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TWO CASE STUDIES OF POST-SEISMIC REGIMES IN THE VRANCEA REGION

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Abstract. The main geophysical conceptions regarding the tectonic seimicity of the Vrancea region are presented, with emphasis on great historical earthquakes as recorded by the Romanian Earthquake Catalogue. Their geographical and in-depth distribution is also presented, as well as their main characteristics. The post-seismic regime of two main events in Vrancea (August 1986 and May 1990) is analyzed, and Omori exponents are derived for the aftershocks distribution. One exponent agrees qualitatively with the usual range of exponents (0.8 with respect to 1), while the other exponent seems to be outside this range (0.3), possibly due to an imperfect definition of the genuine aftershocks.

Key words: Vrancea seismicity, aftershock sequence, Omori's law.

1. INTRODUCTION

According to a usual consensus in Geophysics, during the Mesozoic and early Cenozic periods the Eurasian and African continents were separated by a large oceanic basin called Tethys. Global plate tectonic processes caused a northward motion of the African plate with respect to Eurasia and led to continental collision and the gradual closure of the Tethys Ocean. The collision of the African, Arabian, and Indian plates with Eurasia uplifted the Alpine-Himalayan mountain ranges extending from Spain (the Pyrenees) and northwest Africa (the Atlas) along the northern margin of the Mediterranean Sea (the Alps, Carpathians) into southern Asia (the Himalaya) up to Indonesia. As a result of the convergence of Africa and Eurasia some continental and oceanic microplates where trapped between them, resulting in different styles of subduction and collision [1], [2]. According to Royde [3], [4], orogenic belts with high topographic elevation were formed, where the rate of convergence exceeded the rate of subduction (advancing subduction: *e.g.*, the Alps). Low topographic relief and regional extension in the upper plate characterize subduction boundaries where the rate of subduction exceeded the rate of overall plate convergence (retreating subduction: *e.g.*, the Carpathian belts).

Carpathian Mountains are an almost semicircular shaped mountain belt that is 1,500 km long and 50–150 km wide. The Carpathians are geographically divided into the Western, Eastern, and Southern Carpathians [1].

The Vrancea earthquake zone is at the contact between the following tectonic units: the Eastern European platform (EEP) to the north and north-east, the Scythian platform (SP) to the east, the Dobrogea orogen (DO) to the south-east, the Moesian platform (MP) to the south and south-west, and the Transylvanian basin (TB) to the north-west [5] (Fig. 1). The Moesian Platform extends to the S and SW of the Trotus and Peceneaga-Camena faults, and is composed of two main domains, the “Dobrogean” and “Valachian” parts separated by Intramoesian Fault. The Intramoesian Fault continues southeastwards into the NE corner of Bulgaria (the Shabla region) where large earthquakes ($M_w = 7.02$) were observed in 1901. The East-European and Scythian Platforms are two crustal blocks delimited towards the south by Trotuș Fault and towards the W by the Câmpulung-Bicaz Fault [6].

Seismicity in Vrancea zone is divided into a crustal domain (h < 40 km) with lower magnitudes and an intermediate depth domain (h > 60 km), where all strong earthquakes are located. These domains are separated by an almost aseismic zone between 40 km and 70 km depth (Fig. 2) [7].

At this depth range a zone with reduced seismic velocities was put into evidence [9]. Below about 170 km in depth nearly no seismicity is observed (the

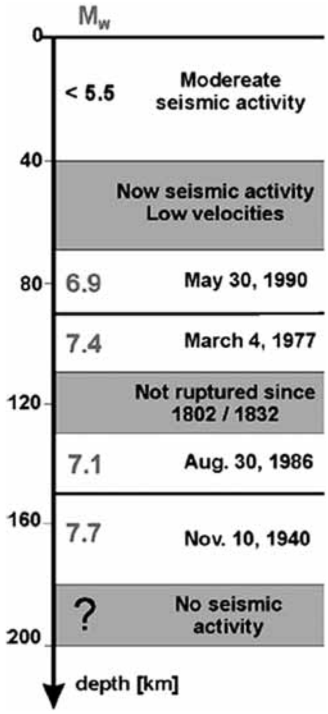


Fig. 2 – Crustal and intermediate depth domains in the Vrancea region, as a function of depth [8].

$M_w = 3.7$ event represents an exception beneath 180 km [7]. The depth interval between 110 and 130 km is unruptured for at least 175 years (since 1832).

The crustal seismicity has a larger spatial distribution with magnitudes $M_w < 6$.

Hypocenters of intermediate depth earthquakes are located within an almost vertical elongated narrow column with an epicentral area about 30×60 km^2, a rectangular shape with the longer side oriented approximately 45 °N [9].

Figs. (3a) and (3b) represent the hypocenter distributions of earthquakes in vertical sections perpendicular to the Vrancea epicentral region, oriented on the SW-NE, and the NW-SE directions, respectively [8].

The almost vertical column of hypocenters correlated with the extent of high velocity body detected by seismic tomography suggests a lithospheric plate fragment having the dimensions of 60 km in length, 30 km in width, and 120 km in depth. The high velocity body imaged in the tomography reaches a depth of 350 km, whereas seismicity ends at about 170 km of depth. Thus, the maximum depth of the slab has to be larger than the maximum depth of the earthquakes (at least 236 km, even extending to a depth of about 350 km [11]).

Several models are proposed for the seismotectonics of this region to explain the distribution of hypocenters and the focal mechanism of intermediate-depth seismicity.

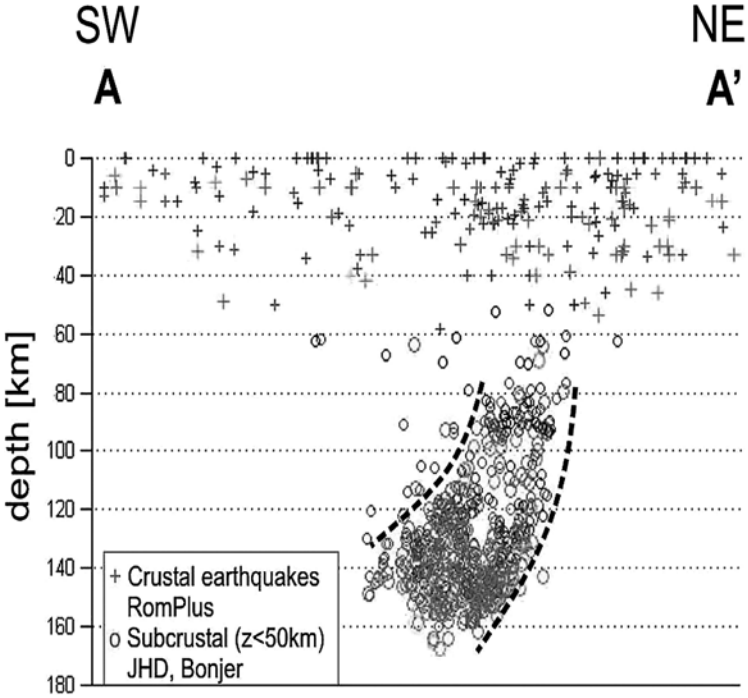
Two primary competing theories for this deep seismicity involve either (1) active subduction of a remnant oceanic slab, or (2) delamination of a thickened lithospheric root.

