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EARTHQUAKE ACTIVITY AND HAZARD IN THE CARPATHIAN BASIN I

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The seismicity and seismic hazard of the Carpathian Basin are studied in this paper based on a recent comprehensive database cataloging over 20 thousands earthquakes between 456 and 1995. The epicentre distributions of these events indicate the geographical positions of the most active tectonic processes in the region. Among them the south-eastern bend of the Carpathians (Háromszék-Vrancea zone, Romania) and the area of south-eastern Alps have the highest seismic activity. The former source area is very specific by its strong seismicity from the intermediate depth domain (70–170 km).

The intermediate-depth sources are deepening nearly vertically but in somewhat SW direction and the separation of the crustal earthquakes from the events connected to the lithospheric plate subsiding into the astenosphere is well observed at about 50 km, which is the depth of the Mohorovičić discontinuity (MOHO) in this region. The lithospheric plate subsiding to the depth of 150–200 km is supposed to be disconnected around 50 km. Some weakness of this slab can also be assumable based on the lower seismic activity observed between 100–120 km.

Keywords: Carpathian Basin; earthquake; earthquake catalog; epicenter; focal depth; Hungary; magnitude

1. Introduction

For studying of the seismic activity of an area we need to know first of all the earthquakes occurred in the past. The first scientific description of the earthquakes in the Carpathian Basin was compiled by János Grossinger, a Jesuit from Komárom (today Komarno in Slovakia), who published his work *Dissertatio de Terrae Motibus Regni Hungariae* in 1783. In the 19th century the most important earthquake catalogues of Hungary were compiled by Henrik Jeitteles (1860a, 1860b) a secondary school teacher of Kassa (today Kosice in Slovakia), and by Ede A Bielz (1862–1863) a natural scientist from Nagyszeben (today Sibiu in Romania). Similarly important works are the seismological compilations of some significant earthquakes of the Pannonian Basin: Jan. 14, 1810 – Mór (Kitaibel and Tomtsányi 1814), Jan. 15, 1858 – Zsolna /Zilina/ (Kornhuber 1858, Schmidt 1858, Hunfalvy 1859, Jeitteles 1859), Oct. 3, 1880 – Central-Transylvania (Koch 1881, Schuster 1881), Nov. 9, 1880 – Zágráb /Zagreb/ (Hantken 1882, Torbar 1882, Wahner 1883), Apr. 14, 1895 – Ljubljana /Laibach/ (Suess 1897). The work of Kitaibel and Tomtsányi (*Dissertatio de Terrae Motu in genere, ac in specie Mórensi anno 1810 die 14. Januarii orto. Budae, 1814*) has a special importance, namely the authors firstly used the concept of isoseismal delineating an area having the same level of shaking. In the great

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earthquake catalogues of the world (e.g. Hoff 1840–1841, Perrey 1846, Mallet 1858, Fuchs 1886) there are also some Hungarian events, but their contributions are much less comparing to the former works.

In this field Antal Réthly did a great step in the middle of the 20th century, by publishing the descriptions of the Hungarian earthquakes in chronological order between 456 and 1918. He collected the observations until the end of World War I, when Hungary was seriously truncated. His collection (A kárpátmedencék földrengései /Earthquakes of the Carpathian Basins/ (455–1918), Budapest, 1952) has still been a major source of earthquakes not only for Hungary, but also for the newer states (e.g. Romania, Slovakia) of the region. The parametric catalogue of Csomor and Kiss (1962) contains only the events occurred in Trianon Hungary (in the present territory of the country) between 1880–1956. The first digital earthquake catalogue was published by T Zsíros, P Mónus and L Tóth in 1988. The content of the last three databases is shown in Table I comparing with the most recent one (Zsíros 2000). The systematic collection of earthquake observations started in the years of 1880–1881 by the establishment of the Seismological Committee of the Hungarian Geological Society. (After Switzerland the Hungarian Earthquake Committee was the second in Europe.) In Hungary the instrumental seismology started at the turn of the 19th and 20th centuries and by the beginning of the First World War (1914) the seismological network of the country (see Fig. 1) belonged to the most developed ones (Biszticsány and Csomor 1981, Szeidovitz 1994, Ferrari 1997). At that time however the instruments were very insensible, so they can record only the extremely large or the very near earthquakes, and the hegemony of macroseismology lasted until the '60s of the 20th century. Among the countries having changeable borders in the Carpathian Basin, Hungary has the most advanced position for the establishment of the most comprehensive database of historical earthquakes of this region, since the whole Carpathian Basin was Hungary for one thousand years and since this country occupies the center part of the Basin.

The source parameters of earthquakes have become to known from the evaluation processes of the macroseismic and/or the instrumental observations. In the earthquake catalogues the basic (source) parameters are usually the following ones: date and time of the event, co-ordinates of the epicenter, focal depth, magnitude, epicentral or maximum intensity. The reliability and the accuracy of the source parameters are naturally determined by the quality of the (literature) sources used. In the case of historical earthquakes (macroseismic data) we always relied on the primary (root) sources (Stucchi and Albini 1991) if they were available. In instrumental observations — if we have more network determinations — the most reliable and accurate parameters were intended to select based on e.g. the similarity with macroseismic results, the number of stations used, error estimations. In the following paragraphs some seismicity and seismic hazard results are presented based on the latest database (Zsíros 2000) for the Carpathian Basin.

