Annals of the Academy of Romanian Scientists
Series on Physics and Chemistry Sciences
ISSN 2559 – 1061 Volume 8, Number 1/2023

WHAT WE KNOW AND WHAT WE DON'T KNOW ABOUT THE EARTHQUAKES IN THE VRANCEA REGION (ROMANIA)

Mircea RADULIAN[1], Mihaela POPA[2], Raluca DINESCU[3]

Abstract. *Vrancea is one of the few seismic sources on the Globe that generates major earthquakes (7 to 8 magnitude) at intermediate depth (60 – 180 km) in a very confined seismogenic volume (seismic nest). Understanding how these earthquakes are generated is of wide interest both scientifically and considering the major impact of these earthquakes in Romania and neighbouring countries. The present paper is an overview of what we know at present and what still remains to be clarified in the future regarding the seismic process in the Vrancea area. The prominent features of the Vrancea prone-earthquake system are critically presented discussing their consistency with observation data, concordances and discrepancies and how to interpret them in the light of the latest research. Key elements are analysed related to geodynamic modelling (nature of the cold and dense material descending into the mantle, coupling of the Vrancea slab with the overlying continental crust) and seismicity patterns showing specific characteristics as geometrical configuration in consistence with the predominant focal mechanism and possible physico-geochemical reactions at critical temperature-pressure conditions.*

Keywords: Vrancea seismic source, seismic nest, seismicity patterns, geodynamic modelling, critical phenomena

DOI https://doi.org/10.56082/annalsarsciphyschem.2023.1.58

1. Introduction

Vrancea is one of the few seismic sources on the Globe that regularly generates major earthquakes (magnitudes up to 8) in an extremely limited seismogenic volume situated at intermediate depths (60 – 180 km). The physico-chemical modelling of the processes that take place in this volume still remains a mystery and a challenge for scientists, both at the scale of an individual event and at the scale of the entire geodynamic system located in the upper mantle beneath the curvature of the South-Eastern Carpathians arc. Besides the strictly scientific interest, the problem of understanding of how the earthquakes in Vrancea are

[1] PhD, National Institute for Earth Physics, Magurele, Romania, full member of the Academy of Romanian Scientists, corresponding member of the Romanian Academy (e-mail: mircea@infp.ro).
[2] PhD, full member of the Academy of Romanian Scientists (e-mail: ndcr2003@yahoo.com).
[3] PhD (ABD), National Institute for Earth Physics, Magurele, Romania, Faculty of Geology and Geophysics, University of Bucharest, Romania (raluca.dinescu@infp.ro).

generated is also of wider interest considering the major impact of these earthquakes both in Romania and in the neighbouring countries.

This work aims to overview what science offers us as sufficiently reliable knowledge and what still remains to be clarified in the future regarding the seismic process in the Vrancea area. At the same time, we will discuss to what extent the current scientific knowledge provides the framework and the most effective means to contribute to the reduction of the effects of these earthquakes.

We will revisit the most prominent features of the Vrancea prone-earthquake system regarding all the significant aspects: geological setting, geotectonics, physics of the source, role of the fluids, attenuation and anisotropy properties of the seismic waves radiated by the source, ground motion pattern. We propose to make a review of these aspects, to discuss their consistency with observation data, concordances and discrepancies and how to interpret them in the light of the latest research. We also intend to emphasize the well-defined aspects and those that are still to be clarified and the impact of all these features on seismic hazard and risk mitigation in Romania and neighbouring countries. Although the attention will be focused on the source from Vrancea, we will consider also how the seismogenic process in Vrancea is linked to the geodynamic processes at the scale of the entire Carpathian-Pannonian system.

2. Geotectonic setting

In the framework of the Mediterranean Basin area, the Vrancea source belongs to the type of sources of intermediate depth located in arch-type structures (Figure 1). Similar sources are located in the Calabrian Arc (Southern Italy), Hellenic Arc (Aegean Sea) and Alboran Arc (Southern Spain). The largest earthquakes ($M > 7$) recorded in this area are located on the one hand in the crust (depth less than 50 km) along the large transcurrent North and East Anatolian faults and Dead Sea fault and the crustal part of the Hellenic Arc and, on the other hand, in the upper mantle (depth greater than 50 km) in the Hellenic, Calabrian, Alboran and Carpathian arc systems (Figure 2).

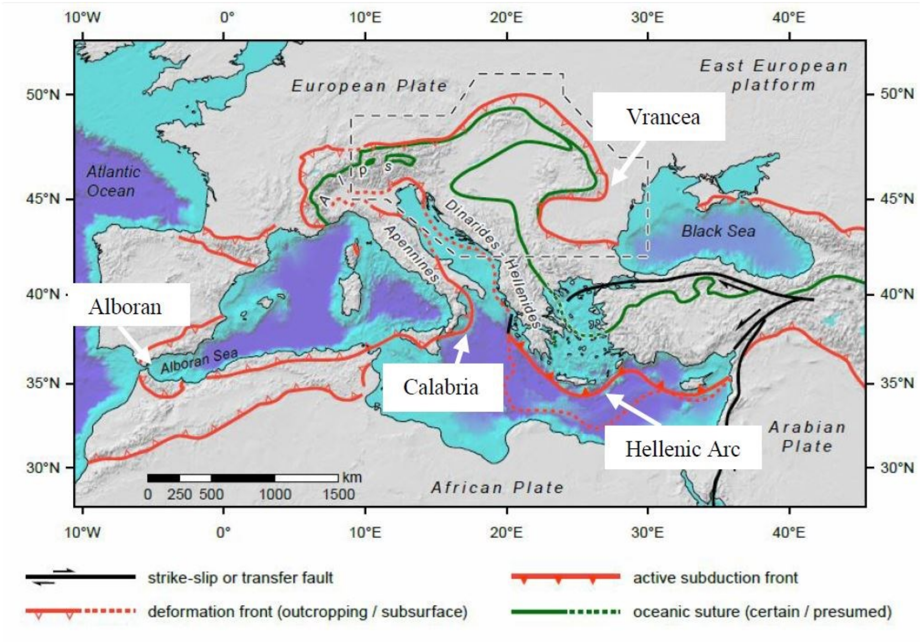


Fig. 1. Sketch map of the tectonics in the Mediterranean Basin (after [84]).

The largest events in the crust were recorded on the North Anatolian fault at Erzincan in 1939 (M_W7.8) and on the East Anatolian fault in the Kahramanmaraş province (M_W7.8), while the largest event in the upper mantle was recorded in the Vrancea region in 1940 (M_W7.7) at intermediate depth (150 km) and in the Gibraltar Strait in 1954 (M_W7.8) at deep depth (626 km). Note that both intermediate-depth earthquakes in the Vrancea and the deep earthquakes south of Spain are generated in narrow lithospheric pieces, isolated from the seismically active configuration of faults located in the eastern part of the Mediterranean Sea.

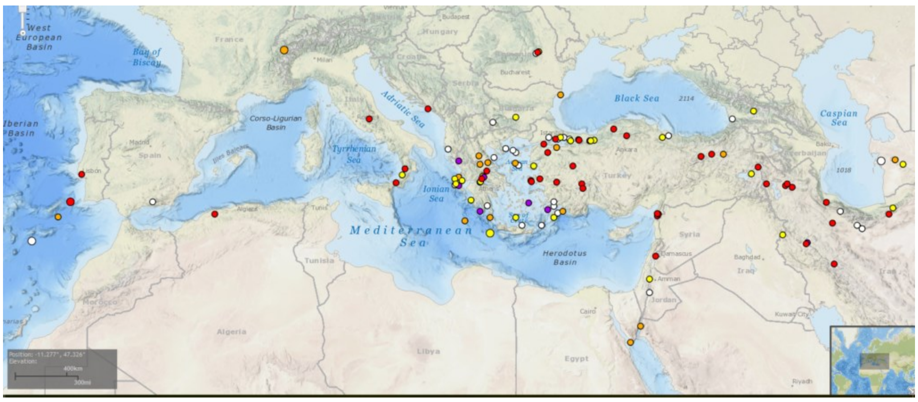


Fig. 2. Epicentral map of the largest earthquakes recorded in Europe ($M_w \geq 7$) (source: NOAA, 2019).

Looking more closely at the tectonic system in which Vrancea earthquakes are generated (Figure 3), we notice some remarkable features. First of all, the push movement towards N of the Adria Plate and the transfer of deformations to the west and east. If we examine the consequences of the eastward movement of the Adria Plate, a phenomenon on a large scale is noted: the opening of the Pannonian Basin, the largest extensional basin in Europe. We cannot explain such a large extensional phenomenon in a collision context unless we introduce some pulling forces into the tectonic system. Such forces appear as soon as a lithospheric body descends into the mantle and due to the increase in weight undergoes a roll-back process. We also draw attention to the important role played by the East European and Moesian platforms in modulating the configuration of the Carpathians (double-arcuate shape). The two platforms acted as resistance blocks in the process of continuous push to the east. A similar role was played by the Bohemian Massif in the push movement to the north.

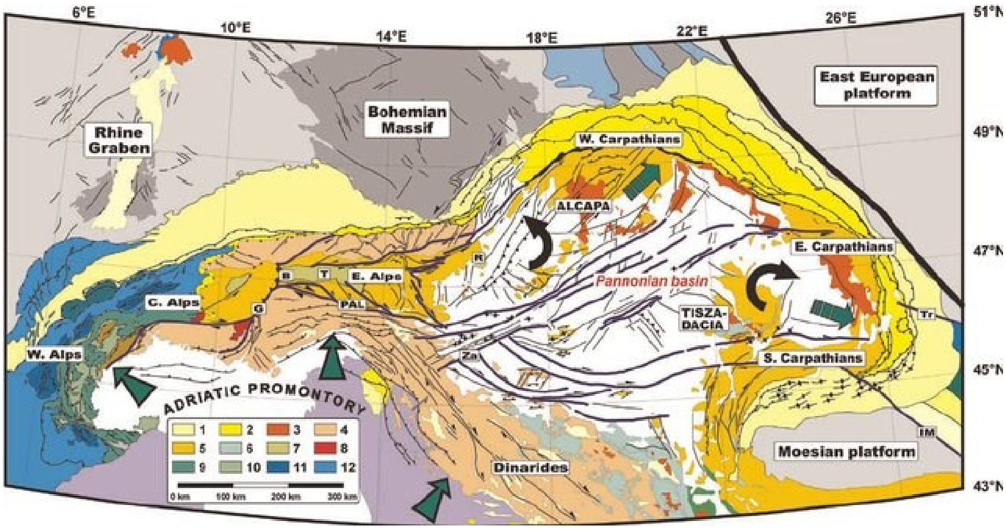


Fig. 3. Sketch of the tectonic forces in the Alpine – Carpathian - Adria region (from [2]).

The Carpathian–Pannonian region where the Vrancea source is located consists of the Carpathian orogen and the Pannonian back-arc basin system. The system evolution in Neogene is characterized by the relative movement of two independently-moving microplates known as the ALCAPA (Alps–Carpathians–Pannonian Basin) and Tisza–Dacia mega-tectonic units. Thanks to these movements, a complex system of faults has developed which crosses from the NE to the SW the Intra-Carpathian area (Mid-Hungarian Line). They were accompanied by complex phenomena related to subduction, rifting, mantle upwelling, and Neogene volcanism.

The tectonic evolution of the Carpathian–Pannonian region in the present-day is a subject of many debates. The proposed models can be grouped into two categories: (1) continental collision process and (2) oceanic subduction process followed by continental collision. The first assumes a gravitational instability (gravitational collapse of the continental lithosphere, [1]) and active continental lithospheric delamination under Carpathians (e.g. [34, 21, 23, 9]). The second group includes the subduction and associated sublithospheric mantle uplift as a key process in the tectonic development of the Carpathian–Pannonian region (e.g. [66, 67, 13, 27, 79, 41, 37, 38, 35]). Both types of models can explain the current presence under the Carpathian arc of a high-velocity lithospheric body descending into asthenosphere in which the Vrancea intermediate-depth earthquakes are generated.