Development of the plate tectonic theory provided a fundamental framework to explain the origin of earthquakes occurring at depths of 70–700 km [12]. If two tectonic plates converge, with one or both of the plates of the oceanic lithosphere, a subduction zone will form. An oceanic plate will sink back into the mantle. In a subduction zone the earthquake foci normally plot along a dipping plane at an angle of 33 to 60 degrees and this plane is called a Benioff zone [13]. The Benioff zone extends to a depth of about 700 km. We now commonly understand intermediate-to deep-focus seismicity as brittle deformation of descending, rigid oceanic slabs at subduction zones.

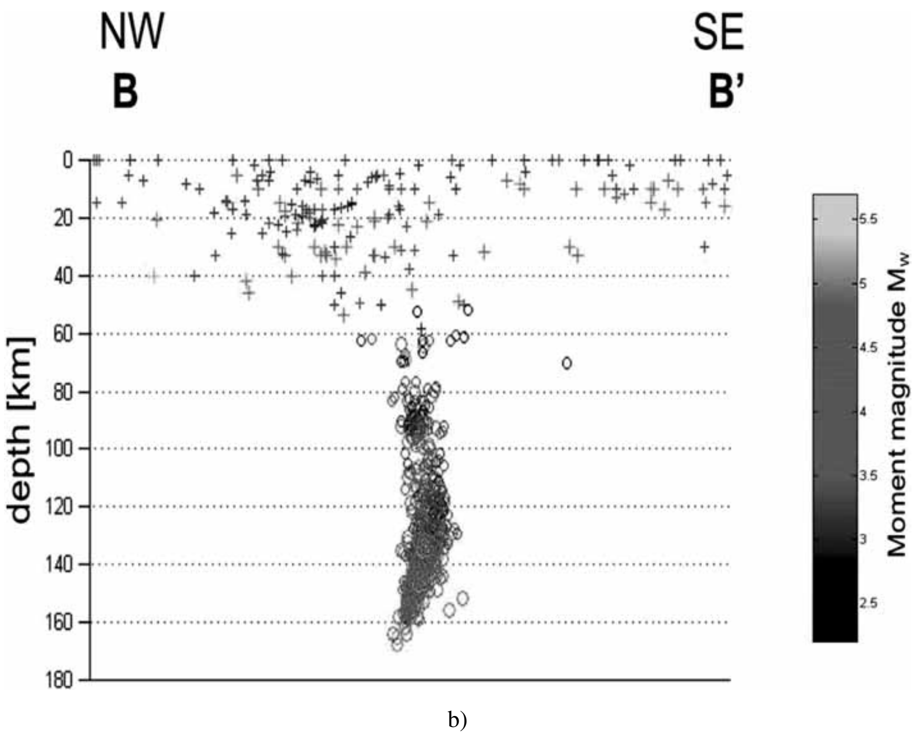
The angle of subduction varies from one subduction zone to another. This angle is largely related to the age and therefore temperature and density of the subducting slab. The rate of convergence is also a factor. The older and colder the slab, the steeper the angle of subduction because it sinks faster.

In the past two decades, delamination of thickened continental lithosphere has been proposed as an alternative mechanism for generation of mantle seismicity [14]. This interpretation is plausible where earthquake foci do not align along a Wadati-Benioff plane, but cluster in a more concentrated volume. Delamination is thought to be caused by gravitational instability of over-thickened lithosphere that detaches along a horizontal interface in the lithosphere and sinks into the mantle.

Despite these considerations the weight of scientific opinion remains in favor of a subducted slab origin for Vrancea seismicity.



a)



b)

Fig. 3 – Hypocenters distribution on the NW-SE and NE-SW sections in the Vrancea area [8].

2. ROMANIAN EARTHQUAKE CATALOGUE

Written accounts of the last five hundred years tell of a sustained seismic activity on the Romanian territory. Old chronicles, the earliest source of information, describe in detail many earthquakes, their disastrous effects, as well as the population's concern regarding these events. Starting from these chronicles and other documents, as well as several evaluations done by the National Institute for Earth Physics, data concerning strong earthquakes (of magnitude 6 and greater on the Richter scale) in the Vrancea region were extracted, as well as data concerning their effects. Among these earthquakes, the most violent took place in 1471, 1620, 1681 ($M_w = 7.1$), 1738 ($M_w = 7.7$), 1802 ($M_w = 7.9$, also known as "the big earthquake"), 1829, 1838. Other significant earthquakes of the XIXth century occurred on the 13th of November 1868, the 17th of August 1893 and the 31st of August 1894.

Table 1 lists earthquakes which occurred in the Vrancea region, having magnitudes $M > 6.5$, in the 1400–1900 period. The statistics has been performed on a data set provided by the Romanian earthquake catalogue for the Vrancea zone in Romania, the ROMPLUS catalogue [15], under continuous update, which has been completed with more recent events as provided by the web-site of the National Institute for Earth Physics (www.infp.ro). This catalogue contains data regarding the most important seismic events since 984.

Romanian catalogues of earthquakes for different periods were elaborated by C. Radu [16], L. Constantinescu and V. Marza [17], C. Trifu and M. Radulian [18].

In the last century, strong earthquakes occurred in 1940 with a magnitude of 7.2, in 1977 with a magnitude of 7.5 [16], in 1986 with a magnitude of 7.2 [20], [21] and in 1990 with a magnitude of 6.9 [22]. Table 2 shows that while the magnitude decreases, the depth at which the events occur varies.