Table I. Number of earthquakes in different catalogues

	Réthly (1952) 455–1918 Carpathian Basin	Csomor and Kiss (1962) 1880–1956 Trianon Hungary	Zsíros et al. (1988) 456–1986 44.5N–49.5N; 15.5E–26.5E	Zsíros (2000) 456–1995 44N–50N; 13E–28E
455–1000	3	–	3	5
1001–1500	21	–	17	74
1501–1600	70	–	82	174
1601–1700	78	–	80	136
1701–1800	245	–	245	446
1801–1850	288	–	313	642
1851–1879	370	–	386	1032
1880–1900	327	100	491	1760
1901–1918	595	233	1010	2475
1919–1956	–	540	1214	4251
1957–1986	–	–	1181	5680
1987–1995	–	–	–	3803
455–1995	1997	873	5022	20478

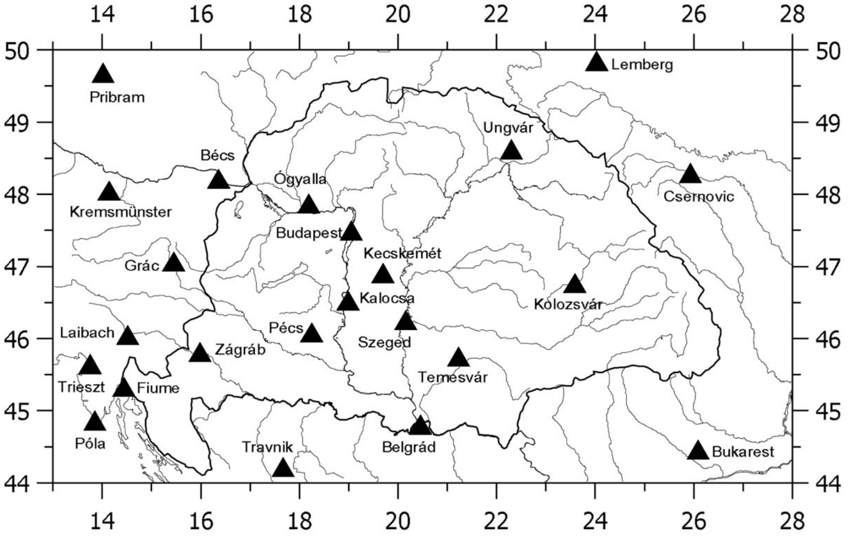

Fig. 1. Seismographic stations in the Carpathian Basin and its vicinity until 1914

2. Epicenter

The vertical projection of the earthquake source (hypocenter) is the epicenter on the surface, which can be determined by instrumental and macroseismic observations. In the later case the epicenter is the center of the most shaken area estimated by some method (Cecic et al. 1996). For historical events naturally the macroseismic tool is the only method. The epicenter shown in the earthquake catalogue (Zsíros 2000) is thought to be the best among the different (instrumental and/or macroseismic) determinations. In general the instrumental epicenter is more reliable than the macroseismic one from the '70s of the last century.

The estimation of the epicenter may be very uncertain due to poor and/or contradicted observations. Five accuracy classes of the epicenters (A: ±5 km, B: ±10 km, C: ±20 km, D: ±50 km, E: it may be more than 50 km) have been used in the Hungarian catalogue. Earthquakes with epicenter accuracy 'E' were excluded in any studies in this paper. A peculiarity of the macroseismic method must however be noted. Namely, if there is only one single location with observation, the position of this location is chosen as the epicenter of the event. Such a case is not rear among historical earthquakes. Nevertheless, it is reasonable to assume that the records of the greatest distractions have a higher probability to survive against to the weak effects in the case of strong earthquakes. On the other hand, when the event is very weak the observation can only be possible near to the epicenter. (The above statements are valid for the vast majority of earthquakes originating from the crust with a focal depth not more than 60–70 km. The stronger intermediate-depth earthquakes at the southeast bend of the Carpathians (see paragraph 3) however can produce weak shaking in a larger area of the epicenter.) The positions of the most recent earthquakes determined by the Hungarian micro-seismic monitoring network (Tóth et al. 1996, 1997, 1998, 1999) seem to be connected to the known macroseismic epicenters in the region.

In general the older the event naturally the poorer the information available and Figs 2–7 demonstrate the changes in seismicity pattern during the past centuries. Until 1500 there is very few earthquake data. While there is no notable difference between the seismicity of the 16th and the 17th century, we have already more data from the 18th century. The epicenters of the 19th century indicate most of the seismic sources known today in the region, but the northern part of the Balkan (Bosnia, Serbia) is nearly free of earthquakes certainly due to the inadequate collection of the observations. The sources of earthquakes occurred between 456–1995 in Fig. 8 — in spite of the fact that they are rather scattered in some area — nevertheless outline the geographical positions of the strong tectonic movements in the Carpathian Basin.

Though the comparisons of the seismicity and the maps or models of other geosciences are out of the scope of this study it is worth to note some peculiarity of this source pattern.

- The two most active regions:

  Southeastern part of the Alps connecting to the Dinarides (southern Austria, northern Italy, Slovenia, western Croatia).

  Southeastern band of the Carpathians (Háromszék-Vrancea region) with the source zone of crustal events in its western neighbourhood (Barcaság region).

- There is a strong seismic source line starting from the valley of the river Mur (Mura) in Austria and continuing through the Little-Carpathians (Kis-Kárpátok) in Slovakia. To this important source zone another very active line is connected along the rivers of Enns and Liesenbach in Austria.