3. Vrancea – seismic nest

The Vrancea earthquake-prone area belongs to the category of nest-type seismic sources. A seismic nest is a compact and well-defined volume of the Earth's lithosphere characterized by an intense seismic activity relative to the surrounding areas and which is generated permanently over time [87]. A seismogenic region is defined as a seismic nest if three specific requirements are fulfilled:

(1) intermediate-depth seismicity,

(2) compact seismogenic volume, isolated from nearby activity, and

(3) steady activity over time, not following mainshock-aftershock sequences or swarm temporal patterns.

Seismic nests appear at the convergent contact between the tectonic plates, which is no longer necessarily active. They are isolated seismic zones in complicated tectonic contexts. The most famous seismic nests in the world are: Bucaramanga in Colombia centred at 150 - 170 km depth, Hindu Kush in Afghanistan with earthquakes at depths between 170 and 280 km and Vrancea in Romania with seismic activity between 70 and 180 km. Bucaramanga is located at the convergence of four plates: North Andes (part of the South American plate), Panama, Caribbean and Nazca plates; Hindu Kush at the collision between two distinct slabs from opposite directions and Vrancea at the collision of three tectonic units: East European, Moesian and Alpine plates.

Tectonic seismic nests provide the best scenario to study the physical mechanism responsible for intermediate depth earthquakes. Intermediate depth earthquakes often occur along the subducting lithosphere, they occur at temperatures and pressures above the point where ordinary fractures ought to occur, but the physical mechanism responsible for promoting brittle faults is not well constrained and remains uncertain. The three main mechanisms proposed for intermediate depth earthquakes are:

(i) dehydration embrittlement [19, 31, 26], in which hydrated minerals release fluids at particular pressures and temperatures allowing brittle failure to occur,
(ii) uncontrolled thermal shear instability [19, 30, 26], which would occur through positive, rapid feedback between shear strain localization and thermal heating, and
(iii) mineral phase transformation [33].

In (i), the dehydration of serpentines results in the generation of fluid volumes that increase the pore pressure, reduce the effective stress, and finally allow brittle failure to occur at depth. While dehydration reactions are accompanied by a decrease in solid volume, it also produces substantial fluid volumes (e.g. [31, 10]), so that brittle failure could include opening tensile failures and thus explain the resolved isotropic components.

4. Seismicity location and patterns

Production of earthquakes, respectively of rapid release of tectonic energy accumulated in a certain area of the Earth's outer shell, implies the presence of a sufficiently rigid material, capable of triggering brittle fracture processes. Otherwise, we will not have high-frequency and high-energy seismic wave radiation. There is no doubt that the geotectonic processes that led to the present configuration of the Carpathian-Pannonian system, also caused the descent of a sufficiently rigid lithospheric body able to host earthquakes at depths where the conditions of pressure and temperature do not normally allow this. The presence of this rigid body is evident in any tomographic image performed in the area of the Carpathian arc. For example, in Figure 4, we show in parallel two tomography images on a vertical profile that crosses the Carpathian arc obtained independently by inverting teleseismic earthquake waveform data (left) and ambient noise data (right). In both images the presence of a high-velocity body (blue) located under the bend of the Carpathians that extends into the asthenosphere to a depth of about 400 km is pointed out.

It is interesting to note that the earthquakes are generated only in a relatively small part of this body, namely in its upper part up to depths of about 180 km, the rest of the volume being aseismic (Figure 5). The representation in Figure 5 on a vertical profile, NE-SW oriented, that crosses the Vrancea source is for the seismic activity recorded for a time interval of 28 years (1982 – 2009), but one may note that the same spatial distribution of the hypocentres is obtained no matter what time window is selected (see Figure 6 below). This finding makes us claim that we are dealing with a configuration that does not have this shape by chance, but reflects well-defined physical-chemical processes. Let's note, for example, the sudden cessation of the production of earthquakes at depths above 60 km and below 180 km. Let's also note the separation of the seismic activity in the overriding crust (black dots) from that in the upper mantle (red dots).

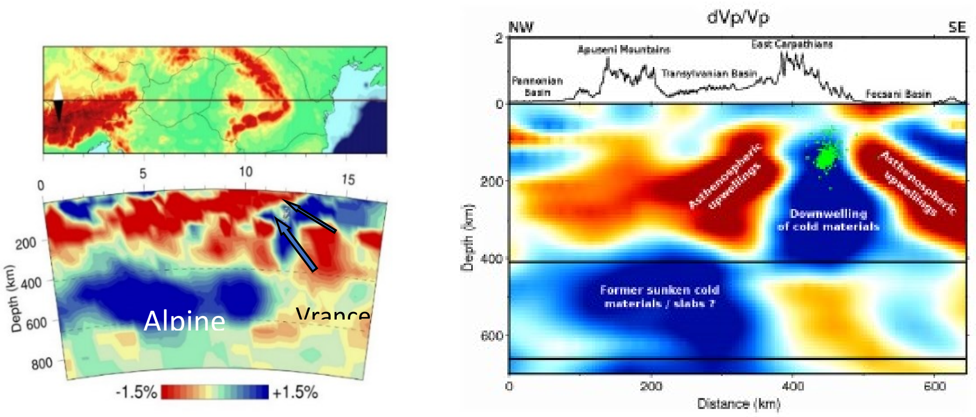


Fig. 4. Tomography image on a vertical cross section E-W oriented as obtained from teleseismic data (left, [90]) and from noise data (right, [68]).

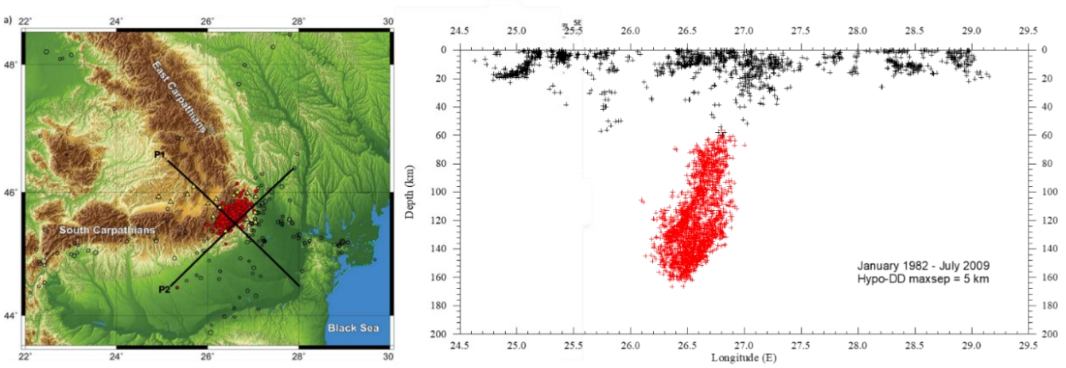


Fig. 5. Seismicity distribution in Vrancea at surface (left) and on the vertical cross section, oriented tangent to the Carpathians Arc bend (after [6]).

The tomographic images in Figure 4 reveal another interesting aspect: the presence of a massive lithospheric body, relatively stiffer and colder than the surrounding mantle, located between 400 and 600 km deep below the Pannonian basin. The observation of this remnant body, which is still differentiated by the elastic properties from the surrounding mantle material, is an argument in favour of a subduction process at the scale of the entire Carpathian-Pannonian basin that would have taken place in the geological past of the system. What we see today in the layer below the upper mantle is the lithospheric plate that has separated from the crust. The only portion still attached and seismically active confines to an approximately vertical finger-like body located under Vrancea.

One striking feature of the intermediate-depth seismicity noticed in any of the earthquake nests in the World is the persistency of the rate of occurrence in time. As concerns the seismic activity in the Vrancea nest, a rate of 2 to 5 major events (magnitude above 7) is observed per century for a time window of several centuries. The Vrancea historical events can be identified relatively easily because of their effects distribution, which is unique among the earthquakes recorded in this part of Europe. The most striking aspect is the huge area where these events are felt (from south Italy to central Russia). In this way, we obtained information about the occurrence of earthquakes in Vrancea available for a period of almost a millennium. The more reliable data spans about five centuries. If we analyse the time evolution of the earthquakes with magnitude above 6 starting from 1600 until now, we notice a grouping tendency of the strongest earthquakes (Figure 6).

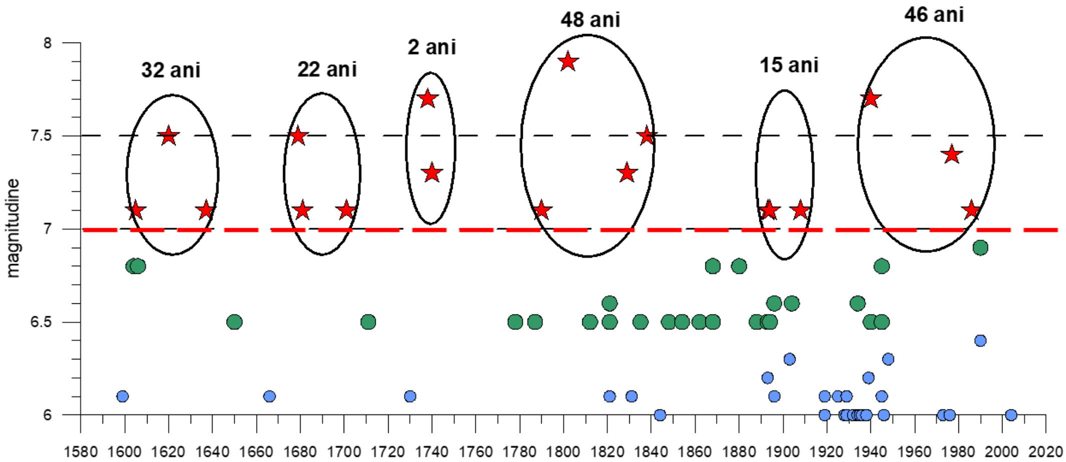


Fig. 6. Time occurrence in the Vrancea earthquakes with magnitude above 6 since 1580. Six clusters of increased activity of major events are illustrated by ellipses.

We separated the earthquakes into two large categories: those with a magnitude above 7 and those below 7 (red dashed line in the figure). The events under 7 are supposed to be incomplete in the catalogue. As proof, let's note the significant increase in statistics starting with the 19th century comparatively with the older time interval. Instead, we consider that the statistics is complete for magnitudes above 7 over the entire time interval considered in the figure. Note the tendency of major earthquakes (M greater than 7) to occur in clusters: intervals of intense activity separated by low-activity intervals. The length of these intervals varies from a few years to tens of years and apparently looks like a random variable. We are at present in a low-activity interval lasting for almost 37 years (since the major shock of 1986). Only one preceding interval of low activity exceeded it, that of the 19th century (55 years). Considering the variability of the interval distribution in time and the limited interval of observation (six centuries), it is impossible to issue any prognosis for the next cluster of major events in Vrancea only based on statistical grounds.

Seismicity patterns which characterize the earthquake production in the Vrancea source show first of all a few striking geometrical features:

(1) concentration in a narrow epicentral area elongated along NE-SW direction;

(2) a well-defined domain in depth between 70 and 180 km with a sharp cut-off outside this domain;

(3) the seismicity in the subducting slab is significantly more abundant and stronger than that in the overriding crust.

The tomography image obtained by inversion of local earthquake data [36] in a vertical projection across Carpathians Arc bend (Figure 7) shows a tight connection between the distribution of hypocentres (black dots) and geometry of the high-velocity body (represented in blue). The image points also a strong contrast in velocity and V_P/V_S ratio between the crustal and the subcrustal domains. Taking into account that the seismic rays for the local earthquakes are passing through an environment located at depths lower than 180 km (the largest hypocentral depth), this tomography image is not representative for depth below, such as in Figure 4 (obtained using teleseismic or seismic noise data).