Most of the seismic energy is released at depths greater than 60 km.Assuming that the data are complete for large magnitudes for the last 600 years, this time interval shows 3–5 earthquake/century with $M_w > 7.2$. We must however insert

Table 1

Seismic events in the 1400–1900 time span, having a magnitude $M > 6.5$ [15]

No.	Day	Month	Year	Depth (km)	M
1	10	10	1446	150	7.5
2	29	8	1471	110	7.5
3	29	8	1473	150	7.3
4	24	11	1516	150	7.5
5	0	0	1543	150	7.1
6	19	7	1545	110	7.1
7	10	5	1571	150	7.1

(continues)

Table 1 (continued)

No.	Day	Month	Year	Depth (km)	M
8	30	4	1590	100	7.3
9	21	4	1595	150	7.1
10	24	12	1605	150	7.1
11	13	1	1606	120	6.8
12	8	11	1620	150	7.5
13	1	2	1637	130	6.6
14	9	8	1679	110	7.5
15	19	8	1681	150	7.1
16	12	6	1701	150	7.1
17	11	6	1738	130	7.7
18	5	4	1740	150	7.3
19	6	4	1790	150	7.1
20	26	10	1802	150	7.9
21	10	2	1821	150	6.6
22	26	11	1829	150	7.3
23	23	1	1838	150	7.5
24	13	11	1868	150	6.8
25	25	12	1880	130	6.8
26	17	8	1893	100	7.1
27	31	8	1894	130	7.1
28	11	3	1896	150	6.6

Table 2

Seismic events recorded in the Vrancea region in the 1900–1998 period, having a magnitude $M_w > 6.4$ [10]

Date	Latitude (N)	Longitude (E)	Depth (km)	M_w
1904/02/06	45.70	26.60	75.	6.6
1908/10/06	45.50	26.50	125.	7.1
1912/05/25	45.70	27.20	90.	6.7
1934/03/29	45.80	26.50	90.	6.6
1940/10/22	45.80	26.40	125.	6.5
1940/11/10	45.80	26.70	150.	7.7
1945/09/07	45.90	26.50	80.	6.8
1945/12/09	45.70	26.80	80.	6.5
1977/03/04	45.77	26.76	94.	7.4
1986/08/30	45.52	26.49	131.	7.1
1990/05/30	45.83	26.89	91.	6.9
1990/05/31	45.85	26.91	87.	6.4

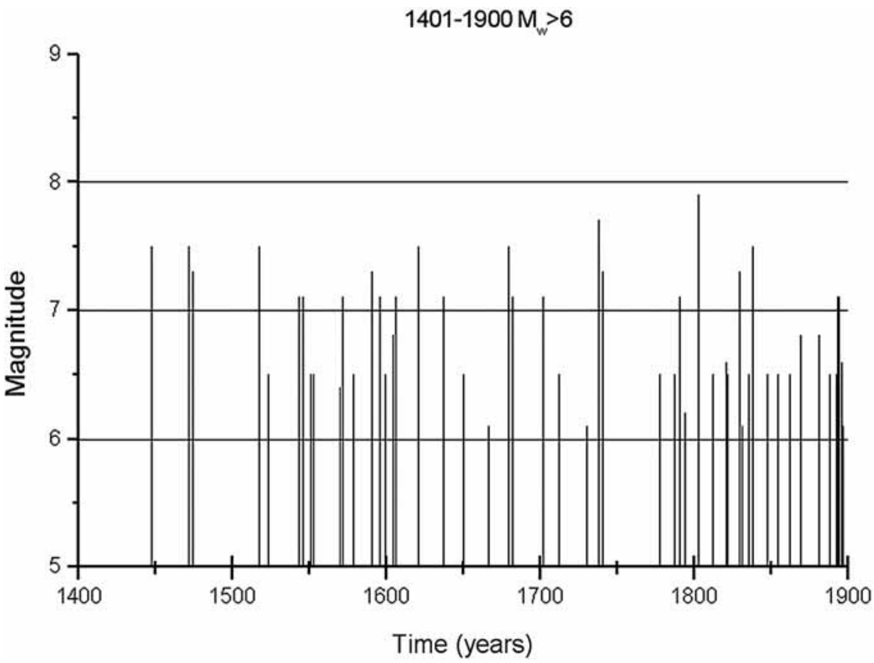


Fig. 4 – Seismic events of magnitude $M_w > 6$ recorded in the 1401–1900 time period [15].

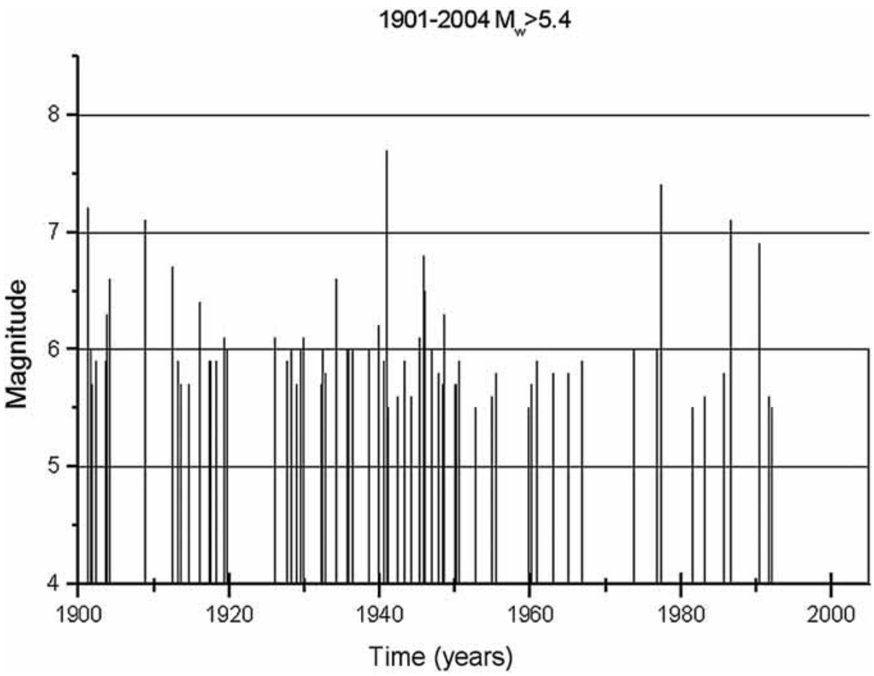


Fig. 5 – Seismic events of magnitude $M_w > 5.4$ recorded in the 1901–2004 time period [15].

here a word of caution, regarding the likelihood of a possible overestimation of the magnitudes of the historical earthquakes.

