensional regime processes.

Considering the continuous observed displacement toward NW of the subcrustal seismicity zone with increasing depth, the WT Southern Fault is north-westward inclined.

C. Combining crustal and subcrustal Vrancea seismicity results a triangular shape that suggests an extensional regime in Vrancea and outer of the East Carpathians Bend (Fig. 33).

The crustal seismicity of the western shoulder of the graben structure is overlapping the subcrustal seismicity, masking this way the two distinct sources of seismic events. More of that, the triangle including crustal and subcrustal seismicity is south-eastward inclined, probably due to strong regional geodynamic drag at crustal depths (Fig. 33).

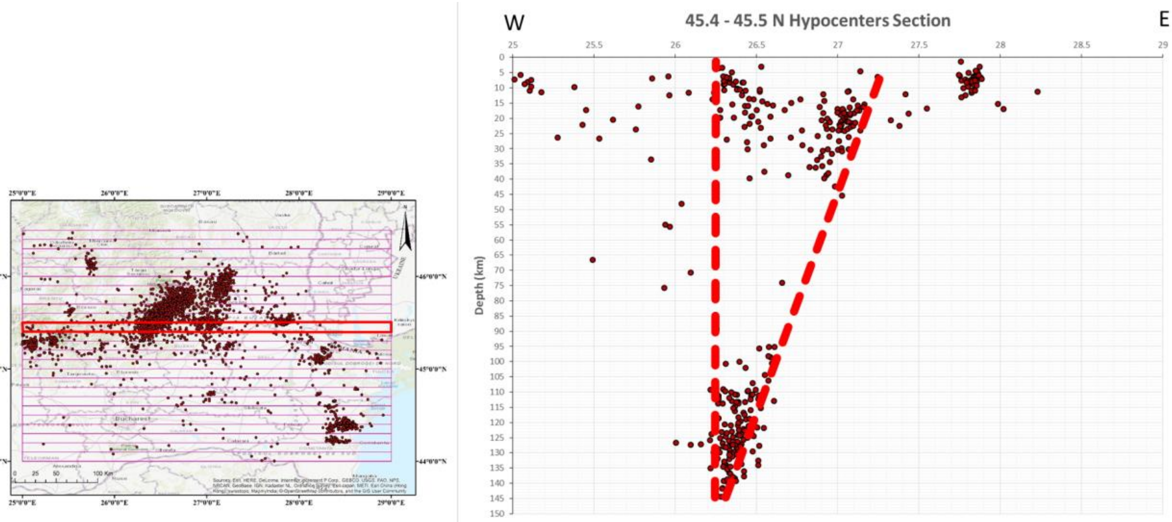


Fig. 33 – Extensional regime in Vrancea shown by overlapping crustal and lithospheric seismicity.

The newly built tectonic and geodynamic model for the Vrancea seismic zone, presented in Fig. 34, follows the seismic tomography transect employed by Wortel and Spakman (2000) and van der Meer *et al.* (2018) across Romania. It consists of basic features interpreted in this study, selected and commented above:

– E.P.: the East European Platform / Eurasian Plate deepened at ca 50 km beneath the Vrancea zone and having its "leading edge", as most north-westernmost part, at ca 100 km depth;

– T.–D.: the Tisza–Dacia tectonic block overriding the East European Platform in the Vrancea zone;

– the red triangle, including the crustal and lithospheric Vrancea seismicity (Fig. 33), its vertical north-western limit consisting of the WT Southern Fault. As it may be observed, the Vrancea seismicity, either crustal or subcrustal, ends at ca 170 km depth, still within the deepened sector of the East European Platform beneath Vrancea. The thinned red layer located at the triangle upper part and developed south-eastward represents the EEP sedimentary cover, including the Permo-Triassic graben-like structure, here interpreted as the Romanian Trough;

– the bended to vertical forefront of the East European Platform, developed below 170 km depth, its thickness and seismic velocity anomaly proving that it is part of an old craton and not an oceanic slab;

– the Vrancea oceanic slab develops much deeper, below 400 km depth.