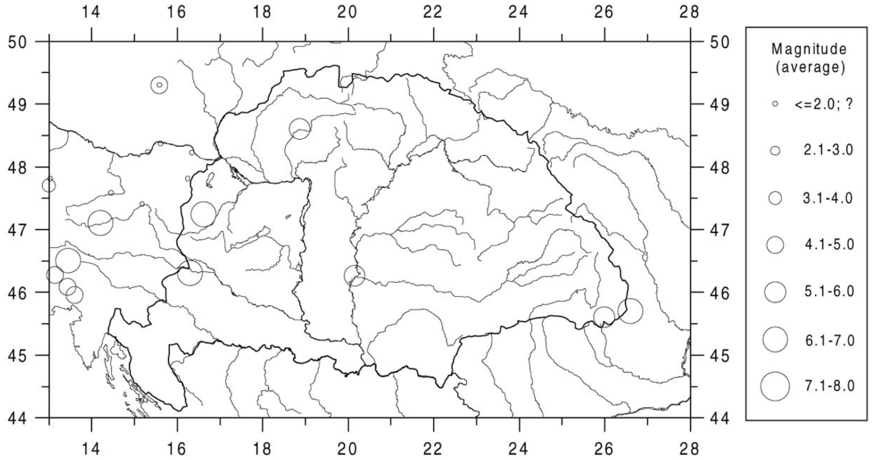

Fig. 2. Earthquake epicenters in the Carpathian Basin (456–1500) (Epicenters having more than 50 km deviations are not plotted)

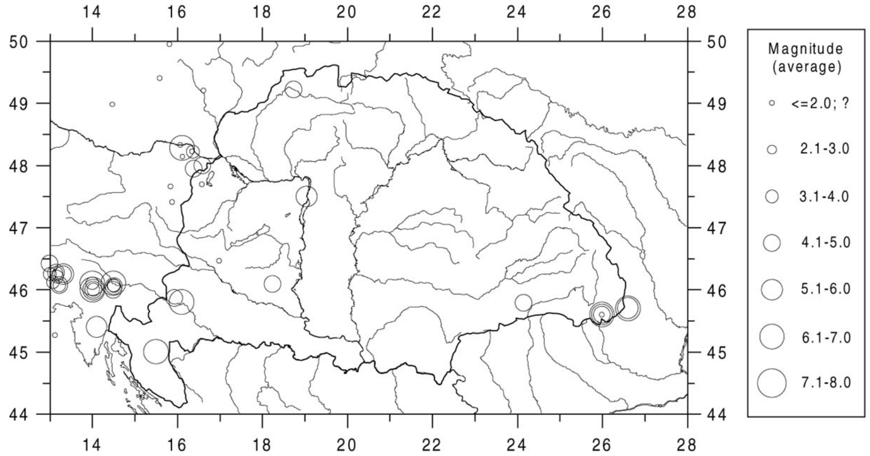

Fig. 3. Earthquake epicenters in the Carpathian Basin (1501–1600) (Epicenters having more than 50 km deviations are not plotted)

- The seismicity of the Sub-Carpathian (Kárpátalja) region is also apparent where the epicenters around the feet of Avas, Gutin, Kőhát and Lápos mountains indicate a very active tectonic process.
- The massive platforms and shields (Bohemia, Ukraine, Oltenia) are also not without earthquakes but naturally the level of seismicity is very low. Furthermore some parts of the Pannonian Basin (e.g. northern part of the Little Hungarian Plain (Kisalföld) above the river Danube, area east of the river Tisza (Tiszántúl), northern Bácska) show smaller seismic activity than e.g. the territory of Bohemia.

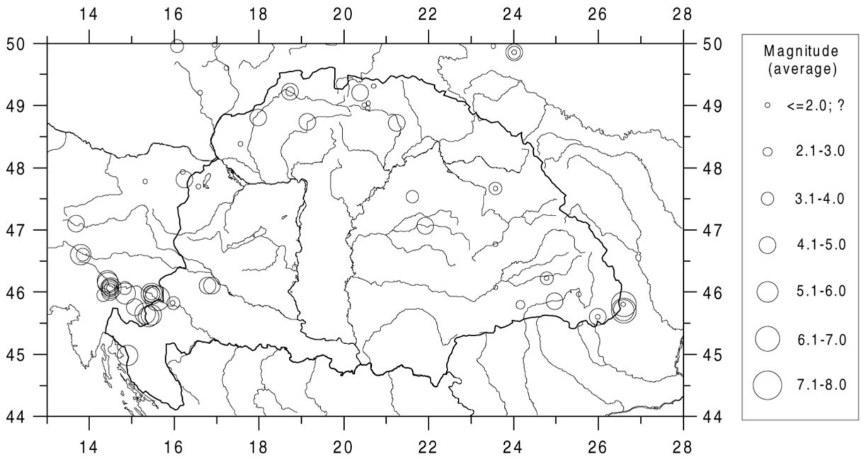

Fig. 4. Earthquake epicenters in the Carpathian Basin (1601–1700) (Epicenters having more than 50 km deviations are not plotted)

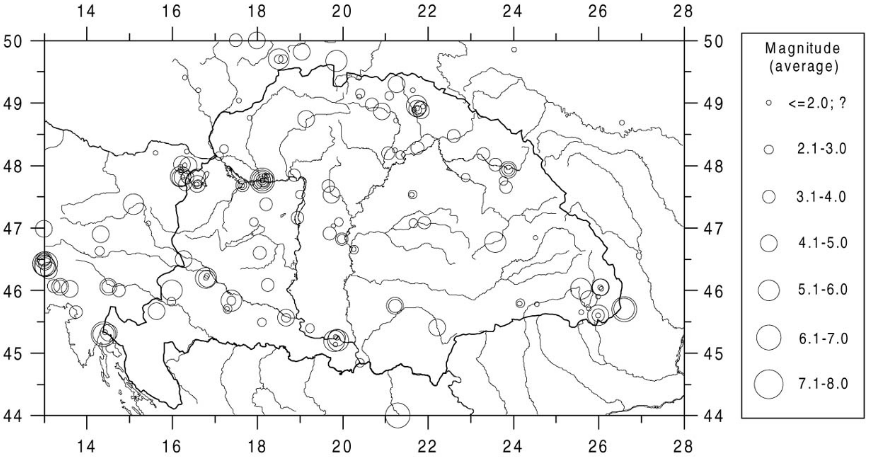

Fig. 5. Earthquake epicenters in the Carpathian Basin (1701–1800) (Epicenters having more than 50 km deviations are not plotted)