3. OMORI'S LAW

Usually, earthquakes occur in groups. After an earthquake, generally, other earthquakes occur in the vicinity or even in the same place as the first one. In order to describe these phenomena, seismologists use three terms: foreshocks, the main shock and aftershocks. When considering a group of earthquakes, the one having the greatest magnitude is called the main shock, while the ones which occur before and after it are labeled foreshocks and aftershocks, respectively.

Aftershocks and foreshocks are actually just normal earthquakes in every physical detail. There is nothing intrinsically characteristic about foreshocks, main shocks, and aftershocks. If one looked at the records (seismograms) of them "out of context", with no clues as to which were followed or preceded by other events, you could never hope to categorize them correctly. The only real difference is that an aftershock follows closely the larger earthquake, and it takes place about in the same location as its predecessor.

More specifically, there are two ways of telling if an earthquake is an aftershock. Firstly, it must occur inside the rupture area of the main shock, or alternatively, inside the aftershock area deduced by seismologists using other aftershocks [23], (Table 3).

Table 3

The distance from the main shock up to which minor events can be considered aftershocks, as a function of magnitude [23]

Magnitude	4.0–4.4	4.5–4.9	5.0–5.4	5.5–5.9	6.0–6.4	6.5–6.9	7.0–7.4	7.5–7.9	8.0–8.4
Distance (km)	30	35	40	47	54	61	70	81	94

Secondly, it must occur in the specified area before the seismic activity levels drop to the background level present before the main shock (Fig. 6).

Obviously, the two conditions above imply a certain degree of uncertainty. The area in which aftershocks take place might overlap the aftershock zone of another main shock. On the other hand background seismic activity levels may vary in time. Furthermore, it is quite difficult to determine the background seismic activity level of a specific area. This requires a good network of recordings in that area. Only then is it possible to determine with good precision when an earthquake sequence ends.

The most important characteristic of aftershocks is their rate of decay in time. The frequency of aftershocks in any given sequence decreases with time. A law which expresses this pattern has been established by the Japanese seismologist

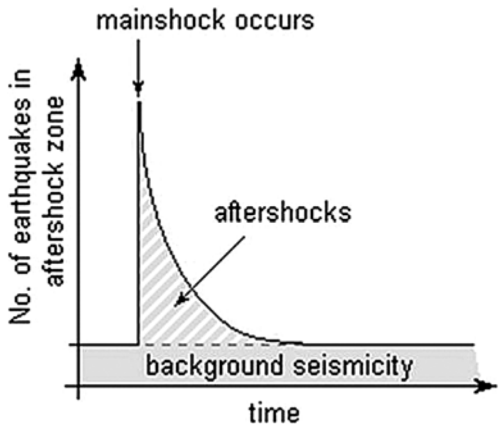


Fig. 6 – Decay of the seismic frequency after the main shock [23].

Omori who first described such a correlation in 1894 [24]. He deduced that the number of aftershocks occurring in a time interval t after the main shock is proportional to t to a negative constant exponent p. The simplest version of Omori's Law is:

$$N(t) \propto t^{-p}$$

This implies that the aftershock frequency decreases rapidly at first, after which the rate of decay becomes smaller until the background seismic activity level is reached. In the above formula $N(t)$ represents the number of earthquakes recorded in a specific time interval, and p is an empirical constant, which usually falls within the interval [0.7; 1.5].

More commonly used is a modified version of this law, which in fact closely resembles the original, empirically-derived model developed by Omori. This modified Omori law describes the rate of decay of an aftershock sequence by equating the number of aftershocks at some time t after a main shock with the quantity t plus c (a constant) to the negative power of p (another constant), all multiplied by K (a third constant) [25], [26]:

$$N(t) = K\,(t + c)^{-p}$$

4. RESULTS

This paper takes into account two major earthquakes which occurred in Romania in the last 25 years, their respective dates being the 30th of August 1986 and the 30th of May 1990. In May 1990 two major earthquakes occurred in an interval of 14 hours. The earthquake on the 30th of May 1990 had a magnitude $M_w = 6.9$ and occurred at a depth of 91 km. The one on the 31st of May had a magnitude $M_w = 6.4$ and occurred at a depth of 87 km. Tables 4 and 5 represent the number of earthquakes in successive 24h intervals after the main shock in 1986 and 1990 respectively [15].

The daily seismic frequency around each event was represented graphically (Figs. 7, 8). In each case, a time interval of approximately a month before and a month after the main shock was considered.

The decay of the seismic frequency after the main shock can be observed in each graph. The aspect of the decay is much easier to observe in the case of the 1990 earthquake, because of the much larger collection of recorded data.

Omori's empirical model was tested using data acquired from these two earthquakes. The fitting of the data was accomplished with the aid of the Microcalc Origin™ 5.0 software (Figs. 9, 10) and the origin of the time scale was chosen to be the time of occurrence of the main shock.

Table 4

Number of recorded earthquakes in successive 24h intervals after the main shock on 03/08/1986

Time interval	**Number of events**
08/30 21:28 – 08/31 21:28	21
08/31 21:28 – 09/01 21:28	8
09/01 21:28 – 09/02 21:28	8
09/02 21:28 – 09/03 21:28	5
09/03 21:28 – 09/04 21:28	6
09/04 21:28 – 09/05 21:28	5
09/05 21:28 – 09/06 21:28	4
09/06 21:28 – 09/07 21:28	6
09/07 21:28 – 09/08 21:28	4

Table 5

Number of recorded earthquakes in successive 24h intervals after the main shock on 03/05/1990

Time interval	**Number of events**
05/30 10:40 – 05/31 10:40	74
05/31 10:40 – 06/01 10:40	22
06/01 10:40 – 06/02 10:40	11
06/02 10:40 – 06/03 10:40	8
06/03 10:40 – 06/04 10:40	6
06/04 10:40 – 06/05 10:40	8
06/05 10:40 – 06/06 10:40	4
06/06 10:40 – 06/07 10:40	5
06/07 10:40 – 06/08 10:40	3
06/08 10:40 – 06/09 10:40	5