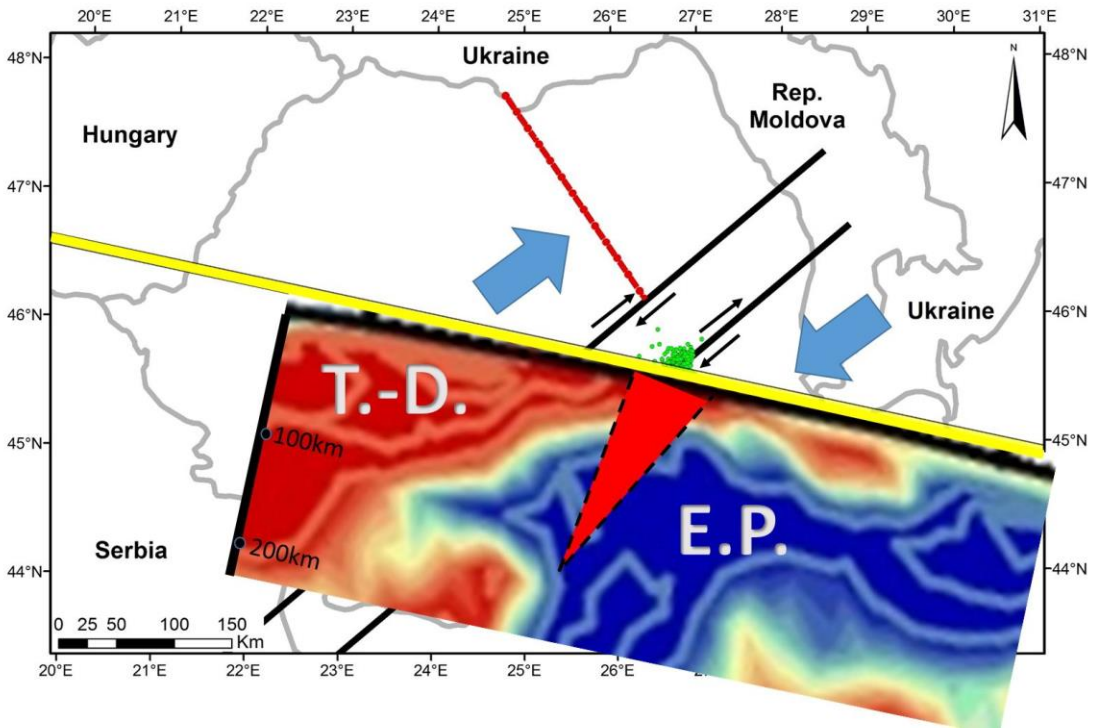


Fig. 34 – Tectonic and geodynamic model of the Vrancea seismic zone.
Blue: E.P – East European Platform / Eurasian Plate; Red: T.–D. Tisza–Dacia overriding tectonic block;
Vertical blue zone below 150 km depth: bended East European Platform forefront;
Red triangle: Vrancea crustal and lithospheric seismic zone; Green dots: subcrustal hypocenters
Seismic tomography data: modified after van der Meer *et al.*, 2018;
Geodynamic data: modified after Ioane & Stanciu, 2018.

8. CONCLUSIONS

The study devoted to Geodynamics, Active Tectonics, Volcanism and Seismicity in the Vrancea zone is mostly based on the interpretation of relevant geophysical data, seismic tomography offering the richest information, sometimes totally unexpected, on the regional, lithospheric and upper mantle geological structures.

The Conclusions section will follow the main chapters of this paper: a) Wrench Tectonics System; b) Regional Geodynamics; c) Tectonics, Volcanism and Seismicity of the Vrancea zone; d) Tectonic Model of the Vrancea zone.

8.1. WRENCH TECTONICS SYSTEM

A wrench tectonics system (WTS) has been recently interpreted crossing the Romanian territory; the two transcurrent faults (WT Northern Fault and WT Southern Fault) are trending NE–SW, and develop between Adriatic Sea and the Dniester river, on ca 1,000 km.