3. Focal depth

Among the total 20478 earthquakes of the database only 3751 earthquakes – about 18 % of the events — have focal depth values. They are either the results of network determinations or macroseismic estimations based on isoseismal maps. The later figure however is very small, only about 4 % of the focal depth data. The estimation of focal depth is the most difficult one comparing to the determination of the other source parameters of earthquakes. In network determination the velocity model used is usually not precise enough and the number of input observations is often very small. The instrumental depth values of the catalogue come from database of different seismological centers. Since most of the earthquakes are not felt, the

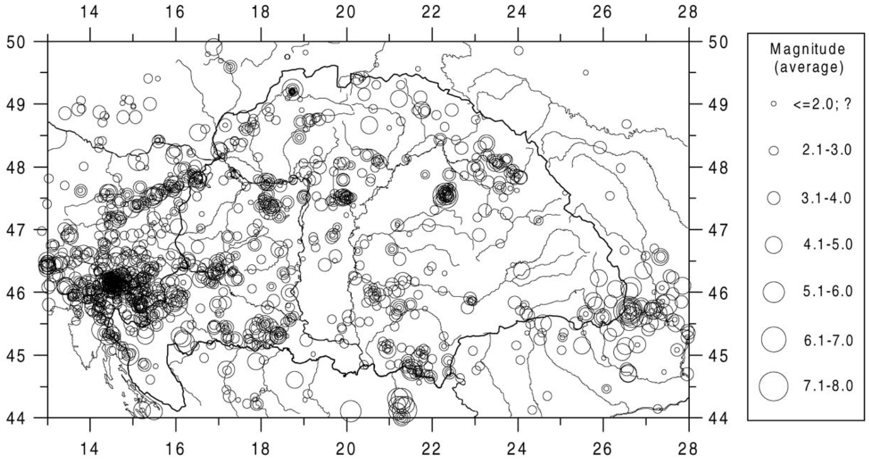

Fig. 6. Earthquake epicenters in the Carpathian Basin (1801–1900) (Epicenters having more than 50 km deviations are not plotted)

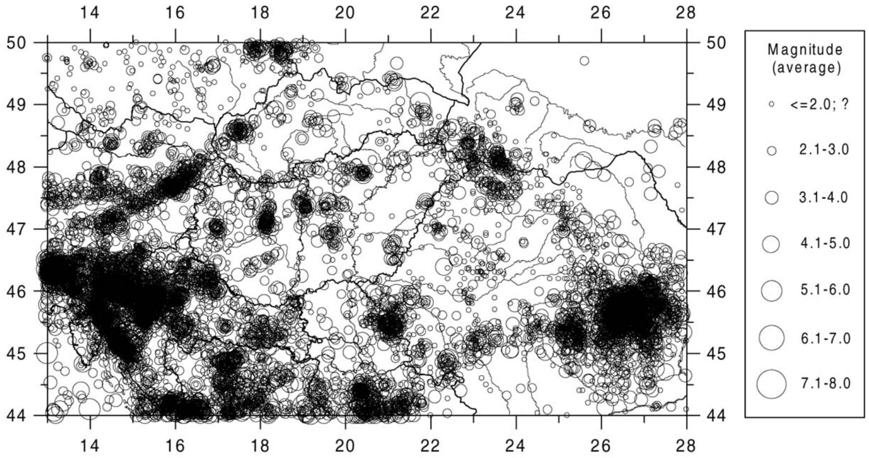

Fig. 7. Earthquake epicenters in the Carpathian Basin (1901–1995) (Epicenters having more than 50 km deviations are not plotted)

macroseismic depth estimation is usually not possible. For earthquakes having an isoseismal map with three isoseismals at least (in order to calculate deviations), the macroseismic focal depth was estimated in uniform way (Zsíros 1996) using the Kövesligethy formula (1906) as the intensity attenuation model.

$$I_0 - I_k = 3 \cdot \log(D_k/h) + 3 \cdot \alpha \cdot \log(e) \cdot (D_k - h)\,, \tag{1}$$

where:

I_0 – epicentral intensity

I_k – intensity value at hypocentral distance D_k

$D_k^2 = R_k^2 + h^2$

R_k – adius value of isoseismal k (km)

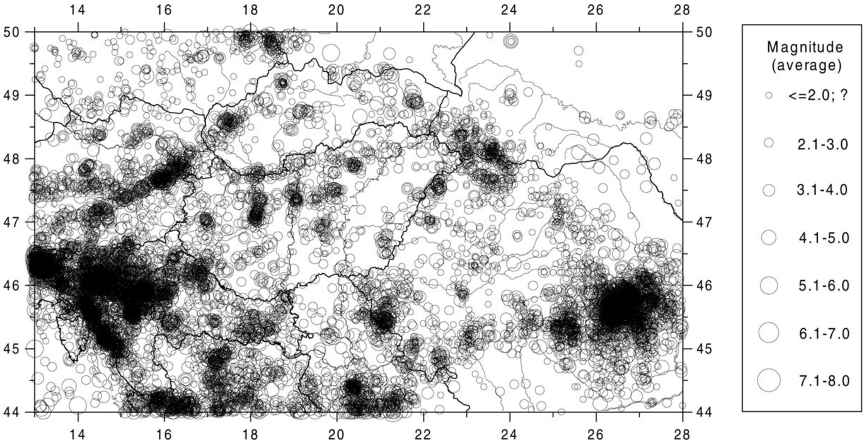

Fig. 8. Earthquake epicenters in the Carpathian Basin (456–1995) (Epicenters having more than 50 km deviations are not plotted)

h – focal depth (km)
α – coefficient of absorption (km^{-1})
$\log(e) \cong 0.4343$.