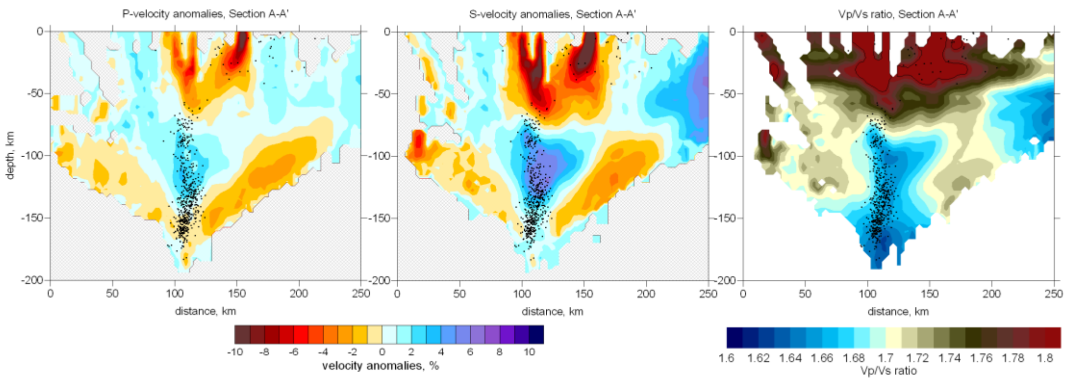


Fig. 7. Tomography image for a vertical cross section in Vrancea obtained using local earthquake data for P-wave velocity (left), S-wave velocity (middle) and V_P/V_S ratio [36]. Black dots are hypocentres.

The geometrical configuration of the hypocentre distribution plotted on two vertical cross sections at the Carpathians Arc bend (Figure 5) was interpreted by various authors as representing a proof of the inhomogeneous structure of the seismically active zone beneath Vrancea. It was thus discussed about a vertical structure with the following stratification (in a simplified representation in Figure 8):

- crustal layer: moderate activity (M less than 5.5)
- seismic gap between 40 and 60 km depth (only sporadic and small events)
- upper active segment (named A in Figure 8): major events of 1977 (M_w 7.5) and 1990 (double shocks of M_w 6.9 and 6.4)
- transition layer around 100 km depth: relative deficit of earthquakes (corresponding at the same time with the Middle Lithosphere Discontinuity, see below)
- lower active segment (named B in Figure 8): major events of 1940 (M_w 7.7) and 1986 (M_w 7.1)
- a single isolated event located below 200 km depth (M_w 3.7)

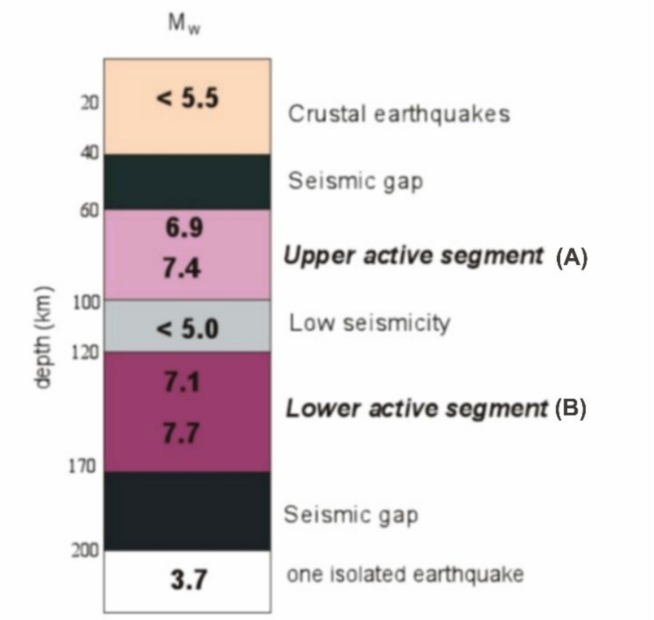


Fig. 8. Schematic representation of the inhomogeneous structure characterizing the seismogenic volume in the Vrancea region (after [49])

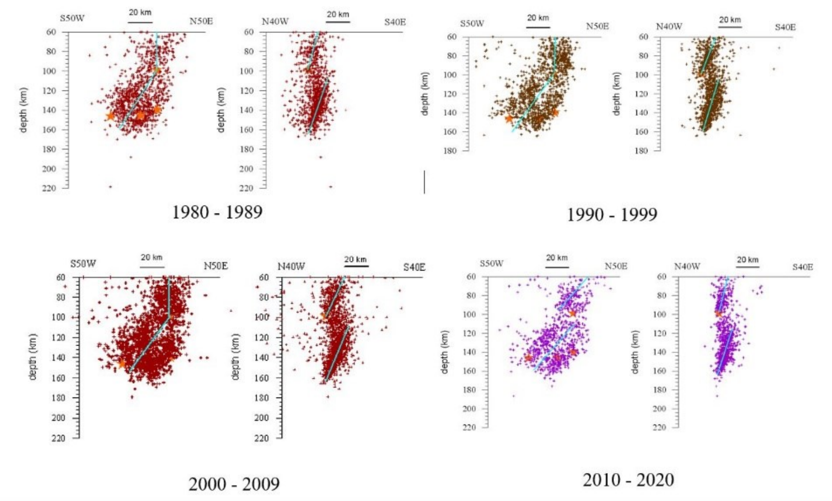


Fig. 9. Intermediate-depth seismicity in two vertical cross sections in the Vrancea seismogenic zone for different 10-year independent time windows.

In Figure 9 we represent comparatively geometrical configurations of the hypocentre distribution plotted on two vertical projections in the Vrancea oriented as shown in Figure 5 (one parallel and other perpendicular to the Carpathians curvature) for different completely independent time windows of 10 years length. Obviously, the change in the configuration located around 100 km depth is preserved in all windows suggesting that this is not a simple random configuration, but highlights an intimate underlying physico-chemical process related to the earthquakes generation.

Seismic activity history in time, represented separately for the two active segments in Figure 10, emphasizes two interesting features: a background seismicity quasi-stationary in time (~ 8 events/6 months in A and ~ 40 events/6 months in B) and a sharp increase due to the aftershock activity following the major events (1977 and 1990 in A and 1986 in B).

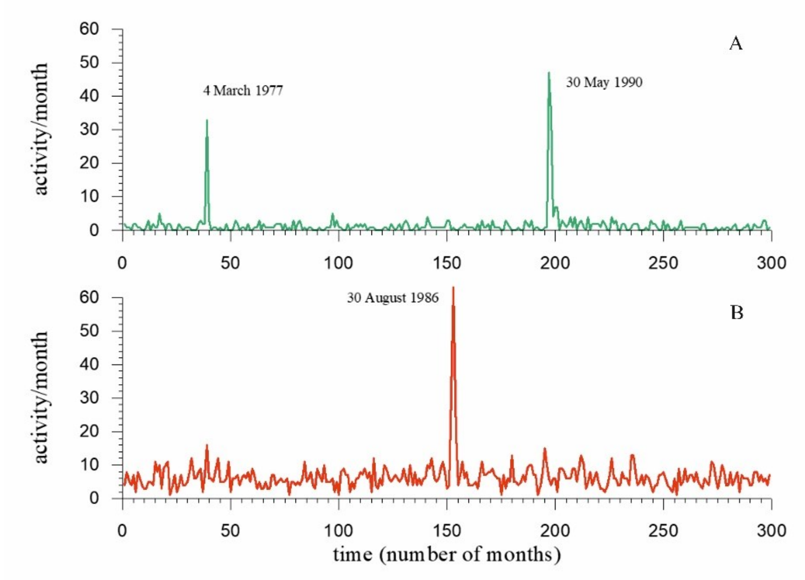


Fig. 10a. Number of earthquakes per 6 months in the two active segments of the Vrancea seismogenic zone (after [4]).

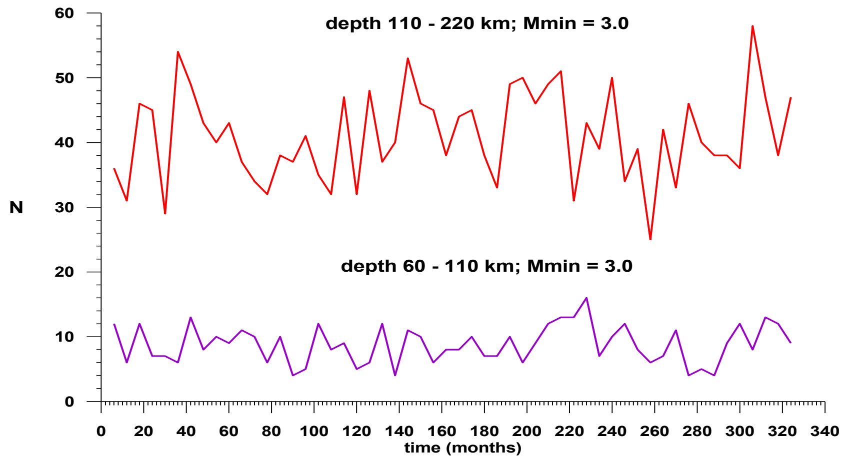


Fig. 10b. Background seismicity time evolution in the two active segments of the Vrancea seismogenic zone. Practically the same activity as in Figure 68a after extracting the anomalous activities associated with the major events.

The fact that the occurrence of a major earthquake in one of the segments does not disrupt in any way the background (current) activity in the other segment (as pointed out in Figure 10a) makes us assume that there is a strong decoupling between these segments and that the processes to prepare the triggering of major earthquakes are taking place to a great extend separately in the two segments. This is also highlighted in the depth distribution of aftershocks of the major earthquakes recorded in A and B (Figure 11). Note that the aftershocks of the events generated in A segment (associated to 1977 and 1990) are spread in a limited depth range of less than 100 km, while the aftershocks of the event of 1986 generated in B segment are spread in a limited depth range of more than 100 km. It follows that the transition layer between A and B segments acts either as a barrier of resistance (difficult to be broken), or on the contrary as a zone of weakness (incapable of accumulating deformation to generate large earthquakes). Considering the hypothesis of the presence of fluids in this layer (as we will discuss in the following sections), we would rather prefer the second hypothesis.

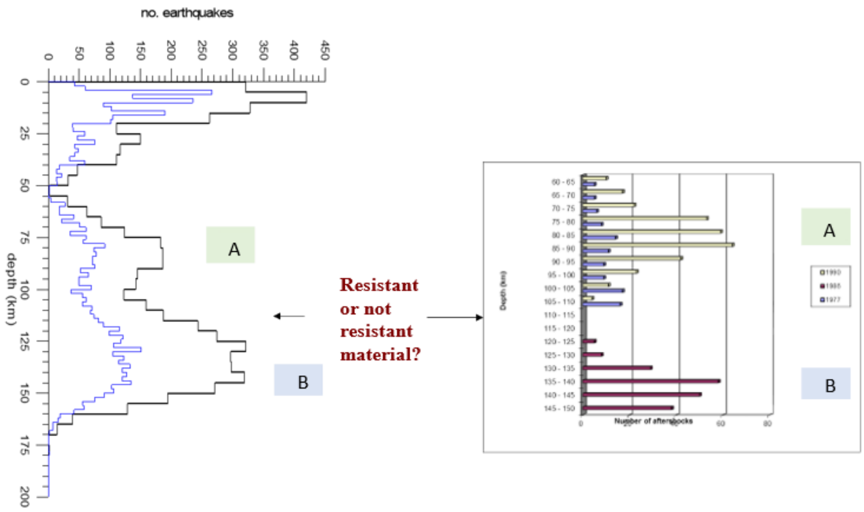


Fig. 11. Depth distribution of earthquakes in Vrancea (left) and depth distribution of aftershocks for 1977, 1986 and 1990 major events (right).

5. Fault plane solutions and stress field

In terms of the earthquake production mechanism, there are a few remarkable characteristics based on the analysis of the observational data:

(1) One of the well-established characteristics of the Vrancea source is the predominance of a single type of focal mechanism over the entire depth domain where intermediate-depth earthquakes are generated. Thus, all the previous studies on the subcrustal seismic activity in the Vrancea region outlined a predominant dip-slip, reverse faulting, characterizing both the moderate and strong earthquakes [15, 48, 50]. In most of the cases, the principal T axis tends to be vertical, the principal P axis tends to be horizontal and oriented perpendicular to the Carpathians arc, and one nodal plane is dipping about 70 toward NW, while the other nodal plane is dipping SE. This kind of fault-plane solution is commonly explained by a slab-pull down process which controls the kinematics of the system.

(2) All mechanisms for earthquakes with magnitude above 6.5 for which fault-plane solutions are available are almost identical (Figure 12A). From the analysis of the aftershock distribution, we can assume that the nodal plane close to vertical, slightly plunging toward NW (to the Transylvanian basin) is the real rupture plane.