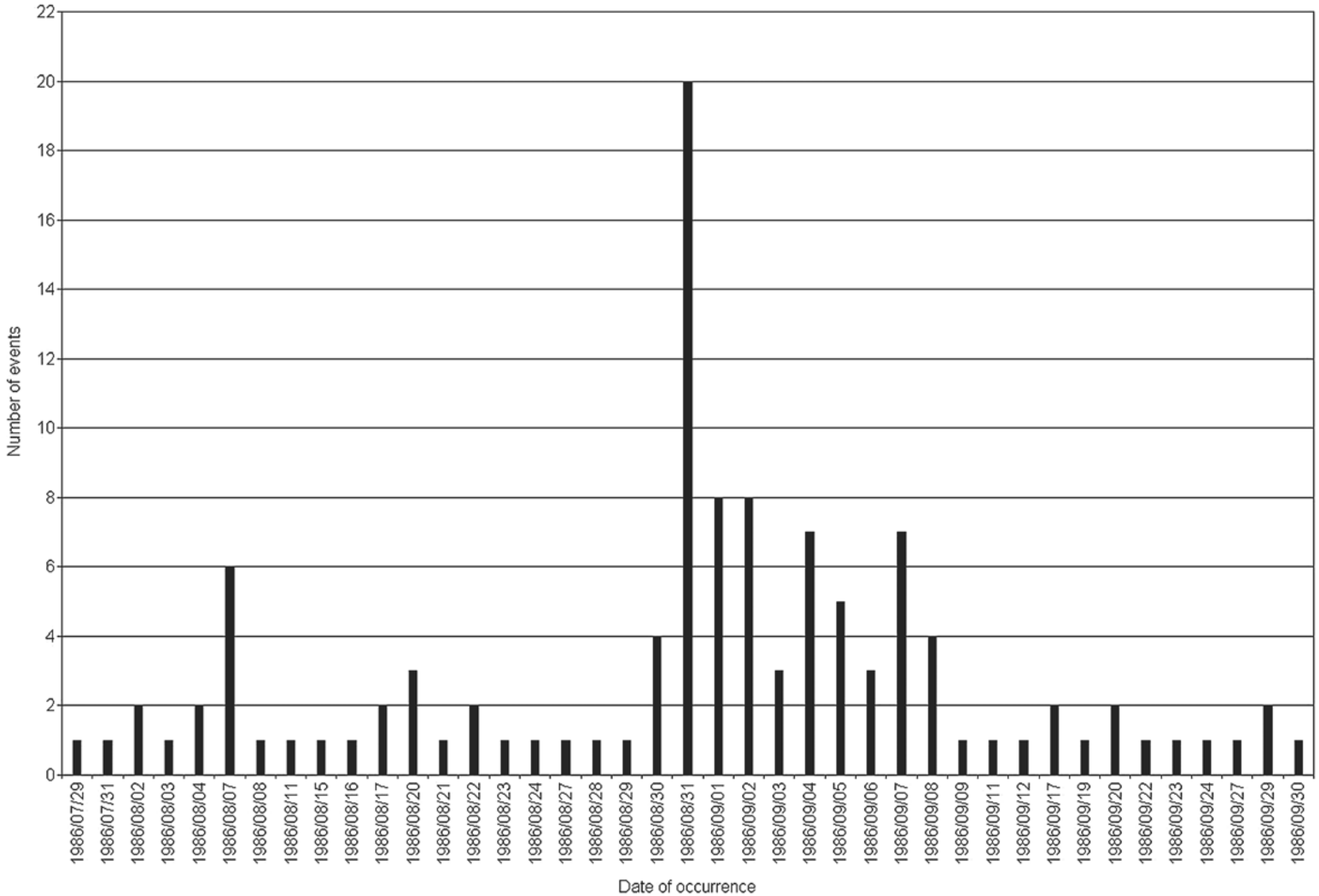


Fig. 7 – Seismic frequency around the time of the 30/08/1986 earthquake, as a function of day [15].