As markers of the horizontal displacements of geological structures determined by the WTS strike-slip transcurrent faults, aeromagnetic anomalies and geomorphological features have been utilized.

Significant geological consequences of the tectonic processes determined by the WTS are structural uplifts:

a) the Vrancea tectonic half-window of the Tarcău sedimentary nappe, uplifted by subjacent geological structures vertical movements and exposed to active erosion processes;
b) the Craiova–Balș structural uplift (western part of the Moesian Platform), where geophysical data showed that the magmatic

bodies represent the upper part of a deeply enrooted intrusion, illustrated by seismic tomography data till 175 km depth.

8.2. REGIONAL GEODYNAMICS

Romania and the Vrancea seismic zone are situated in a region characterized by active geodynamics determined since the Miocene by the collision between the African and Eurasian plates, leading to subduction processes in three areas situated in a triangular area: Adriatic Sea (ended subduction, continental collision, high seismicity), East Carpathians (ended subduction, continental collision, volcanism, high seismicity) and the Hellenic Arc (active subduction, volcanism, high seismicity) – when considering the compressional tectonic regime determined by the African and Arabian plates, the resulted field velocity vectors display a sort of ***clockwise regional tectonic vortex***.

The ***East European Platform*** was further discussed in this paper on a larger area based on regional geophysical data interpretation, being continued southward to include the North Dobrogean Orogen, the North Dobrogean Promontory and the Moesian Platform eastern compartment.

The ***graben-like structure***, interpreted on the refraction seismics velocity model, is considered in this study to represent the prolongation of the Polish Trough along the EEP western margin; it continues south-westward as the Romanian Trough, along the western EEP limit toward the Alexandria Depression. The continuity of the Polish Trough into the Romanian Trough along the East European Platform western margin may be preserved till the Alexandria Depression (southern Romania), only if the Moesian Platform eastern compartment is part of the East European Platform.

The ***regional wrench tectonics system*** was probably initiated during the Pannonian, as a consequence of the compressional tectonic regime climax determined by the Adriatic microplate lateral escape, suite of post-subduction collision and docking processes in the East Carpathians. The position of wrench tectonics transcurrent faults was conditioned by the northward limit of the Hellenic Arc subduction zone, presently advanced till southern Bulgaria at ca 100 km depth.

One of the most important tectonic events, generated during the Miocene (Pannonian) in this region by the Adriatic microplate compressional regime, was the break of a block of the East European Platform western margin of ca 200 km long and 250 km thick, as shown by seismic tomography data.

The aeromagnetic map illustrates the area where upper crustal Tisza–Dacia metamorphic structures, characterized by low magnetic anomalies, have been displaced eastward and replaced the East European Platform highly magnetic ones, having as main tectonic consequences:

a) the north-western part of the North Dobrogean Promontory was abruptly diverted toward ENE, between the WT transcurrent faults;
b) the broken sector of the EEP western boundary was pushed eastward, and then north-eastward, up to the Prut river.

Due to the replacement of high magnetic EEP metamorphic basement with lower magnetic Tisza–Dacia one in the area situated between Siret river and the East Carpathians sedimentary nappes, a Caledono–Hercynian platform was geophysically interpreted and geologically located between the East European Platform and the Carpathian Orogene, aiming to explain the large low magnetic anomaly. Considering the new geodynamic and tectonic interpretation, presented in this paper, there is no longer need of another platform, such as the Scythian Platform, between the East European Platform and the Tisza–Dacia tectonic block.

When the western margin of the East European Platform was broken and Tisza–Dacia crustal structures moved eastward for tens of km into the EEP realm, volcanism in the East Carpathians magmatic belt changed direction. The Neogene–Quaternary volcanism migration along the arc in S Gurghiu and Harghita Mts. changed direction from NW–SE to W–E and then NW–SE. The W–E migrating volcanism took place during the EEP crustal rupturing.