(3) The rupture plane of the major shocks roughly coincides with the alignment NE-SW on which all the Vrancea earthquakes are located (Figure 5) and apparently the dimension of the source on horizontal plane for the largest shocks (around 70-80 km) coincides with the horizontal dimensions of the seismicity pattern (Figure 5).

Certainly, in order to reach the conclusion that these features are invariant over time, we would need observation data extended over significantly longer time intervals. The predominance of reverse focal mechanism (1) seems to be well founded considering that mechanisms with normal faulting or strike-slip are reported only sporadically and for smaller earthquakes. Therefore, we can explain these deviations through processes of stress accommodation at local scale in the slab. They do not change the general image of a dominant field of horizontal compression and vertical extension. A tendency to change the focal mechanism in a narrow band around 100 km depth was also suggested [49, 50, 62], but for now the observations are not enough to confirm this for sure.

The similarity of failure in case of major earthquakes (2) is not as certain. First, there are cases of earthquakes below 6.5 with the fault plane oriented perpendicular to the NE-SW plane. The best-known case is the second shock of 31 May 1990 (M_w 6.4) that followed a few hours after the major shock of 30 May 1990 (M_w 6.9). The 90-degree rotation of the nodal planes partially explained the differences between the distributions of macroseismic effects and peak accelerations among the two shocks. However, as pointed out by [40], we should be careful when interpreting such distributions since the focal mechanism seems to play a secondary role in controlling them [57]. Also, there are some doubts when interpreting the macroseimic observations for the largest estimated Vrancea earthquake of 1802 (M_w 7.9). The analysis of the historical data led to the conclusion that, except Bucharest, the largest macroseimic effects were recorded in the eastern Transylvania [69]. To explain this result, we can consider either a focal mechanism different from the typical one, or an eccentric hypocentre position (towards Transylvanian Basin or below 150 km depth).

A clue factor which could tentatively explain in an integrated view the observational features pointed above could be the coupling of the seismic processes at different scales. Thus, we may assume [60, 61, 81, 82] that the occurrence of large events is prepared in time by the background seismicity.

Such model would provide an explanation for the coincidence of the strong earthquake source spatial dimension with the dimension characterizing the seismicity (item (3)) and the existence of two types of fault plane solutions with perpendicular rupture planes. If the rupture process for major earthquakes can be produced only where background seismicity is generated, then the limitation of the focal mechanisms with the rupture plane oriented across Carpathians arc bend to events with magnitude below 6.5 could be explained by the geometrical limitation of the seismicity in this direction (~ 30 km), while the rupture process for the largest earthquakes can be deployed only on a perpendicular plane (NE-SW oriented) since the seismicity dimension on this direction allows the rupture extensions up to ~ 70 km.

Bălă et al. (2021) [5] analysed the stress regime on depth in the Vrancea region by inverting the fault plane solutions. They found a predominant downdip extensive regime in the entire seismogenic volume in the upper mantle, as well as in the crustal layers located above the Vrancea slab. The stress field computed by applying the inversion separately for two active segments, one located in the upper part of the seismogenic volume (55 – 105 km), the other in the lower part (105 – 180 km), is practically identical with a nodal plane dipping toward NW closer to vertical. It is interesting to note that the similarity observed for the fault plane solutions of the major Vrancea earthquakes (e.g. [65]) fits the principal mechanisms as they come out from the inversion approach (Figure 12). This is a strong argument to consider that the stress field regime acting upon the entire slab volume generating intermediate-depth earthquakes in Vrancea is compatible with a plane which defines at the same time the seismicity pattern. In other words, the stress regime inferred by us from inversion of focal mechanisms is controlling the earthquake generation at all scales.

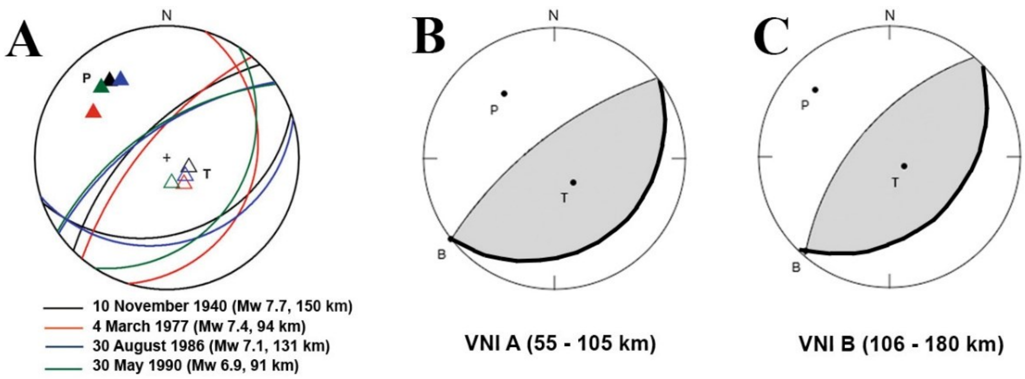


Fig. 12. Comparative illustration of the similarity between the individual fault plane solutions for the major Vrancea earthquakes (A) and the solutions obtained by inverting the groups of fault plane solutions for the events in the upper segment (VNI A) and lower segment (VNI B), considered separately. From [5].

The release of the deformation in the Vrancea intermediate depth domain is controlled both at small scale (small and moderate magnitude) and at major earthquake scale by a predominant faulting plane NE-SW oriented and inclined toward NW. We assume that it is not by chance that this plane coincides with the plane around which the seismicity in Vrancea is located.

6. Geodynamic modelling

The current geotectonic context in the Carpathians Arc bend area is represented by the collision of at least three tectonic plates/subplates: East-European, Moesian and Intra-Alpine, which are all of continental type. A key question is how the tectonic system reached the current situation with the presence of a rigid lithospheric piece down in the mantle, isolated like a finger, and how it is possible to release unusually large tectonic energies in such a compact lithospheric volume.

Several geodynamic models have been proposed to explain the nature of the seismogenic body beneath the Vrancea region [28]. One crucial issue about these models is the nature of the material of the slab. Three models were discussed:

(1) a relic oceanic lithosphere, either attached or already detached from the continental crust
(2) a continental lithosphere that has been delaminated, after continental collision and orogenic thickening
(3) a combination of a relic oceanic lithosphere and delaminated continental lithosphere.

In any of these three cases, to explain the completely particular position and geometry of the slab, we have to take into account a process of detachment/delamination that arises after the continental collision comes into play. A few possible scenarios are represented in the Figure 13: (A) Break-off of the oceanic subducting lithosphere; (B) Oceanic slab roll-back followed eventually by a progressive tearing process; (C) Delamination of the continental lithosphere.

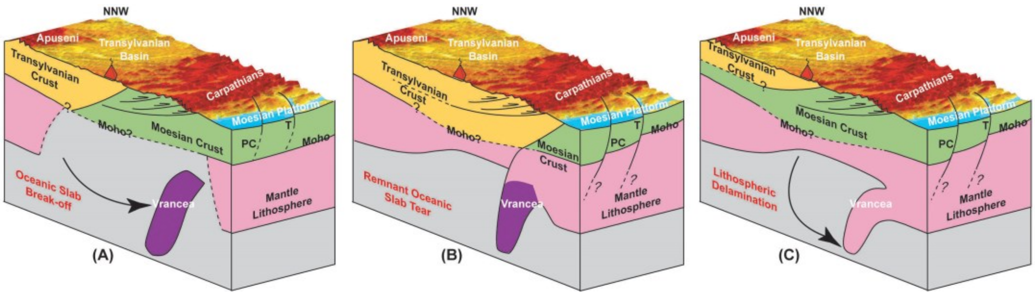


Fig. 13. Three possible scenarios to explain the present geometry of the slab beneath Vrancea region [34].

6.1 Subduction of an oceanic relic lithosphere

Considering that the tectonic system configuration nowadays, at least as it appears at the surface, does not involve any oceanic piece, we must admit the hypothesis of the presence of an ocean basin sometime in the history of the area's evolution. Thus, according to some authors, a marginal oceanic basin once occupied the Carpathian–Pannonian region (e.g. [11, 73]. It sunk into asthenosphere as a result of the collision forces. The basin closed in the Tertiary and active subduction stopped about 10 Ma ago [88], followed by a continental collision. Currently, the collision is almost blocked at the surface, while the process continues to be active at depth in the area of the Carpathian Arc bend.

Evidence for subduction and closure of an ocean basin during Miocene formation of the Eastern Carpathians is preserved in ophiolites (Transylvanides) between the Southern Carpathians and northern Apuseni Mountains [72, 73]. Mainly two alternative models regarding the reconstruction of the past evolution of the system were proposed: (1) an oceanic lithosphere attached to the East European craton that was subducted W- and SW-ward along the Carpathians during Miocene time [3, 13] and (2) a subducting basin attached to the Moesian platform that was subducted NW-ward beneath the Carpathian orogen [41, 22, 47].

The slab probably underwent a retreat process from NW to SE that lasted the entire time interval of subduction [41]. The retreat process led to the Adriatic Plate intrusion to the east and to the curvature of the Carpathians range [71], as shown in Figure 3. At the same time, the retreat process explains the nearly vertical position of the Vrancea slab at present as the final stage of the rollback process [41].

In the final stage of the subduction, when the oceanic slab was practically completely consumed, the ocean-continent collision regime changed to a continent-continent collision regime. The thicker and more buoyant continental plate (portion of East European or Moesian platform continental lithosphere) created an additional pressure upon the subducted oceanic plate able to tear it. Possibly, the subducted plate has undergone lateral tearing which migrated along the Carpathians orogen strike [90, 77]. Such a model is in agreement with:

- the migration and diminution of Neogene calc-alkaline magmatism in the Eastern Carpathians from northwest to southeast along the arc [47], and
- the NW-dipping geometry of the Vrancea seismic body [22].

Probably one of the strongest arguments for subduction of an oceanic slab beneath the Eastern Carpathians is the presence of a linear arc of Neogene volcanism within the hinterland. This volcanic chain, comprised of both calc-alkaline and alkaline magmas, was active from Middle Miocene to Quaternary time (13.4–0.2 Ma), and migrated successively from north to south [47]. The geochemistry of the calc-alkaline lavas suggest they are subduction-related (e.g. [55, 47]).

There has been recently some debate (e.g. [75, 28]) on the hypothesis of a slab detachment having propagated along the entire length of the Eastern Carpathians range; such a controversy still does not preclude the possibility that currently, lateral tearing could be developing just within a slab fragment preserved in Vrancea area (as suggested by [90, 25, 8]). More than that, it is still an open question if the subducted lithospheric block is currently completely separated from the overriding crust [20] or if the slab is still partially attached to the upper lithosphere [77].

6.2 Arguments for a relic oceanic slab in Vrancea

The results of [6] regarding the dispersion of P waves and the hypothesis of a "double seismic zone" [7, 12, 64] bring evidence in favour of an oceanic nature of the subducting lithosphere. Analysing in detail the characteristics of the seismicity, [7] brought into discussion the hypothesis of a double seismic zone. Going in the same direction, [64] and [12] showed that two somewhat distinct active segments accommodate the major Vrancea earthquakes (see Figure 8 above). The existence of a double seismic zone is characteristic for oceanic subduction as it assumes the existence of some dehydration processes that can only take place in the minerals of the oceanic lithosphere (e.g. [32]).

In the hypothesis of an oceanic lithosphere, it comes naturally from the lithospheric layer initially located on the earth's surface. This layer contains before entering into subduction a low-velocity layer (the oceanic crust) together with a high-velocity mantle lid. We can assume that the layer keeps its structure as it progresses in the subduction process, with the difference that the layer will change its position, from a horizontal one to an inclined one and finally to a vertical one, as it is the case in Vrancea. [6] studied the dispersion of the body waves coming from Vrancea intermediate-depth source as they are recorded by the stations located above the slab (Figure 14). They observed that the first-arriving P waves at high frequencies (~ 8 Hz) show an anormal dispersion, in the sense of being delayed relative to 0.5 Hz by an average of 0.7 s. This anomaly is attributed to the existence of a thin low velocity layer on top of the slab (corresponding to the oceanic crust, rotated to vertical position at present), which acts as a waveguide for high frequencies, but is too thin to be "recognized" by long wavelengths. Therefore, the observed dispersion is consistent with the presence of a subduction zone composed of oceanic lithosphere under the Eastern Carpathians.