Based on the above Eq. (1) the focal depths of 147 earthquakes have been determined, altogether.

In network determinations of source parameters of earthquakes the focal depth has often been fixed in order to obtain a stable result for epicenter co-ordinates, consequently these depth values were intended to exclude from the catalogue. The depth values having more than 100 % standard deviations were also removed from the database. The values of focal depths vary between 1 and 291 km in the catalogue and the frequency of the individual depth values shows considerable difference.

Shallow depth (1–65 km) events occur in the whole territory of the Carpathian Basin, however the sources of the earthquakes with intermediate depth (66–300 km) have been concentrated at the southeast bend of the Carpathians (Háromszék-Vrancea region). The distributions of the shallow and the intermediate earthquakes in space are shown in Fig. 9 and in Fig. 10, respectively.

Studying the histogram of focal depths of earthquakes (Fig. 11) occurring in the Carpathian Basin without the Háromszék-Vrancea region it can be concluded that 7 km is the most frequent depth value and 65 % of the whole 1804 events are originated from the 5–15 km depth domain. The average depth is 12.6 km.

Figure 12 shows the histogram of the focal depths of the Háromszék-Vrancea region between 1 and 300 km. The total 1919 events consist of 555 shallow depth (1–65 km) earthquakes (29 %) and 1364 intermediate depth (66–300 km) earthquakes (71 %). The average depth is 95.2 km. The striking high frequencies at 100, 120, 130, 140 and 150 km are probably due to the fact that some of the depth values are not calculated but fixed during the estimation process of source parameters. Roughly three groups can be outlined in Fig. 12 with the depth centers of ~ 15 km, ~ 80 km and ~ 130 km, respectively.

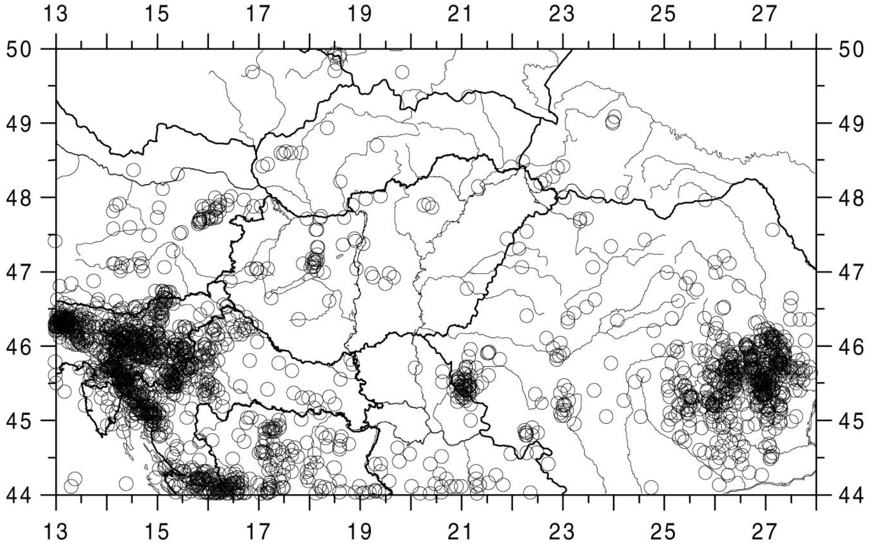

Fig. 9. The spatial distribution of earthquakes with shallow focal depth (1–65 km). Number of earthquakes used: 2359

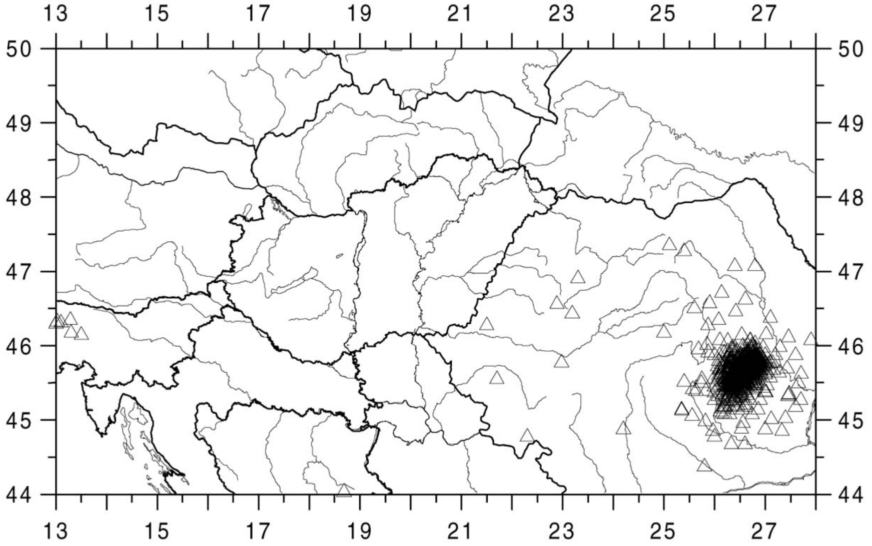

Fig. 10. The spatial distribution of earthquakes with intermediate focal depth (66–300 km). Number of earthquakes used: 1392