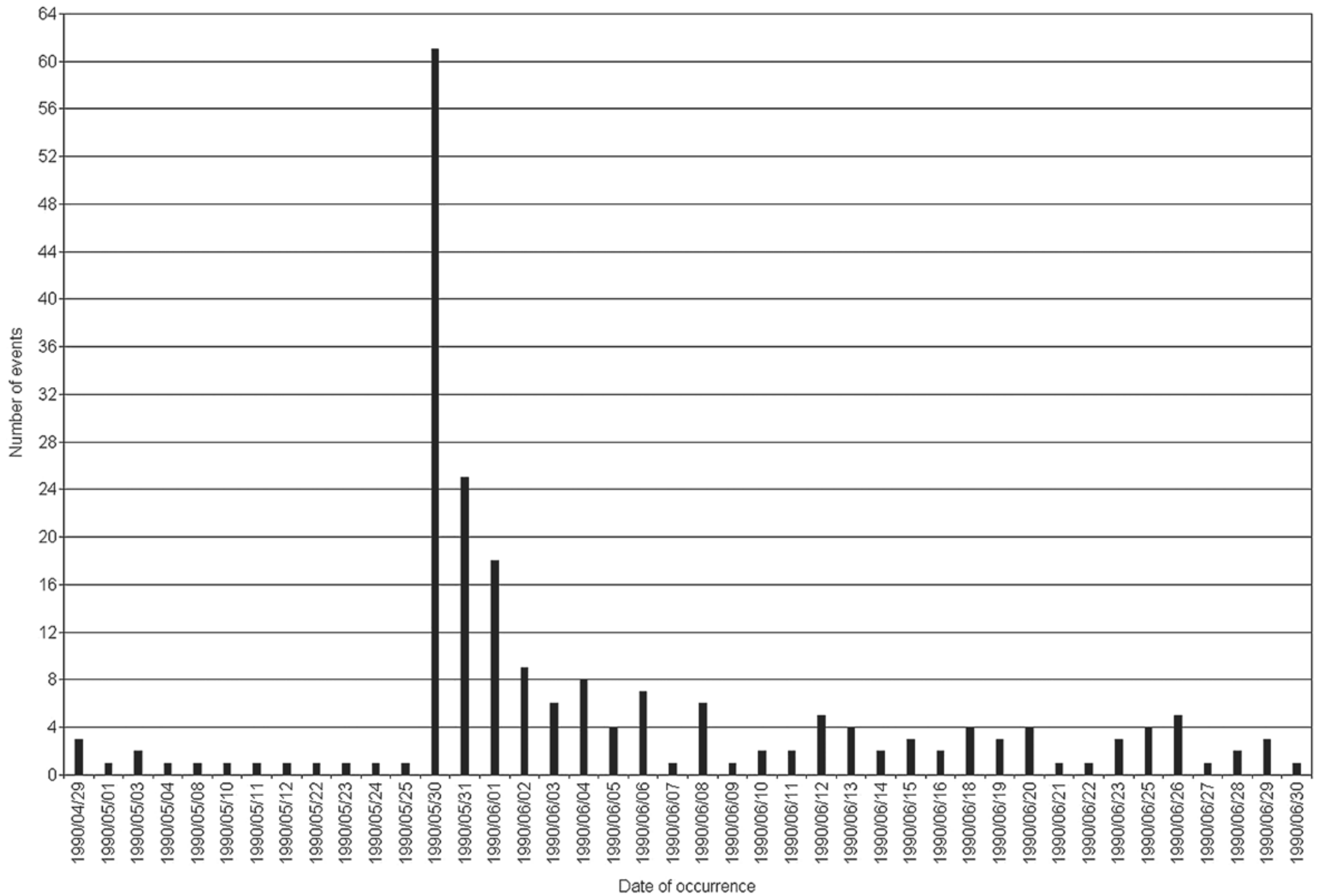


Fig. 8 – Seismic frequency around the time of the 30/05/1990 earthquake, as a function of day [15].

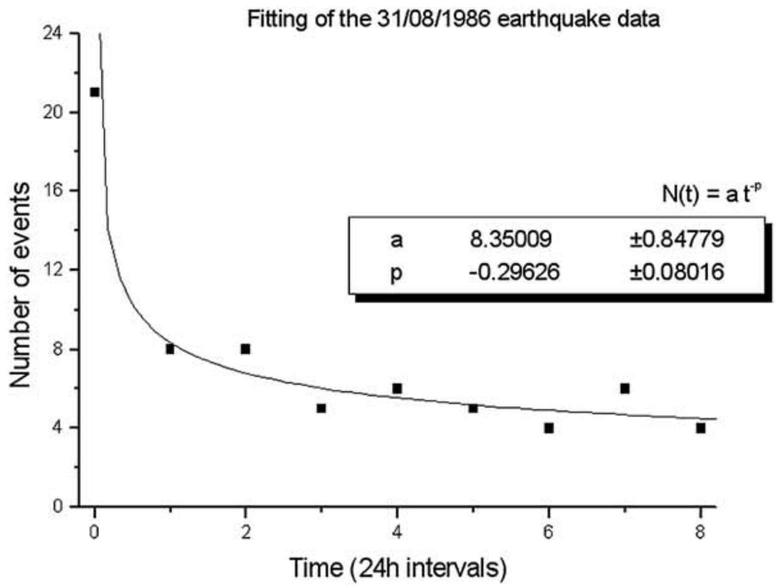


Fig. 9 – Fitting of the 31/08/1986 earthquake data (using [15]).

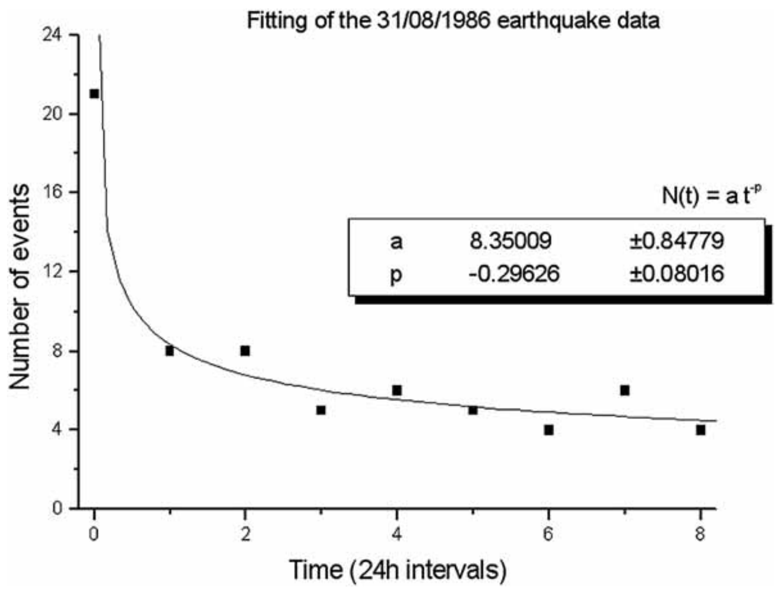


Fig. 10 – Fitting of the 30/05/1990 data (using [15]).

The fitting curve is, according to the Omori model:

$$N(t) \propto t^{-p}$$

The values computed for the constant p are $p = 0.29 \pm 0.08$ in the case of the

03/08/1986 earthquake and $p = 0.83 \pm 0.07$ in the case of the 30/05/1990 earthquake. In the second case, the constant falls within the usual range of values of the Omori model, namely [0.7; 1.5]. The computed proportionality constants are a = 8.35 ± 0.85 and a = 21.47 ± 1.25 respectively.

Concerning the epicenter localization of the events following the 30/05/1990 earthquake (30/05/1990 – 08/06/1990, Fig. 11), it is possible to see that the majority of events are grouped, mostly to the west of the main shock. There are also several isolated occurrences, which took place at a considerably larger distance from the main shock, the farthest ones being listed in Table 6.

The depth distribution of earthquakes during the same time period (30/05/1990 – 08/06/1990, Fig. 12) shows that the majority of events occurred