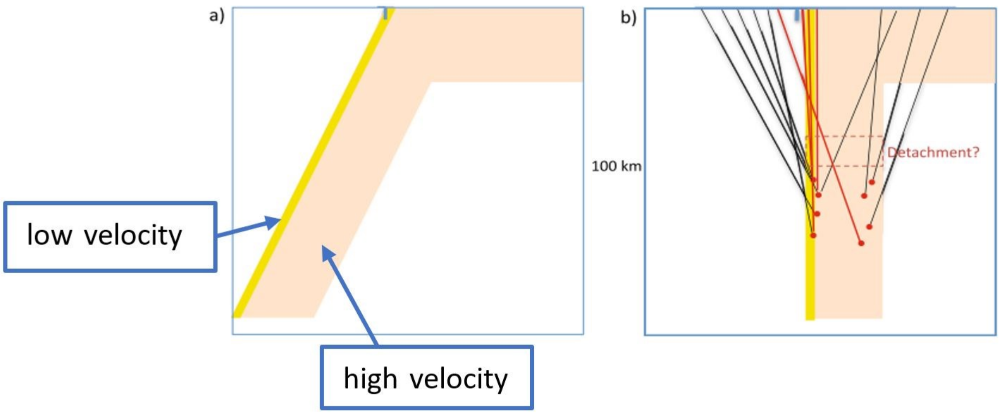


Fig. 14. Schematic representation of an oceanic slab beneath Vrancea. Red spots – hypocentres; red lines – first P-wave paths for epicentral stations, located in and close to the low-velocity lid (yellow); black lines - first P-wave paths for stations located away from epicentre (modified after [6].

[17] starting from the 3D tomographic image under Vrancea, showed that in the conditions of pressure and temperature at depths of 80-180 km associated with earthquakes, dehydration reactions of minerals typical for the superficial oceanic mantle are favoured.

High-resolution 3-D tomography image as obtained using data from the CALIXTO experiment [45] can be used as basis for subsequent modelling. For example, Ferrand and Manea (2021), starting from 3D tomography image in Vrancea infer the pressure and temperature conditions for the Vrancea intermediate-depth earthquakes. The pressure–temperature diagrams associated to hypocentres match the thermodynamic stability limits for the minerals typical of the uppermost oceanic mantle (antigorite dehydration between 2 and 4.5

GPa). So, their work provides evidence of the current dehydration of an oceanic slab beneath Carpathians.

6.3 Continental delamination process

In major contradiction with the hypothesis of the presence of an oceanic plate in Vrancea, a series of authors advanced the hypothesis of the presence of a piece of continental lithosphere. Thus, [52] and [53] showed that there is no geological evidence for the presence of an oceanic crust in the Eastern Carpathians evolution since Miocene. The lithosphere descending in the mantle is likely a narrow continental crust or of transition. On the same line, [34] and [18] argued against the interpretations on oceanic origin of the seismogenic body in Vrancea taking into account that they are not consistent with the geological constraints in the Eastern Carpathians and adjacent foreland. According to [34], the Neogene strata of the Eastern Carpathians are found much to the west, in the Transylvania Basin, while the geological structure in the Carpathians foredeep area, including Moho are sub-horizontally oriented toward east and above the Vrancea seismogenic zone. At the same time, the present interpretations of existing data from petroleum exploration and reprocessing of deep seismic reflection data suggest a continuity of continental crust beneath the external nappes of the Eastern Carpathians and beneath the Vrancea seismic zone as well. These surface and subsurface data appear to preclude the possibility that a slab, either still attached or now detached, was subducted either in place within the Carpathian foreland (e.g. [90]) or beneath the Eastern Carpathians (e.g. [88, 22, 24]).

The tectonic and geodynamic consequences of lithospheric delamination are generally agreed to include:

- post-orogenic extensional collapse,
- regional uplift,
- deep-seated alkaline magmatism,
- elevated heat flow,
- subcrustal seismicity

6.4 Arguments for a continental slab in Vrancea

In their paper [70] explained the strong contrast in the attenuation of the seismic waves generated in the Vrancea intermediate-depth source for the stations located on one side and the other side across Carpathians Arc bend assuming a model of delamination of continental lithosphere beneath Vrancea region (Figure 15).

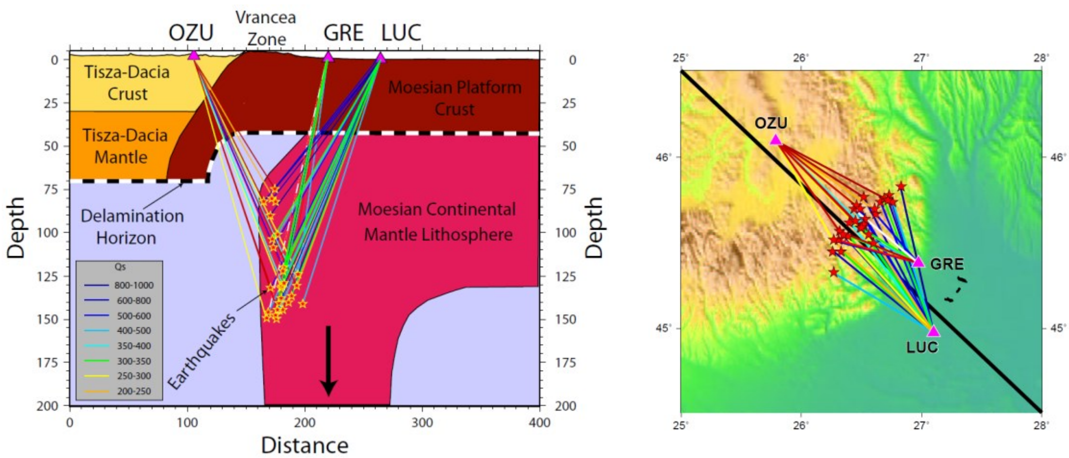


Fig. 15. Model of delamination of the continental mantle lithosphere beneath Vrancea region (vertical section across Vrancea zone NW-SE oriented - left) and justification of the strong asymmetry in the seismic waves propagation from the intermediate-depth source towards NW versus SE. Example for three stations located symmetrically relative to the Carpathians Arc bend [70].

The process of delamination of the continental lithosphere and the descending movement towards the present-day vertical position (caused by the increased weight of the continental material as a result of the thickening of the layer by collision and the triggering of phase transformations in the thickened part that reaches the depths at which the critical conditions of temperature and pressure allow this process) induces an upward movement of the hotter and more plastic material of the asthenosphere behind the delaminated plate. We can explain the strong asymmetry in attenuation behind the orogenic arc compared to its front by this influx of asthenospheric material that significantly attenuates the propagation of seismic waves. For example, for a moderate Vrancea earthquake, the amplitude of the ground motion recorded at OZU station (behind orogenic arc) is by a factor of about 10 smaller than the amplitude recorded at stations located symmetrically on the other side of the orogenic arc (such as GRE and LUC).

Recently, [39] investigated the possibility to trigger delamination in a thickened continental mantle lithosphere. The most common mineral in the continental lithosphere that contains water is pargasite. It is stable at pressures and temperatures lower than ~3 GPa and ~1100 0C respectively (which correspond to a depth of ~100 km). When these values are reached, the pargasite becomes unstable and suddenly releases 'water'-rich fluids in a narrow zone (up to a few kilometres) in the upper mantle between the Moho and the LAB (Lithosphere-Asthenosphere Boundary) which is defined as MLD (Middle Lithosphere

Boundary) in older continental lithospheres or in locked continental collision settings. In this way, a horizon of weakness is created around the depth of 100 km (Figure 16).

Pargasite hypothesis is very attractive from two points of view: it can directly explain how a process of delamination of the lithosphere is feasible and why the geometric configuration of the seismicity suddenly changes at a depth of ~100 km (see section above “Seismicity location and patterns”).

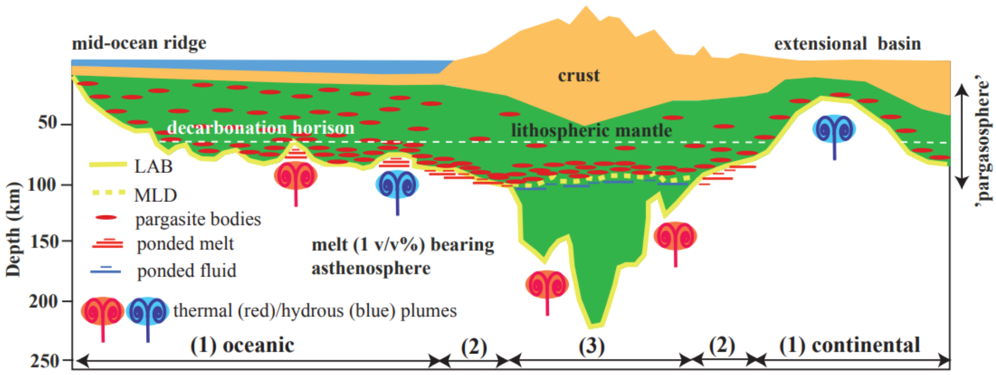


Fig. 16. Schematic view of the thermal-tectonic structure of a continental lithosphere. The position of the pargasite-rich layer coincides with the Mid Lithosphere Discontinuity (MLD), situated above the Lithosphere-Asthenosphere Boundary (LAB). Positions of ponded melts, fluids and plumes are also plotted [39].

In any of the proposed models, with or without oceanic subduction, the intervention of a decoupling process and a retreat process (after slab break-off or delamination) is assumed during the evolution of the system. The retreat process gradually led to plate migration from NW to SE some 130 km into its present position beneath Vrancea (steepening the sinking lithosphere dip to near vertical).

Starting from their inversion using velocity and gravity data, [80] proposed a geodynamic model in Vrancea as a combination of a relic oceanic subduction and a continental lithospheric delamination. The distribution of the ratio V_P/V_S (P-wave velocity / S-wave velocity) on depth (Figure 17) reveals significant changes differences in the material above and below the 100 km depth. As it is known, the value of the ratio can be directly related to the presence of fluids in the respective material: a high V_P/V_S value indicates a high percentage of fluids, while a low V_P/V_S value indicates a rigid and cold material. Thus, the high V_P/V_S values in the seismic gap (40 – 80 km) may result from delamination of the European mantle lithosphere and the upwelling of hot asthenospheric material. The decrease of V_P/V_S below ~ 100 km depth is interpreted as characterizing an old oceanic slab, while the upper part is related to continental lithosphere. The 100 km horizon is considered as a transition from continental to oceanic slab. This variation of the properties of the subducted material in the mantle coincides with the position of the Vrancea hypocentres. The transition at about 100 km depth from high to low values of the V_P/V_S ratio also corresponds to the transition from two regimes of intermediate-depth seismicity, as revealed by the seismicity patterns (segments A and B in Figure 8). It also coincides with the MLD horizon proposed by [39] as weakened zone due to the critical release of fluids at this level.

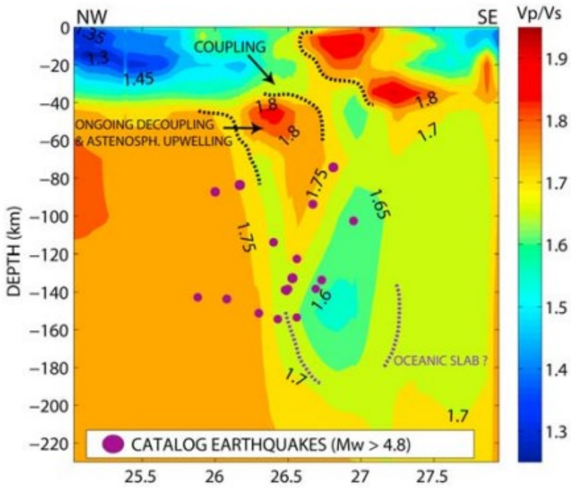


Fig. 17. Distribution on depth of the V_P/V_S values beneath Vrancea seismic region. A vertical NW-SE cross section is plotted [80].