The intermediate depth sources of the Háromszék-Vrancea region are deepening nearly vertically but in somewhat SW direction (Fig. 13). The most dominant part is between 70 and 170 km and below 200 km the events are rear. In Fig. 13 the separation of the crustal earthquakes and the events connected to the lithospheric plate subsiding into the asthenosphere is well observed at about 50 km, which is the

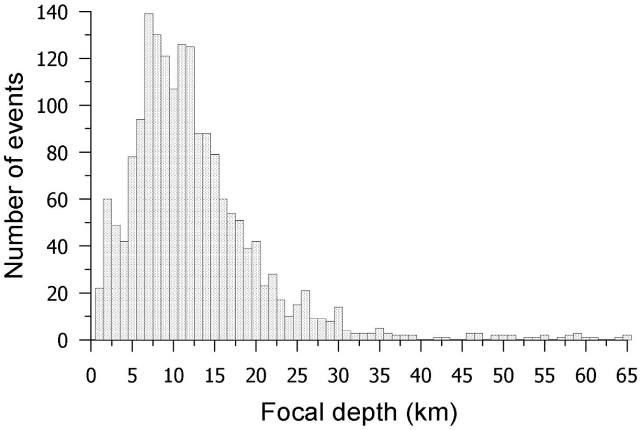

Fig. 11. Distribution of focal depths between 1 and 65 km in the Carpathian Basin (44–50 N; 13–28 E). Earthquakes of the Háromszék-Vrancea region (44.5–46.5 N; 25.5–28 E) are excluded. Number of events used: 1804

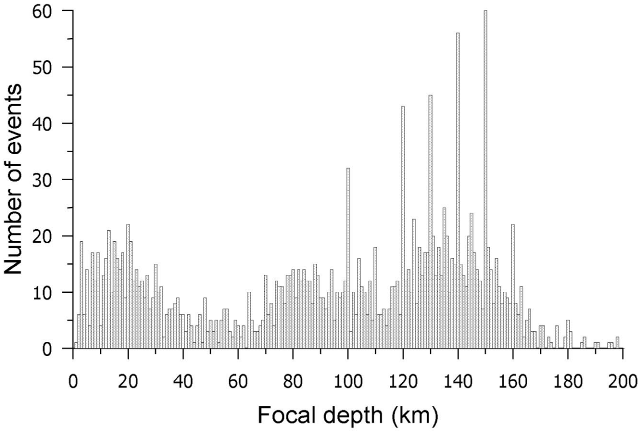

Fig. 12. Distribution of focal depths between 1–200 km in the Háromszék-Vrancea region (44.5–46.5 N; 25.5–28 E). Number of events used: 1908

depth of the Mohorovičić discontinuity (MOHO) in this region (Lenkey 1999). The lithospheric plate deepening to the depth of 150–200 km (Horváth 1993, Lenkey 1999) is supposed to be disconnected around 50 km (Oncescu et al. 1984, Spakman 1990). Some weakness of this lithospheric plate can also be assumable based on the lower seismic activity observed between 100–120 km depth (see Figs 12 and 13).

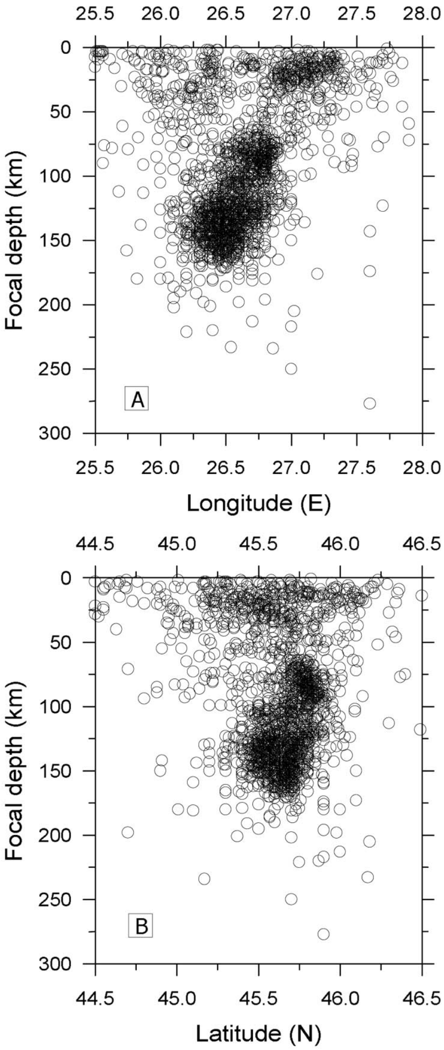

Fig. 13. Distribution of focal depths along the longitude East (A) and the latitude North (B), respectively in Háromszék-Vrancea region (44.5–46.5 N; 25.5–26.5 E). Number of events used: 1919

4. Magnitude

The magnitude value was introduced to provide an instrumental measure of the size of earthquakes based on the records of seismic waves by a convention (Willmore 1979). Since there are different types of seismic waves, different magnitude scales have been used. Unfortunately there is some inconsistency between the different scales and the deviations of magnitudes are often considerable ones even measured on the same scale. In the database used the most frequent types of magnitudes are the followings: MS — surface wave magnitude, MB — body wave magnitude, ML

— local (Richter) magnitude, MD — duration magnitude. Among them the last two types of magnitudes are the most frequent ones due to their relatively easier determinations.

The regression analysis of the different types of magnitudes has the following results:

- The relation of M_S and M_B magnitudes:

$$M_S = 0.97(\pm 0.05)M_B + 0.04(\pm 0.24)\,. \tag{2}$$

  Number of earthquakes used: 127. Magnitude intervals: $M_S = 2.5 - 7.0$; $M_B = 2.1 - 6.4$.