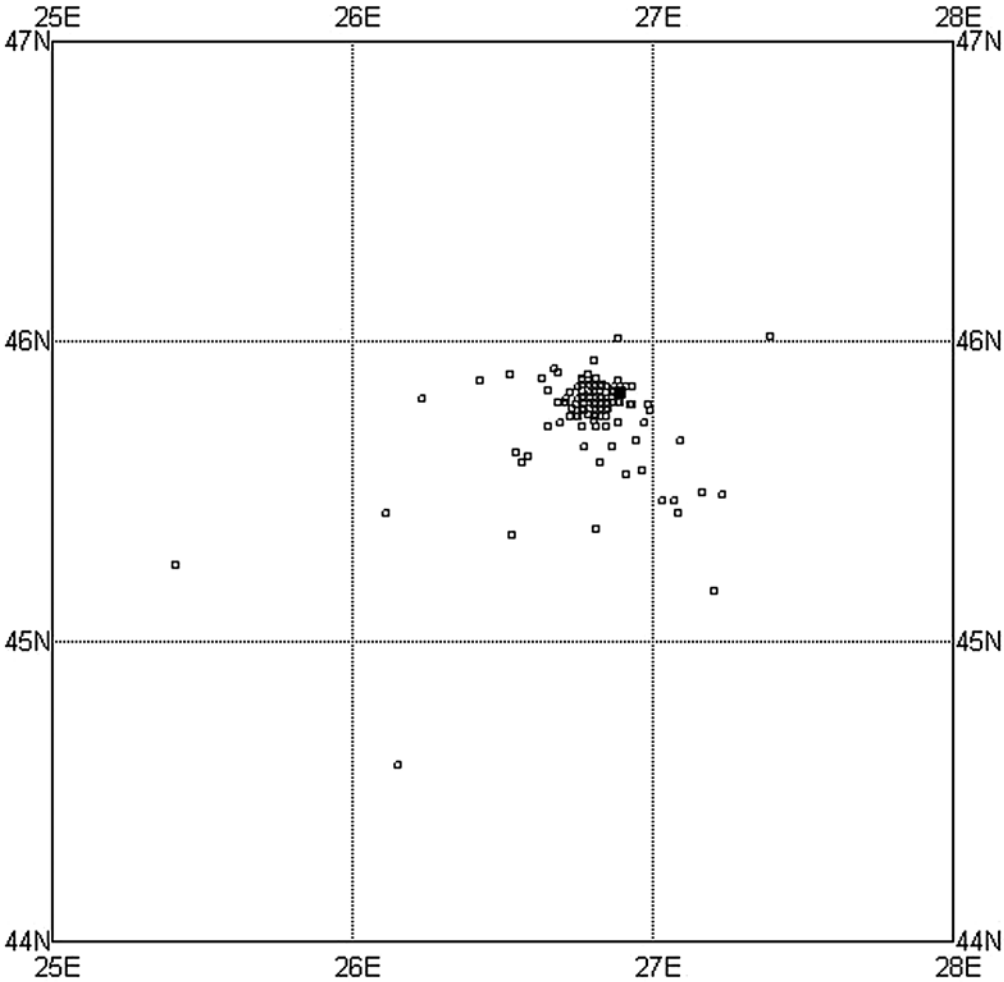


Fig. 11 – Latitude and Longitude of epicenters in the 30/05/1990–08/06/1990 time period [15].

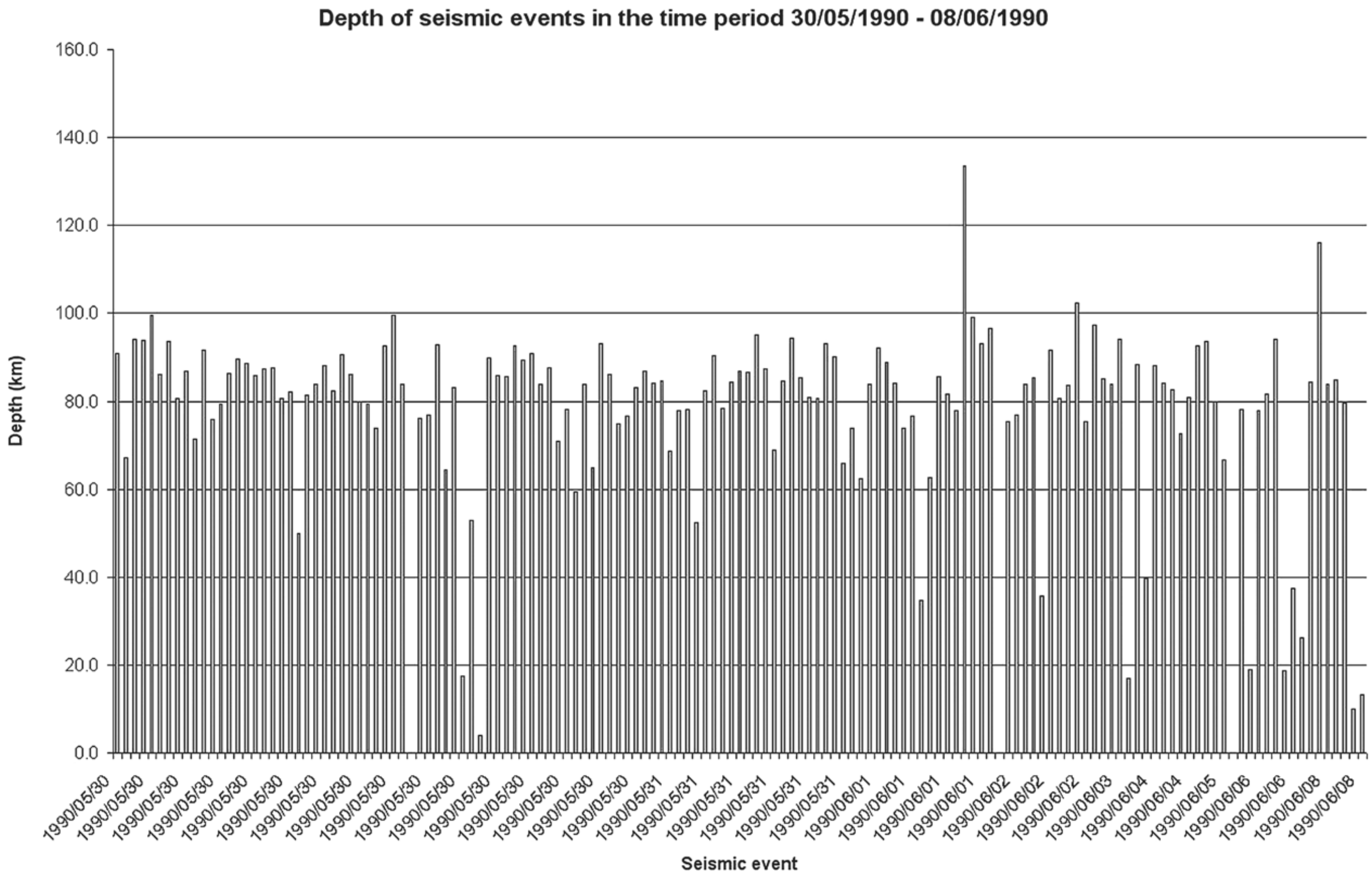


Fig. 12 – Depth distribution of earthquakes in the 30/05/1990–08/06/1990 [15] time period.

between the depths 60 and 100 km. Approximately 85% fall within this interval, their average depth being 83.6 km. Also, among the remaining 15%, one can find the isolated epicenters identified in Table 6.