7. Distribution of effects

Analysis of the macroseismic and instrumental data from the intermediate-depth Vrancea earthquakes revealed several peculiarities of the earthquake effects (e.g. [28, 40, 44]) that can be summarized as follows:

– Extended areas, N-W elongated, are strongly affected.

– NE-SW enhancement of effects coincides with the geometry of seismicity and of the fault-plane solutions.

– Source directivity caused by particular rupture orientation can play a significant role in distributing asymmetrically the intensity effects at regional scale.

– Local and regional geological conditions can control the amplitudes of earthquake ground motion to a larger degree than magnitude or distance.

– Apparently the focal depth can shape to some extent specific patterns in the ground motion distribution.

Figure 18 illustrates the concordance among different aspects characterizing Vrancea source: seismicity NE-SW alignment, typical focal mechanism, source directivity and effect distribution following the same alignment.

Our interpretation regarding the correlations revealed in Figure 13 is that they cannot be simple coincidences, but reflect some underlying common processes and properties.

The asymmetric distribution of the effects is obvious both in macroseismic maps for the Vrancea major shocks (one example for 1977 event is shown in Figure 19), peak ground acceleration maps and naturally in the seismic hazard maps.

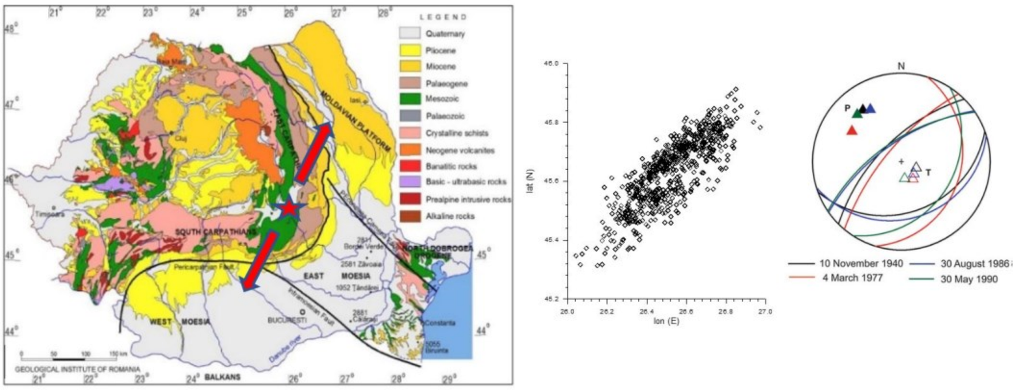
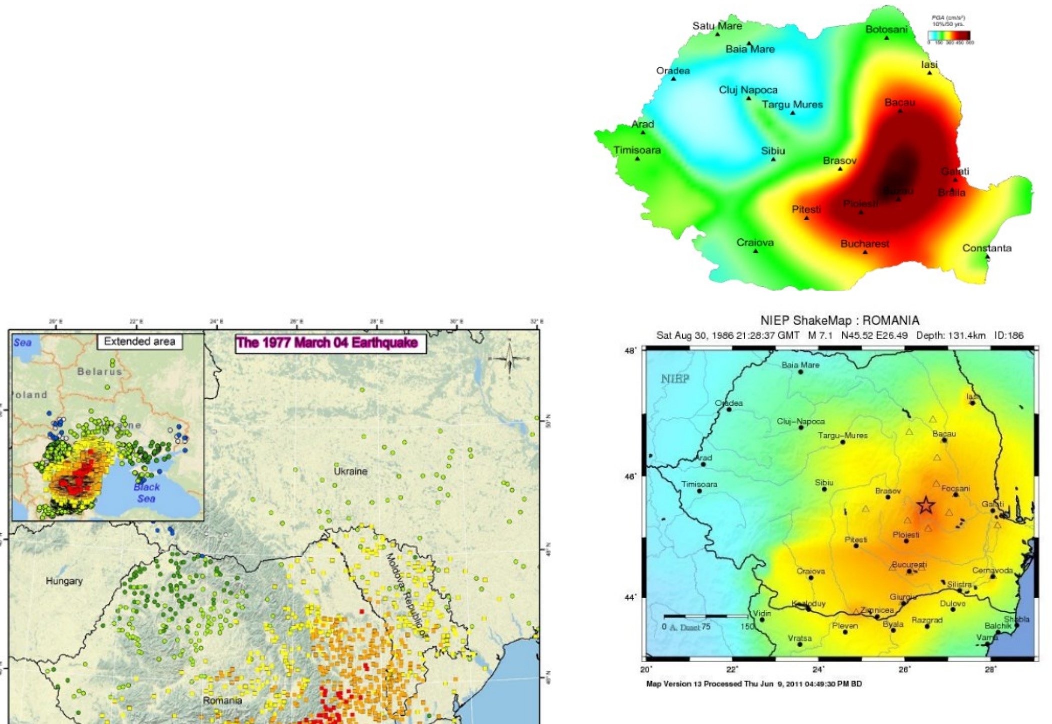


Fig. 18. Predominant NE-SW alignment for the Vrancea source (after [64, 65])



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Fig. 19. Examples showing the asymmetric distribution of the effects recorded for Vrancea major events NE-SW: macroseismic map for 1977 event (left), shakemap of the 1986 event (bottom right) and hazard map in terms of 10% exceeding probability of PGA (top right) [54].

8. Properties of seismic wave propagation

The seismic waves coming from the Vrancea intermediate-depth source travel across a lithosphere–asthenosphere structure beneath the SE-Carpathians with strong lateral variations, particularly beneath the arc bend in Vrancea. One major feature of the structure in this area is the sharp contrast between the high-velocity body sinking into the mantle and the asthenospheric upwelling located NW behind the arc (Figure 15). This is considered to be the main cause of the particular shape of the distribution of effects, and of the seismic hazard respectively (Figures 18 and 19) with direct impact on the populated areas.

The strong attenuation of the seismic waves propagating toward inner side of the Carpathians in contrast with those travelling toward outer side of the Carpathians has been reported in many studies (e.g. [51, 57, 70]). Attenuation effect observed for strong events is pointed out for small and moderate events as well. Thus, [57] and [63] investigated the waveform characteristics recorded for small and moderate Vrancea intermediate-depth earthquakes and showed the asymmetric pattern relative to the epicentral area of the ground motion. The velocity amplitudes are reduced by a factor of 20 on average in the Transylvanian Basin and in the East Carpathians (along the inner volcanic chain) relative to the values recorded in front of Carpathians at similar hypocentre distance. At the same time, the high frequencies are strongly attenuated in the inner side of Carpathians compared to the foreland platform. Note that the areas of strong attenuation include the regions of recent volcanic activity (Persani Mountains and the volcanic chain along inner side of the Eastern Carpathians).

The anisotropy of the seismic waves is a common phenomenon observed in any of the tectonic setting of the Earth. The degree of anisotropy is measured from the polarization of the S phase and the delay between the fast and slow S-wave travel times. It is generally accepted that the main source of seismic anisotropy is the alignment, coherent at large scale, of minerals in the crust and mantle (e.g. [42]). Since olivine, which is the most abundant and anisotropic mineral in the mantle, follows the maximum shear stress orientation or the maximum extension direction, the anisotropy provides key insights into upper-mantle deformation and flow.

The analysis of the SKS waves (core-refracted shear phases) splitting is one of the best methods to constrain upper mantle azimuthal anisotropy (e.g. [74, 76]). When an initially radially-polarised shear wave enters an anisotropic medium, it splits between two orthogonally polarised waves, resulting in elliptical particle motion and energy on the radial and tangential seismogram components. The polarisation direction of the fast shear wave and the delay time provide information on the orientation, strength, and/or thickness of the anisotropic layer.

Application of SKS splitting method in the Pannonian-Carpathian system by several papers emphasized a complex flow field around the Vrancea slab in Romania. The general trend observed in the Central and Eastern Europe is the NW-SE orientation of the polarisation of the fast shear wave (e.g. [29]). This is in agreement with the recent stress and deformation characterizing the region attributed to the counter-clockwise rotation of the Adria microplate (Figure 3). Fast polarisation directions gradually rotate in the Transylvanian Basin and across the East Carpathians, paralleling the orogen and the craton margin, but the most striking perturbation is observed at the South-East Carpathians corner, where the steeply sinking seismogenic lithospheric block that experienced lateral tear-off and possible rotation is located. The fast polarisation direction here suddenly rotates by 90^0 to a position tangent to the orogen arc [29, 56, 58, 78]. This perturbation is likely to be in connection with the processes of subduction and slab roll-back which introduce poloidal and toroidal flow patterns in the surrounding asthenosphere (e.g. [16, 85, 86). On the other side, the smaller SKS delay times measured to the NW side of the Vrancea region (in the Transylvanian Basin), which reveal weaker anisotropy [56], is consistent with the asymmetric upwelling adjacent to the slab, slower mantle velocities, and recent volcanism. Thus, we note that the anisotropy features fit well the tomography investigations, attenuation properties and geodynamic modelling.

9. Repeated earthquakes

Earthquake nests have seismicity which is highly localized in space and has the tendency to have earthquakes that occur repeatedly at the same or almost the same location. The question that arises is whether a significant number of these earthquakes represent repeated rupture of the same fault plane. Typically, repeating earthquakes can be identified because they exhibit nearly identical seismograms at common stations, suggesting nearby locations, similar focal mechanisms and rupture of the same asperity or patch (see for example [83]).

The observation of possible repeating events and their precise location is key for constraining the physical mechanism involved in intermediate-depth and deep earthquakes. [89] interpret the repeating earthquakes they found as rupturing the same fault patch, and suggest that these earthquakes are due to a thermal shear runaway process. Mechanisms involving dehydration embrittlement or phase transformations might not be expected to foster repeating earthquakes.

[59] investigated the detectability of repeated earthquakes in the Vrancea nest and the seismicity patterns of repeated earthquakes in space, time and size in order to detect potential interconnections with larger events. Even though they show that there is a relatively high probability to identify repeated earthquakes in the Vrancea subducting slab, it remains an open question if the repeated earthquakes are located in a close proximity or if they are really rupturing the same patches.

10. Conclusions

This paper represents a critic review of the known or less known aspects characterizing the unusual geodynamic phenomenon of the Vrancea source. In the presentation we balance what we know and what we don't know about the seismogenic process and what are the most critical issues that are at present reliably constrained and what we have to further investigate. Considering that Vrancea represents a key element of the Carpathian-Pannonian system and is assumed to be part of a key stage of the evolution of the subduction systems, the subject of our presentation is of particular interest to the scientific community. At the same time, taking into account the major impact of the Vrancea earthquakes that have caused major damage over time in Romania and in the neighbouring countries, as well, the interest for society is as great as for science. Scientific knowledge provides the framework and the most effective means to contribute to the reduction of these effects.

First of all, we show that there are a few fundamental aspects related to the process of generating earthquakes in the Vrancea area. We present them outlining the aspects we know with sufficient precision, as they result from studies and observational data and in balance the aspects that are less known and that raise many question marks to be clarified by future research.

As concerns the geodynamic modelling a key issue is the nature of the cold and dense material that is descending into the deeper mantle: Oceanic lithosphere – paleosubduction or continental lithosphere: subduction or delamination. The tomography results, regardless of the data used (earthquake teleseismic or local data, seismic noise data), unanimously highlight the presence of a high-velocity lithospheric body in the mantle, but cannot resolve the ambiguity oceanic subduction/continental collision. There are arguments in favour and against these two types of models. Oceanic-type models involve break-off process [20, 77, 90], lateral migration of an oceanic slab [22, 24], or subduction and lateral tearing of a slab [46, 88, 90]. Continental-type models involve active delamination [34, 36] or gravitational instability [43, 68].