The oblique subduction, determined by the EEP broken and displaced margin, generated a NE–SW directed oceanic slab, partly preserved beneath the Moesian Platform western compartment.

8.3. TECTONICS, VOLCANISM, AND SEISMICITY IN THE VRANCEA ZONE

The East European Platform, in fact the Eurasian Plate, was involved in subduction and collision processes in the Vrancea zone, the overriding microplate being represented by the Tisza–Dacia tectonic block. The newly interpreted south-western continuation of the East European Platform, that incorporates the eastern compartment of the Moesian Platform, offered EEP a good opportunity to actively interact with Tisza–Dacia in subduction and post-subduction collision.

The Wallachian tectonic phase, whose tectonic mechanism was not clearly described in the past, represents in fact intense folding, faulting and uplifting of Quaternary sediments generated by horizontal movements along the WT Southern Fault. That is why Quaternary Cândeşti gravel has been mapped on top of Măgura Odobeşti, at 1000 m altitude.

What was previously considered as the vertical oceanic slab generating the Vrancea high seismicity is here interpreted as the bended EEP forefront due to intense continent-continent collision processes. The oceanic slab resulted from the SE–NW subduction in Vrancea is better observed in recent seismic tomography data as a vertical blue thinner feature, attached to the bended EEP lithosphere and engulfed in the upper mantle between 350 and 660 km depth.

Active faults were not generally considered to be of interest when trying to explain Vrancea clustered high seismicity in most tectonic models. This was probably due to the high depth of strong subcrustal earthquakes and to the fact that tectonic models describing subduction, collision, oceanic slabs and lithosphere delamination have been much more attractive. The wrench tectonics system recently interpreted in Romania opened new possibilities for involving active faults in explaining Vrancea zone seismicity, the transcurrent faults affecting in a strike-slip sense the entire crust and subjacent lithosphere. The tectonic models discussing ever since the Vrancea seismic zone by our research team, associated the WT Southern Fault with the subcrustal seismicity in a transtensive regime.

Almost all geological and geophysical studies dedicated to Vrancea considered or stated that volcanism or magmatism is absent in that area, since it does not outcrop. Two geophysical and geological observations determined us to investigate traces of past volcanic processes and to look for concealed magmatic products covered by overthrusted sedimentary nappes:

a) the aeromagnetic anomaly in the Vrancea zone;
b) the inferred metallogenical genesis for the Jitia metallic sulphides occurrences mapped in Jitia area.

The Vrancea aeromagnetic anomaly is here interpreted as being determined by a large intrusive body, probably of dioritic petrographical composition, emplaced suite of subduction processes in the Vrancea zone. Considering the dimensions (ca 200 km^2) and intensity of the Vrancea aeromagnetic anomaly, it is likely that the dioritic intrusion represents a deeply enrooted batholith that has been intruded beneath the Vrancea zone during the Late Pliocene, probably during the Romanian.

In a lesser extent, the large high aeromagnetic anomaly may be generated by remnants of andesitic volcanic structures, tuff layers, volcaniclastic deposits and andesitic sandstone, the latter volcanic products being already mapped in Vrancea and the neighboring areas.

Besides indirect geological evidences for magmatic procceses beneath Vrancea, such as hot groundwater emergences, sulphurous springs and hydrothermal metallic sulphides occurences, there are also a number of indirect geophysical ones: heat flow anomalies computed at 20 km depth, seismic refraction section, seismic tomography map at 27 km depth and couples of high and low gravity anomalies located in past subduction zones.

Due to increased precision in positioning and depth determination, seismicity data have been used to illustrate active faults at crustal and lithospheric depths in the Vrancea seismogenic zone. Aiming at separating the seismicity generated by active tectonics at crustal, subcrustal and lithospheric depths, and considering the "official" seismicity gap between 60 and 90 km, the seismicity data have been splitted into three depth intervals: 0–60 km, 60–90 km and 90–200 km.