- The relation of M_S and M_L magnitudes:

$$M_S = 0.86(\pm 0.06)M_L + 0.57(\pm 0.27)\,. \tag{3}$$

  Number of earthquakes used: 97. Magnitude intervals: $M_S = 2.0 - 7.0$; $M_L = 2.0 - 6.6$.

- The relation of M_S and M_D magnitudes:

$$M_S = 1.21(\pm 0.11)M_D - 1.23(\pm 0.52)\,. \tag{4}$$

  Number of earthquakes used: 27. Magnitude intervals: $M_S = 2.3 - 6.9$; $M_D = 2.8 - 6.5$.

- The relation of M_B and M_L magnitudes:

$$M_B = 0.59(\pm 0.05)M_L + 1.75(\pm 0.22)\,. \tag{5}$$

  Number of earthquakes used: 259. Magnitude intervals: $M_B = 2.6 - 6.4$; $M_L = 2.1 - 6.6$.

- The relation of M_B and M_D magnitudes:

$$M_B = 0.90(\pm 0.08)M_D + 0.20(\pm 0.32)\,. \tag{6}$$

  Number of earthquakes used: 160. Magnitude intervals: $M_B = 2.6 - 6.3$; $M_D = 3.2 - 6.5$.

- The relation of M_L and M_D magnitudes:

$$M_L = 1.14(\pm 0.02)M_D - 0.69(\pm 0.06)\,. \tag{7}$$

  Number of earthquakes used: 894. Magnitude intervals: $M_L = 0.8 - 5.5$; $M_D = 1.4 - 5.6$.

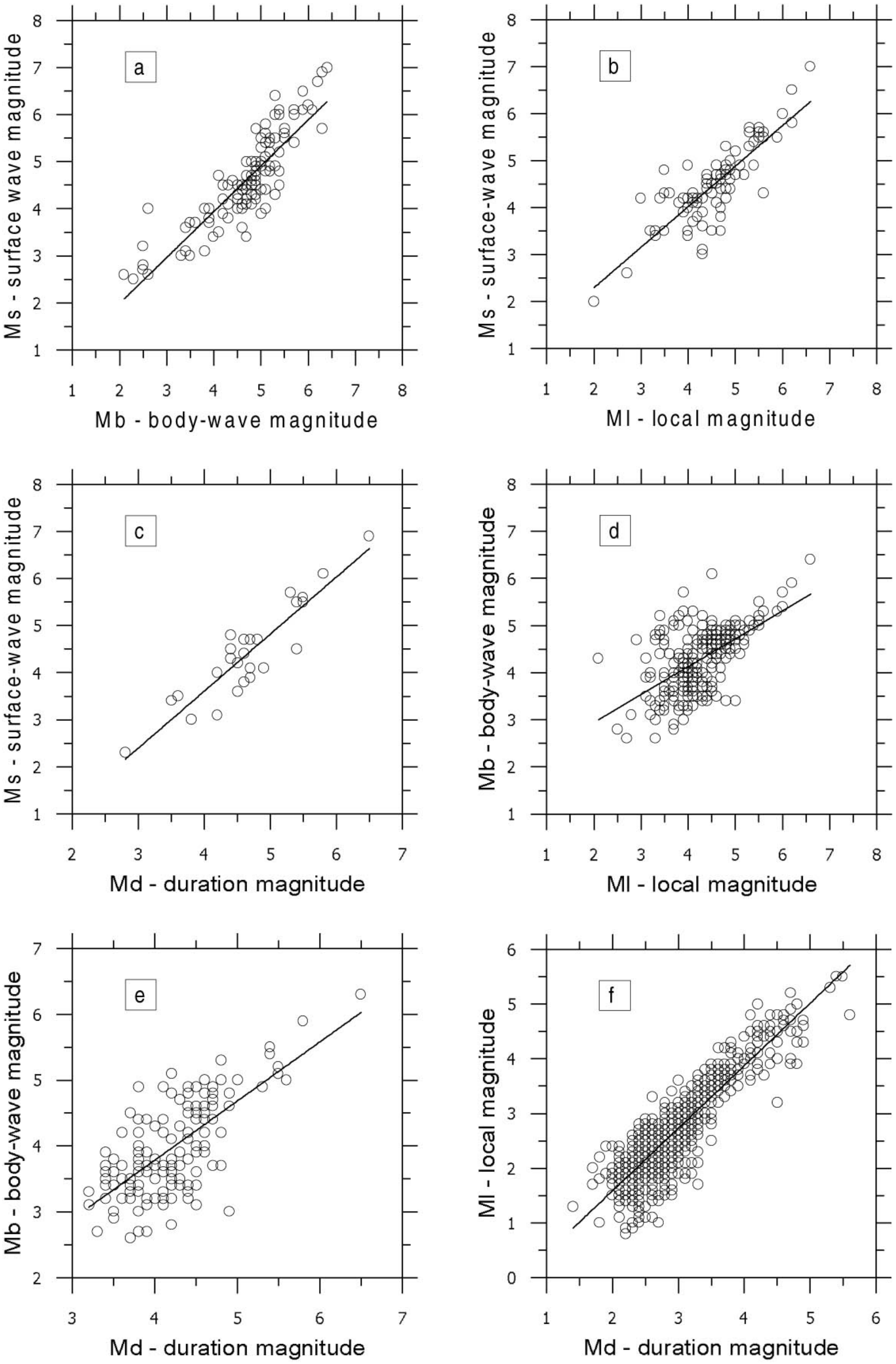

Fig. 14. Relations between different types of magnitudes based on earthquakes of the Carpathian Basin (44–50 N; 13–28 E)

The fit of the regression curves is shown in Fig. 14.

Relationship between the average magnitude (M) and the epicentral intensity (I_0).