Table 6

Isolated earthquakes in the 30/05/1990 – 08/06/1990 time interval

Date	**Longitude**	**Latitude**	**Magnitude**	**Depth (km)**
1990/05/30	26.11E	45.43N	2.5	50.0
1990/06/05	25.41E	45.26N	2.5	0.0
1990/06/06	26.15E	44.59N	2.6	37.5
1990/06/08	27.39E	46.02N	2.7	10.0
1990/06/08	27.20E	45.17N	2.8	13.2

REFERENCES

1. B. C. Burchfiel, 1976. *Geology of Romania:* Geological Society of America Special Paper 158, 82 p.
2. B. C. Burchfiel, 1980. *Eastern Alpine System and the Carpathian Orocline as an Example of Collision Tectonics:* Tectonophysics, v. 63, p. 31–62.
3. L. H. Royden, B. C. Burchfiel, 1989. *Are systematic variations in thrust belt style related to plate boundary process? (The Western Alps versus the Carpathians).* Tectonics, 8, 51–61.
4. L. H. Royden, 1993. *Evolution of retreating subduction boundaries formed during continental collision.* Tectonics, 12, 629–638.
5. L. Constantinescu, P. Constantinescu, I. Cornea, V. Lazarescu, (1976). *Recent seismic information on the lithosphere in Romania*, Rev. Roum. Géol., Géophys., Géogr. Sér. Géophys, 20, 33–40.
6. D. P. Radulescu, M. Sandulescu, 1973. *The plate-tectonics concept and the geological structure of the Carpathians*. Tectonophysics 16, 155–161.
7. M. C. Oncescu, *Deep structure of Vrancea region, Romania, inferred from simultaneous inversion for hypocenters and 3-D velocity structure*, Ann. Geophys., 2, 23–28, 1984.
8. M. C. Oncescu, K.-P. Bonjer, 1997. *A note on the depth recurrence and strain release of large Vrancea earthquakes*, Tectonophysics 272, 2–4, 291–302.
9. F. Hauser, V. Raileanu, W. Fielitz, A, Bala, C. Prodehl, G. Polonic, A. Schulze, 2001. *VRANCEA99 – the crustal structure beneath the southeastern Carpathians and the Moesian Platform from a seismic refraction profile in Romania*. Tectonophysics 340, 233–256.; M. C. Oncescu, 1984. *Deep structure of the Vrancea region, Romania, inferred from simultaneous inversion for hypocentres and 3-D velocity structure*. Ann. Geophys. 2, 23–28 [7].
10. M. C. Oncescu, K.-P. Bonjer, M. Rizescu, 1998. *Weak and strong ground motion of inetrmediate depth earthquake region*. In: F. Wenzel, D. Lungu, O. Novak (Eds.), *Vrancea Earthquake: Tectonics,Hazard and Risk Mitigation*. Kluwer Academic Publishing, Dordreeht, Netherlands, pp. 27–42.
11. M. J. R. Wortel, W. Spakman, 2000. *Subduction and slab detachment in the Mediterranean-Carpathian region*. Science 290 (5498), 1910–1917.
12. K. Wadati, 1928. *Shallow and deep earthquakes*. Geophysical Magazine 1, 162–202.
13. H. Benioff, 1949. *Seismic evidence for the fault origin of oceanic deeps*. Geological Society of America Bulletin 60, 1837–1856.
14. D. Seber, M. Barazangi, A. Ibenbrahim, A. Demnati, 1996. *Geophysical evidence for lithospheric delamination beneath the Alboran Sea and Rif-Betic mountains*. Nature 379, 785–790.

15. M. C. Oncescu, I. V. Marza, M. Rizescu, M. Popa, *The Romanian earthquake catalogue between 1984–1996*, in: F. Wenzel, D. Lungu, O. Novak (Eds.): *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation*, 43–47, 1998.
16. C. Radu, *Catalogue of Strong Earthquakes originated on the Romanian Territory: Part 1 – Before 1901; Part II – 1901–1979* (in Romanian), Cerc. Seism., CFPS, Bucharest (unseen), 723–752, 1979.
17. L. Constantinescu, V. I. Marza, 1980. *A computer-compiled and computer-oriented catalogue of Romanian's earthquake*. Rev. Roum. Géol. Géophys. Géogr. 24, 193–234.
18. C. I. Trifu, M. Radulian, *Depth-magnitude catalogue of Vrancea intermediate depth microearthquakes*, Rev. Roum. Géophys. 35, 31–45, 1991.
19. K. Fuchs, K. Bonjer, G. Bock, I. Cornea, C. Radu, D. Enescu, D. Jianu, A. Nourescu, G. Merkler, T. Moldoveanu, G. Tudorache, 1977. *The Romanian earthquake of March 4, 1977. II. Aftershocks and migration of seismic activity*. Tectonophysics 53, 225–247.
20. C. I. Trifu, M. C. Oncescu, 1987. *Fault geometry of 1986, August 30 Vrancea earthquake*. Ann. Geophys. 5B: 727–730.
21. M. C. Oncescu, 1989. *Investigation of a high stress drop earthquake on August 30, 1986 in the Vrancea region*, Tectonophysics 163: 35–43.
22. C. I. Trifu, A. Deschamps *et al.*, 1990. *The Vrancea earthquake of May 30, 1990. An estimate of the source parameters*, Proc. XXII ESC General assembly, Barcelona, September 1990 II: 449–454.
23. J. K. Gardner, L. Knopoff, 1974. *Is the sequence of earthquake in southern California, with aftershocks removed, Poissonian?*, Bull. Seism. Soc. Am., 64, 1363–1367.
24. F. Omori, *On the after-shocks of earthquakes*, J. College Sci., Imp. Univ, Tokyo, 7, 111–200, 1894.
25. T. Utsu, *A statistical study on the occurrence of aftershocks*, Geoph. Magazine, 30, 521–605, 1961.
26. T. Utsu, Y. Ogata, R. S. Matsu'ura, *The centenary of the Omori formula for a decay law of aftershock activity*, J. Phys. Earth, 43, 1–33, 1995.