An important question: is the Vrancea slab still attached to the crust or has been already detached? The models assuming a complete detachment of the sinking slab from the continental crust [20] are in agreement with the apparent gap of seismicity between the crust and the slab (40 – 60 km), as illustrated in Figure 5. They would also explain to some extent the weak coupling between the deep seismic activity and the shallow one in the overriding crust. The geodetic measurements [14] revealing relative uplift rates of at least 10 mm/year (mean uplift rate of 22 mm/year with an average confidence range of 13.4 mm/year) in the Vrancea region, provide an additional argument for the decoupling (or still decoupling) of the descending slab from the overlying crust. Hence the load of the slab decreases, and as a result the released crust starts to uplift. On the other hand, the focal mechanisms of the Vrancea earthquakes clearly indicate a predominant process of vertical extension that cannot be explained only by the presence of gravitational forces, but would also involve coupling forces in the upper part of the slab. To reconcile these aspects, a combined model was proposed that assumes a partial decoupling at the upper edge of the slab. For example, [22] assumed first a break-off affecting only the crustal portion of the slab, followed then by the horizontal delamination of its lower portion.

The seismicity patterns and focal mechanism characteristics at the SE Carpathians Arc bend should reflect in some way the tectonic and geodynamic features of the earthquake-prone system. A significant feature worth to mention is the fitting of the fault plane solutions of the major shocks with the geometrical configuration of the seismic activity. This possibly reflect an intrinsic coupling of the background seismicity stationary production with the critical triggering mechanism leading to the larger events.

The lithosphere-asthenosphere structure shows significant lateral inhomogeneities across Carpathians Arc bend with implications on seismic tomography, seismic wave attenuation, thermal field, seismic anisotropy. The properties of seismic waves attenuation and seismic anisotropy outline strong perturbations in the area corresponding to Vrancea intermediate-depth source. Investigating and understanding why these perturbations occurred and imaging with increased resolution their space-time distributions will increase our ability to model the complex processes, such as retreat, break-off and rotation, that have acted recently at the South-Eastern Carpathians arc bend and to better predict the seismic hazard and risk produced by the Vrancea strong earthquakes.

REFERENCES

[1] Z. Alasonati Tašárová, J. Fullea, M. Bielik, P. Środa, *Lithospheric structure of Central Europe: Puzzle pieces from Pannonian Basin to Trans-European Suture Zone resolved by geophysical-petrological modeling*, Tectonics, **35**, 3, 722-753, doi.org/10.1002/2015TC003935 (**2016**).

[2] G. Bada, F. Horvath, *On the structure and tectonic evolution of the Pannonian Basin and surrounding*, Acta Geologica Hungarica, **44**(2): 301-327 (**2001**).

[3] Z. Balla, *Tertiary paleomagnetic data for the Carpatho-Pannonian region in the light of Miocene rotation kinematics*, Tectonophysics, **139**, 1-2, 67-98 (**1987).**

[4] O. Bazacliu, M. Radulian, *Seismicity variations in depth and time in the Vrancea (Romania) subcrustal region*, Natural Hazards **19**, 165-177 (**1999**).

[5] A. Bălă, M. Radulian, D. Toma-Dănilă, *Present-day stress field pattern in the Vrancea seismic zone (Romania) deduced from earthquake focal mechanism inversion*, Annals of Geophysics **64**, 6, SE661, doi:10.4401/ag-8632 (**2021**).

[6] G. Bokelmann and F. Rodler, *Nature of the Vrancea seismic zone (Eastern Carpathians) – New constraints from dispersion of first-arriving P-waves*, Earth and Planetary Science Letters, doi:10.1016/J.EPSL.2013.12.034 (**2014**).

[7] K.-P. Bonjer, C. Ionescu, V. Sokolov, M. Radulian, B. Grecu, M. Popa, E. Popescu, *Source parameters and ground motion pattern of the October 27, 2004 intermediate depth Vrancea earthquake*, EGU General Assembly 2005, Vienna (**2005).**

[8] K.-P. Bonjer, C. Ionescu, V. Sokolov, M. Radulian, B. Grecu, M. Popa, E. Popescu, *Ground motion patterns of intermediate-depth vrancea earthquakes: the October 27, 2004 event*. In: Zaicenco A, Craifaleanu I, Paskaleva I (eds) Harmonization of seismic hazard in Vrancea zone, NATO Science for Peace and Security Series – C. Springer, Dordrecht, 47–62 (**2008**).

[9] A.J.J.Bracco Gartner, I. Seghedi, I. K. Nikogosian, P. R. Mason, *Asthenosphere-induced melting of diverse source regions for East Carpathian post-collisional volcanism*, Contributions to Mineralogy and Petrology, **175**, 54 (**2020**).

[10] N. Brantut, I. Stefanou, J. Sulem, *Dehydration-induced instabilities at intermediate depths in subduction zones*, Journal of Geophysical Research: Solid Earth, **122**(8), DOI:10.1002/2017jb014357 (**2017**).

[11] B.C. Burchfiel, *Geology of Romania*, GSA Special Paper, **158**, doi.org/10.1130/SPE158 (**1976).**

[12] O.F. Cărbunar and M. Radulian, *Geometrical constraints for the configuration of the Vrancea (Romania) intermediate-depth seismicity nest*, Journal of Seismology, **15**(4):579-598, doi:10.1007/s10950-011-9233-z (**2011).**

[13] L. Csontos, A. Nagymarosy, F. Horváth, M. Kovác, *Tertiary evolution of the Intra-Carpathian area: A model*, Tectonophysics, **208**, 1-3, 221-241 (**1992).**

[14] G. Dinter, M. Nutto, G. Schmitt, U. Schmidt, D. Ghitau, C. Marcu, *Three dimensional deformation analysis with respect to Plate Kinematic in Romania*, Reports on Geodesy **2/57**, 29-41 (**2001).**

[15] D. Enescu, *Contributions to the knowledge of the focal mechanism of the Vrancea strong earthquakes of March 4, 1977*. Rev Roum Géol Géophys Géogr Ser Géophys **24**(1):3–18 (**1980**).

[16] M. Faccenda, F. A. Capitanio, *Seismic anisotropy around subduction zones: Insights from three-dimensional modeling of upper mantle deformation and SKS splitting calculations*, Geochemistry, Geophysics, Geosystems, **14** (1), 243-262, doi:10.1002/ggge.20055 (**2013)**.

[17] T.P. Ferrand and E.F. Manea, *Dehydration-induced earthquakes identified in a subducted oceanic slab beneath Vrancea, Romania*, Scientific Reports **11**, 10315 (**2021).**

[18] M.A. Fillerup, J.H. Knapp, C.C. Knapp, V. Raileanu, *Mantle earthquakes in the absence of subduction? Continental delamination in the Romanian Carpathians*, Lithosphere **2**(5):333-340, doi.org/10.1130/L102.1 (**2010).**

[19] C. Frohlich, *Deep earthquakes*, Cambridge University Press, Cambridge, doi.org/10.1017/CV09781107297562 (**2006).**

[20] K. Fuchs, K.-P. Bonjer, G. Bock, *The Romanian earthquake of March 4, 1977. II. Aftershocks and migration of seismic activity,* Tectonophysics **53**: 225–247 (**1979).**

[21] L. Gemmer and G. Houseman, *Convergence and extension driven by lithospheric gravitational instability: evolution of the Alpine-Carpathian-Pannonian system*, Geophysical Journal International, DOI:10.1111/J.1365-246X.2006.03327.X (**2007).**

[22] R. Girbacea, W. Frisch, *Slab in the wrong place: lower lithospheric mantle delamination in the last stage of the Eastern Carpathian subduction retreat*, Geology, **26**:611–614 (**1998).**

[23] O. Göğüş, R. Pysklywec, C. Faccenna, *Postcollisional lithospheric evolution of the Southeast Carpathians: Comparison of geodynamical models and observations*, Tectonics, DOI:10.1002/2015TC004096 (**2016).**

[24] Z. Gvirtzman, *Partial detachment of a lithospheric root under the southeast Carpathians: toward a better definition of the detachment concept*, Geology **30**(1):51–54 (**2002).**

[25] R. Hackney, M. Martin, A. Ismail-Zadeh, B. Sperner, *The gravity effect of the subducted slab beneath the Vrancea region, Romania*, Geologica Carpathica **53** (**2002).**

[26] A. Hasegawa, J. Nakajima, *Seismic imaging of slab metamorphism and genesis of intermediate-depth intraslab earthquakes*, Prog. Earth Planet. Sci. **4**(1):12 (**2017).**

[27] F. Horváth, *Towards a mechanical model for the formation of the Pannonian basin*, Tectonophysics, **226**, 333-357 (**1993).**

[28] A. Ismail-Zadeh, L. Maţenco, M. Radulian, S. Cloetingh, G.F. Panza, *Geodynamics and intermediate-depth seismicity in Vrancea (The South-Eastern Carpathians): current state-of-the art,* Tectonophyiscs 530–531:50–79 (**2012).**

[29] M. Ivan, M. Popa, D. Ghica, *SKS splitting observed at Romanian broad-band seismic network*, Tectonophysics **462**, 89-98 (**2008**).

[30] T. John, S. Medvedev, L.H. Rüpke, T.B. Andersen, Y.Y. Podladchikov, H. Austrheim, *Generation of intermediate-depth earthquakes by self-localizing thermal runaway*, Nat. Geosci. **2**(2):137–40 (**2009).**

[31] H. Jung, H.W. II Green, L.F. Dobrzhinetskaya, *Intermediate-depth earthquake faulting by dehydration embrittlement with negative volume change*, Nature **428**(6982):545–49 (**2004).**

[32] H. Kawakatsu, *Double seismic zones: Kinematics*, Journal of Geophysical Research, Solid Earth, doi.org/10.1029/JB091iB05p04811 (**1986).**

[33] S.H. Kirby, W.B. Durham, L.A. Stern, *Mantle phase changes and deep-earthquake faulting in subducting lithosphere*, Science, **252**(5003):216–25 (**1991).**

[34] J.H. Knapp, C. C. Knapp, V. Raileanu, L. Matenco, V. Mocanu, and C. Dinu, *Crustal constraints on the origin of mantle seismicity in the Vrancea Zone, Romania: The case for active continental delamination*, Tectonophysics, 410, 311– 323, doi:10.1016/j.tecto.2005.02.020 (**2005**).

[35] V. Konečný, M. Kovac, J. Lexa, J. Sefara, *Neogene evolution of the Carpatho-Pannonian region: An interplay of subduction and back-arc uprise in the mantle,* in Stephan Mueller Special Publication Series, DOI: 10.5194/smsps-1-105-2002 (**2002).**

[36] I. Koulakov, B. Zaharia, B. Enescu, M. Radulian, M. Popa, S. Parolai, J. Zschau, *Delamination or slab detachment beneath Vrancea? New arguments from local earthquake tomography*, Geochem Geophys Geosyst **11**(G3):Q03002. doi:10.1029/2009GC002811 (**2010).**

[37] M. Kováč, I. Baráth, M. Kováčová-Slamková, R. Pipík, I. Hlavatý, N. Hudáčková, *Late Miocene paleoenvironments and se-quence stratigraphy: northern Vienna Basin*, Geol. Carpathica, **49**, 6, 445-458 (**1998).**

[38] M. Kováč, *Geodynamical, paleographical and structural development of the Carpathian-Pannonian region in Miocene.New view on Slovak Neogene basins*. *Geodynamický, paleo-geografický a štruktúrny vývoj karpatsko-panónskeho regiónuv miocéne: Nový pohlad na neogénne panvy Slovenska*, Veda, Bratislava, 202pp, (in Slovak) (**2000).**

[39] I. Kovács, N. Liptai, L. Patkó, T. Lange, L. Matenco, S.A.P.L. Cloetingh, M. Radulian, G. Molnár, A. Szakács, M. Berkesi, A. Novák, V. Wesztergom, Cs. Szabó, *The „pargasosphere" concept: or looking at global plate tectonics from a new perspective?*, Global and Planetary Change, vol. **204**, 103547, https://doi.org/10.1016/j.gloplacha.2021.103547 (**2021**).

[40] T. Kronrod, M. Radulian, G.F. Panza , M. Popa, I. Paskaleva, S. Radovanovich, K. Grjibovski, I. Sandu, L. Pekevski, *Integrated transnational macroseismic data set for the strongest earthquakes of Vrancea (Romania)*, Tectonophysics, **590**, 1-23 (**2013).**

[41] H.G. Linzer, *Kinematics of retreating subduction along the Carpathian arc, Romania*. Geology **24**: 167–170 (**1996**).