The crustal seismicity (1 – 60 km) reveals in the Vrancea zone two lineaments trending NNE–SSW and crossing the WT Southern Fault. The two high seismicity lineaments have been interpreted as being determined by the re-activated tectonic contacts of the graben-like Permo-Triassic structure and illustrated till 50 km depth by refraction seismics, due to extensional processes.

The subcrustal seismicity, recorded between 60 and 90 km depth, depicts a compact NE–SW seismic sector along the inner part of the WT Southern Fault, showing that the in-depth Vrancea seismicity is not totally interrupted at mid-lithospheric depths.

The deep lithospheric seismicity, recorded at depths ranging from 90 to 200 km, illustrates a compact, NE–SW trending clustered sector developed on both sides of the WT Southern Fault.

The analysis of the recent crustal and lithospheric Vrancea seismicity (2014–2020) led to the following seismotectonic interpretations:

– the most active seismicity, both at crustal and lithospheric depths, occurs at the junction area between the NE–SW trending WT Southern Fault and the NNW–SSE trending "Romanian Trough", the graben-like crustal structure;
– seismicity sections, built for depths between 1 km and 160 km across the Vrancea zone, illustrate active extensional tectonics, either due to the transtensional transcurrent fault at lithospheric depths, or to the south-eastward geodynamic regional drag.

The in-depth seismicity data illustrates the triangular shape of the seismogenic sector, with deep earthquakes generated by the transcurrent fault and shallower ones on normal faults on both sides of the graben-like tectonic structure. Seismicity data also illustrates effects of past compressional regimes exerted at lithospheric depths.

8.4. TECTONIC MODEL OF THE VRANCEA SEISMIC ZONE

The East European Platform was illustrated by seismic tomography to have thickness ranging between 200 and 400 km. Since the Vrancea deep seismicity is usually recorded between 70 and 170 km, and the East European Platform is deepened at ca 100 km beneath Vrancea, suite of both subduction and collision processes, it results that the intermediate-depth earthquakes occur within the East European Platform.

The lithospheric high seismic velocity body, previously considered as oceanic slab attached to the East European Platform in a vertical position, develops between 200 and 400 km and have thickness of 150–200 km – it does not represent the subducted oceanic slab, but the bended forefront of the platform and cannot be directly involved in the Vrancea subcrustal seismicity.

The oceanic slab is still attached to the EEP bended forefront in a vertical position between 400 and 700 km depth and its thickness is of ca 50 km.

Present day geodynamic processes show a south-eastward displacement of the East Carpathians Bend Zone and its foreland. A consistent displacement of this area towards SE is also observed on remote sensing imagery data, while a crustal stretching of 10 to 15 km, due to extensional processes, was illustrated in the Vrancea seismogenic zone by refraction seismic data.

The **new tectonic and geodynamic model for the Vrancea seismic zone** consists of the following main components:

– the East European Platform is deepened at ca 50 km beneath the Vrancea zone and has its "leading edge", as most north-westernmost part, at ca 100 km depth;
– the Tisza-Dacia tectonic block is overriding the East European Platform in the Vrancea zone;

– the red triangle, including the crustal and lithospheric Vrancea seismicity, its vertical north-western limit consisting of the WT Southern Fault. The Vrancea seismicity, either crustal or subcrustal, ends at ca 170 km depth, within the deepened sector of the East European Platform beneath Vrancea. The red layer located at the triangle upper part represents the EEP sedimentary cover, including the Permo-Triassic graben-like structure;
– the bended to vertical forefront of the East European Platform, developed below 170 km depth, its thickness and seismic velocity anomaly proving that it belongs to an old craton and not to an oceanic slab.
– the Vrancea oceanic slab develops much deeper, below 400 km depth.

Acknowledgements. This study is dedicated, when celebrating 50 years since the first Vrancea tectonic model using Plate Tectonics concept was published, to all geoscientists who devoted their time and energy to understand its deep geological structure, to create tectonic models and disseminate their valuable knowledge to younger generations.

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