Magnitudes of earthquakes have frequently to be estimated from macroseismic data due to the lack of instrumental data. It seems to be reasonably supposed that the magnitude value depends first of all on the epicentral intensity and the focal depth of the earthquake. The constant parameters of the empirical formula (8) were estimated by the least-square method.

$$M = a \cdot I_0 + b \cdot \log(h) + c \tag{8}$$

where:
M – average instrumental magnitude
I_0 – epicentral intensity
h – focal depth (km)
a, b, c – constant parameters.

The regression analysis was carried out for two territories:

- The whole Carpathian Basin (44–50 N; 13–28 E) but without the Háromszék-Vrancea region (44.5–46.5 N; 25.5–28.0 E) which contains the intermediate-depth events.
- The Háromszék-Vrancea region (44.5–46.5 N; 25.5–28.0 E).

The resulted relationships are as follows:

- Carpathian Basin:

$$M = 0.68(\pm 0.02)I_0 + 0.96(\pm 0.07)\log(h) - 0.91(\pm 0.10)\,. \tag{9}$$

Number of earthquakes used: 514. Depth interval: 1–65 km. Range of the epicentral intensities: from III to IX–X. Magnitude interval: 0.6–6.2.

Using 12.6 km as the average focal depth determined from 1804 earthquakes (see paragraph 3) in Eq. (9) the relation between M and I_0 is the following:

$$M = 0.68 \cdot I_0 + 0.146\,. \tag{10}$$

- Háromszék-Vrancea region:

$$M = 0.52(\pm 0.02)I_0 + 0.55(\pm 0.11)\log(h) + 1.18(\pm 0.20)\,. \tag{11}$$

Number of earthquakes used: 130. Depth interval: 1–200. Range of epicentral the intensities: from II to IX. Magnitude interval: 2.4–7.3.

Using 95.2 km as the average focal depth determined from 1919 earthquakes (see paragraph 3) in Eq. (11) the relation between M and I_0 can be written as:

$$M = 0.52 \cdot I_0 + 2.27\,. \tag{12}$$

The fitting of Eqs (10) and (12) to the observations is shown in Fig. 15. Some earlier determined magnitude-intensity relationships for the regions studied:

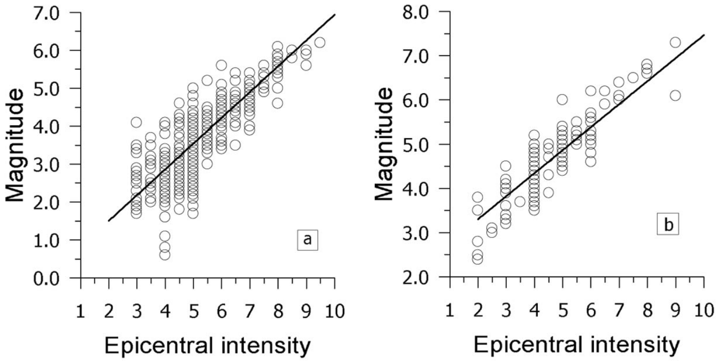

Fig. 15. Relation between the (average) magnitude and the epicentral intensity: a) Carpathian Basin (44–50 N; 13–28 E) (without Háromszék-Vrancea region (44.5–46.5 N; 25.5–28.0 E)). The regression curve calculated with a mean depth of 12.6 km. Number of data used: 514. b) Háromszék-Vrancea region (44.5–46.5 N; 25.5–28.0 E). The regression curve calculated with a mean depth of 95.2 km. Number of data used: 130

— Present territory of Hungary:

$$M = 0.6 \cdot I_0 + 0.3 \qquad \text{(Csomor and Kiss 1959)}\,.$$

— Carpathian Basin:

$$M = 0.53 \cdot I_0 + 0.96 \qquad \text{(Kárnik 1968)}\,.$$

Number of earthquakes used: 30. Range of the epicentral intensities: V–IX.

— Háromszék-Vrancea region:

$$M = 0.56 \cdot I_0 + 2.18 \qquad \text{(Radu 1974).}$$

Plotting these relationships with our results in Fig. 16 it can be concluded that the new magnitude-intensity Eq. (10) predicts greater magnitude than the equation of Csomor-Kiss (1959) but smaller than the relation of Kárnik (1968) at a given epicentral intensity in the Carpathian Basin. For the Háromszék-Vrancea region the new relationship (12) predicts smaller magnitude comparing to the one of Radu (1974).

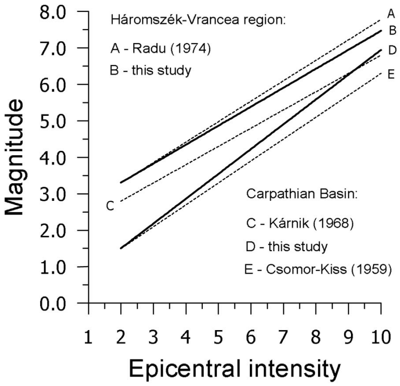

Fig. 16. Comparison of magnitude - epicentral intensity relationships

Appendix I

Location names in different languages

Hungarian	Austrian	Croat	Moravian	Rumanian	Serb	Slovak	Ukrainian
Belgrád					Beograd		
Bécs	Wien						
Bukarest				Bucureşti			
Csernovic							Csernovtsi
Fiume		Rijeka					
Grác	Graz						
Kassa						Košice	
Kolozsvár				Cluj-Napoca			
Lemberg							Lviv
Nagyszeben				Sibiu			
Ógyalla						Hurbanovo	
Temesvár				Timişoara			
Ungvár							Uzhchorod
Zágráb		Zagreb					
Zsolna						Zilina	

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