[42] M.D. Long, T.W. Becker, *Mantle dynamics and seismic anisotropy*, Earth Planet. Sci. Lett., **297** (3), 341{354, doi:10.1016/j.epsl.2010.06.036 **(2010**).

[43] P. Lorinczi, G.A. Houseman, *Lithospheric gravitational instability beneath the Southeast Carpathians*, Tectonophysics **474**:322–336 (**2009).**

[44] N. Mandrescu, M. Radulian M., *Macroseismic field of the Romanian intermediate-depth earthquakes*. In: Wenzel et al. (eds) Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation. Kluwer Academic Publishers, Dordrecht (**1999**).

[45] M. Martin, F. Wenzel, CALIXTO working group, *High-resolution teleseismic body wave tomography beneath SE-Romania – II. Imaging of a slab detachment scenario,* Geophysical Journal International, **164**, 3, 579-595 (**2006**).

[46] S. Martin and A. Rietbrock, *Guided waves at subduction zones: dependencies on slab geometry, receiver locations and earthquake sources*, Geophys J. Int., **167**:693–704 (**2006).**

[47] P.R.D. Mason, I. Seghedi, A. Szakács, H. Downes, *Magmatic constraints on geodynamic models of subduction in the Eastern Carpathians, Romania*, Tectonophysics*,* **297**, 157-176, (**1998**).

[48] M.C. Oncescu, *On the stress tensor in Vrancea region*, J. Geophys. Res. **62**:62–65 (**1987).**

[49] M.C. Oncescu, K.-P. Bonjer, *A note on the depth recurrence and strain release of large Vrancea earthquakes*, Tectonophysics **272**: 291–302 (**1997**).

[50] M.C. Oncescu, and C.-I. Trifu, D*epth variation of moment tensor principal axes in Vrancea (Romania) seismic region*, Ann. Geophys., **5B**, 149–154 (**1987).**

[51] A. Oth, D. Bindi, S. Parolai, F. Wenzel, *S-Wave Attenuation Characteristics beneath the Vrancea Region in Romania: New Insights from the Inversion of Ground-Motion Spectra*, Bulletin of the Seismological Society of America **98**, 2482–2497 (**2008).**

[52] D. Pană and P. Erdmer, *Kinematics of retreating subduction along the Carpathian arc, Romania: Comment*, Geology **24**, 862-863 (**1996).**

[53] D. Pană and G.A. Morris, *Slab in the wrong place: lower lithospheric mantle delamination in the last stage of the Eastern Carpathian subduction retreat: comment*, Geology **27**, 665-666, (**1999).**

[54] F. Pavel, R. Văcăreanu, J. Douglas, M. Radulian, C. Cioflan, A. Barbat, *An updated probabilistic seismic hazard assessment for Romania and comparison with the approach and outcomes of the SHARE project*, Pure and Applied Geophysics, **173** (6), 1881 – 1905 (**2016**).

[55] Z. Pécskay, O. Edelstein, I. Seghedi, A. Szakács, M. Kovacs, M. Crihan, A. Bernad, *K-Ar datings of the Neogene-Quaternary calc-alkaline volcanic rocks in Romania*, Acta Vulcanologica, **7**, 53-63 (**1995**).

[56] L. Petrescu, M. Andrei, F. Borleanu, *Slab tear and rotation imaged with core-refracted shear wave anisotropy*, Journal of Geodynamics, doi:https://doi.org/10.1016/j.jog.2023.101985 (**2023**).

[57] M. Popa, M. Radulian, B. Grecu, E. Popescu, A.O. Plăcintă, *Attenuation in Southeastern Carpathians area: result of upper mantle inhomogeneity*, Tectonophysics, **410**, 235-249 (**2005**).

[58] M. Popa, M. Radulian, C. Panaiotu, F. Borleanu, *Lithosphere–asthenosphere interaction at the Southeastern Carpathian Arc bend: Implications for anisotropy*, Tectonophysics, **462**, 83-88 (**2008).**

[59] E. Popescu, A.O. Plăcintă, F. Borleanu, M. Radulian, *Repeated earthquakes in the Vrancea subcrustal source and source scaling*, Proceeding of the World Multidisciplinary Earth Science Symposium WMESS 2017, IOP: Earth and Environmental Sciences, 95, doi: 10.1088/1755-1315/95/3/0320052017 (**2017**).

[60] M. Radulian, C.I. Trifu, *Would it have been possible to predict the August 30, 1986 Vrancea earthquake?*, Bull. Soc. Seism. Am. **81**, 2498-2503 (**1991)**.

[61] M. Radulian, C.I. Trifu, F.O. Carbunar, *Numerical simulation of earthquake generation process*, Pure and Applied Geophysics **136**, 499-514 (**1991**).

[62] M. Radulian, A. Bălă, E. Popescu, *Earthquakes distribution and their focal mechanism in seismogenic zones of Romania,* Roman Report Phys **47**:945–963 (**2002).**

[63] M. Radulian, G.F. Panza, M. Popa, B. Grecu, *Attenuation of Vrancea events revisited*, J. Earthquake Engineering **10**, 411-427 (**2006**).

[64] M. Radulian, K.-P. Bonjer, E. Popescu, M. Popa, C. Ionescu, B. Grecu, *The October 27th, 2004 Vrancea (Romania) earthquake*, ORFEUS Newsletter **1**(7), Jan 2007 (**2007).**

[65] M. Radulian, *Mechanisms of earthquakes in Vrancea*, In: Beer M, Patelli E, Kougioumtzoglou I., Siu-Kui Au I (eds) Encyclopedia of earthquake engineering, Springer, Berlin, Heildelberg, doi.org/10.1007/978-3-642-36197-5_302_1 (**2014).**

[66] L. Ratschbacher, W. Frisch, H.G. Linzer, O. Merle, *Lateral extrusion in the Eastern Alps, part 2.: structural analysis*, Tectonics, **10**, pp. 257-271 (**1991a).**

[67] L. Ratschbacher, O. Merle, P. Davy., P. Cobbold, *Lateral extrusion in the Eastern Alps, part 1: boundary conditions and experiments scaled for gravity*, Tectonics, **10**, pp. 245-256 (**1991b).**

[68] Y. Ren, G.W. Stuart, G.A. Houseman, B. Dando, C. Ionescu, E. Hegedüs, S. Radovanović, Y. Shen, South Carpathian Project Working Group, *Upper mantle structures beneath the Carpathian–Pannonian region: implications for the geodynamics of continental collision*, Earth Planet Sci Lett 349–350:139–152 (**2012**).

[69] M. Rogozea, M. Radulian, M. Popa, D.N. Paulescu, E. Oros, C. Neagoe, *Comparison of three major historical earthquakes with three recent earthquakes,* in "Effects and Lessons from November 10th, 1940 Vrancea Earthquake" Proceedings of the Symposium Commemorating 75 Years from November 10, 1940 Vrancea Earthquake (eds. R. Vacareanu, C. Ionescu), Springer Natural Hazards, 267 – 283 (**2016)**.

[70] R. Russo, V. Mocanu, M. Radulian, M. Popa, K.-P. Bonjer, *Seismic attenuation in the Carpathian bend zone and surroundings,* Earth and Planetary Sciences Letters **237**(3-4):695-709, DOI:10.1016/j.epsl.2005.06.046 (**2005).**

[71] L.H. Royden, *Evolution of retreating subduction boundaries formed during continental collision,* Tectonics **12**, 3, p. 629-638 (**1993).**

[72] L.H. Royden and T. Baldi, *Early Cenozoic tectonics and paleogeography of the Pannonian and surrounding regions*, in L.H. Royden and F. Horvath, eds., The Pannonian Basin: A study in basin evolution: AAPG Memoir **45**, p. 1-16 (**1988).**

[73] M. Sandulescu, *Cenozoic Tectonic History of the Carpathians*, In: Royden, L.H. and Horváth, F., Eds., The Pannonian Basin: A Study in Basin Evolution, Am. Assoc. Pet. Geol. Memoir, **45**, 17-25 (**1988).**

[74] M. Savage, *Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting?*, Rev. Geophys., **37**, 65{106, doi:10.1029/98RG02075 (**1999)**.

[75] I. Seghedi, L. Maţenco, H. Downes, P.R.D. Mason, A. Szakács, Z. Pécskay, *Tectonic significance of changes in post-subduction Pliocene–Quaternary magmatism in the south east part of the Carpathian–Pannonian Region*, Tectonophysics, **502** (1-2), 146-157 (**2011**).

[76] P. Silver, G. Chan, *Shear wave splitting and subcontinental mantle deformation*, J. Geophys. Res., **96** (B10), 16,429{16,454, doi:10.1029/91JB00899 (**1991)**.

[77] B. Sperner, F. Lorenz, K.-P. Bonjer, S. Hettel, B. Muller, F. Wenzel, *Slab break-off – abrupt cut or gradual detachment? New insights from the Vrancea region (SE Carpathians, Romania)*, Terra Nova **13**: 172–179 (**2001**).

[78] A.C. Stanciu, R.M. Russo, Mocanu V. I., Munteanu L., *Shear-wave splitting within the Southeastern Carpathian Arc, Transylvanian Basin*, *Romania*, J. of Geodynamics, **70,** 61-69, (**2013)**.

[79] C. Tomek and J. Hall, *Subducted continental margin in the Carpathians of Czechoslovakia,* Geology, DOI: 10.1130/0091-7613(1993)021<0535:SCMIIN>2.3.CO (**1993).**

[80] R. Tondi, U. Achauer, M. Landes, R. Davi, L. Besutiu, *Unveiling seismic and density structure beneath the Vrancea seismogenic zone, Romania*, Journal of Geophysical Research, Solid Earth, doi.org/10.1029/2008JB005992 (**2009).**

[81] C.I. Trifu, M. Radulian, *Asperity distribution and percolation as fundamentals of earthquake cycle*, Phys. Earth Planet. Interiors **58**, 277-288 (**1989**).

[82] C.I. Trifu, M. Radulian, *Frequency - magnitude distribution of earthquakes in Vrancea: relevance for a discrete model*, J. Geophys. Res. **96**, 4301-4311 (**1991**).

[83] N. Uchida, T. Matsuzawa, W.L. Ellsworth, K. Imanishi, T. Okada, A. Hasegawa, *Source parameters of a M4.8 and its accompanying repeating earthquakes off Kamaishi, NE Japan: Implications for the hierarchical structure of asperities and earthquake cycle*, Geophys. Res. Lett. **34**, L20313, doi:10.1029/2007GL031263 (**2007**).

[84] K. Ustaszewski, S.M. Schmid, B. Fügenschuh, M. Tischler, E. Kissling, W. Spakman, *A map-view restoration of the Alpine-Carpathian-Dinaric system for the Early Miocene*, Swiss J. Geosci.**101**, supplement 1, S273-S294 (**2008**).

[85] C. Venereau, R. Martin-Short, I. Bastow, R. Allen, R. Kounoudis, *The Role of variable slab dip in driving mantle flow at the eastern edge of the Alaskan Subduction Margin: Insights from shear-wave splitting*, Geochem. Geophys. Geosyst., **20**, doi:733 10.1029/2018GC008170 (**2019**).

[86] G. Zandt, E. Humphreys, *Toroidal mantle flow through the western US slab window*, Geology, **36** (4), 295-298, doi:10.1130/G24611A.1 (**2008**).

[87] Z. Zarifi, J. Havskov, A. Hanyga, *An insight into the Bucaramanga nest*, Tectonophysics, **443**, 1-2, 93-105, doi.org/10.1016/j.tecto.2007.06.004 (**2007).**

[88] F. Wenzel, U. Achauer, D. Enescu, E. Kissling, R. Russo, *The final stage of plate detachment. International tomographic experiment in Romania aism to a high-resolution snapshot of this process*, EOS, Trans., Amer. Geophys. Union **79**, H. 48 S. 589,592-594 (**1998).**

[89] D.A. Wiens and N.O. Snider*, Repeating deep earthquakes: Evidence for fault reactivation at great depth*, Science, **293**, 5534, 1463-1466, DOI: 10.1126/science.1063042 (**2001).**

[90] M.J.R. Wortel, W. Spakman, *Subduction and slab detachment in the Mediterranean Carpathian region*, Science **290**: 1910–1917 (**2000**).