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Research Article

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Unification of data from various seismic catalogues to study seismic activity in the Carpathians Mountain arc

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Abstract: The Carpathian Mountains arc is the most seismically active area in Central Europe. Analysis of the seismicity of entire Carpathian arc requires data from each of the particular catalogues which have to be properly and uniformly entered, standardized and merged. For our study we first had to prepare a database of seismic events ($M_L \geq 1.6$) compiled from the data of earthquakes taken from individual national seismic networks as well as data from international seismic centers. However, a careful review of these catalogues has uncovered significant inconsistencies, particularly discrepancies in the description of the location, magnitude and completeness of seismic events. To address these inconsistencies, a newly created compound earthquake catalogue was compiled from the aforementioned seismic catalogues and included events that occurred in the Carpathian Mountains arc area between 1976 and 2017. This work is intended to point out some of the problems associated with collecting data from various seismic catalogues as well as the need for their very careful verification, in order to create a uniform set of seismic data across a large area spanning numerous countries. The results suggest that compiling a uniform and dependable earthquake catalogue is crucial for reliable seismic studies.

Keywords: earthquakes, Carpathians, seismic catalogues, magnitude

1 Introduction

Earthquake catalogues represent the most important data sets for studying different aspects of seismicity within a given area. The homogeneity of the data is considered to be a principal requirement of a catalogue. Many scientists developed unified earthquakes databases, for example homogeneous earthquake catalogues are essential in comparing geodetic and seismic estimates of crustal strain rates [1, 2] and in implementing various probabilistic seismic hazard approaches [3–5]. Also uniform databases covering individual countries [6, 7] as well as extensive areas [8]. Unfortunately, most earthquake catalogues are non-homogeneous because of a variety of factors that depend on both random and systematic errors introduced during the acquisition process and database construction procedure [9]. Homogeneous earthquake catalogues with high quality data covering large territories and long historical time spans are lacking for many parts of the Earth [10]. For the planned future study the elaboration of one unified database of seismic events containing information about strong earthquakes occurred in the Carpathian Mountains arc was essential for us. The general purpose of our research is to check if seismic activity of the Central and Southern Europe flows the occurrence of strong seismic shocks in the Upper Silesian Coal Basin (USCB) in Poland. Former research of seismicity in the USCB showed that it has a bimodal character. Tremors occurring in this area group into two energetic modes – those caused directly by the underground coal exploitation (low-energy mode) and regional ones (high-energy mode), the genesis of which are not yet fully explained. The second type of seismicity is probably induced by the combination of two factors: the mining and tectonic one. These high-energy shocks occurred in areas of tectonic zones and frequently are felt in the surface. The cause of the strongest tremors can be the cumulation of mining and tectonic stresses acting in the same parts of the rock mass. Confirmation or denial of this hypothesis could be important for explaining the genesis of strong seismic events in the USCB. We focus on a detailed analysis of seismic catalogues connected with the Carpathian arc as the area having the possible impact on the occurrence of strong events in the USCB. For our further research we needed an uniform seismic database con-

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taining basic information on earthquakes occurring there. Because of the data available in the seismic catalogue from the USCB we needed to compile the database containing events occurred between 1976-2017 which strength was expressed by local magnitude (M_L), similarly like in the USCB catalogue.

Until now, there has been not any study that focused on the analysis of seismicity of the whole Carpathian arc, although some papers have discussed the seismicity of particular regions. Analyses of the entire Carpathian area would require data from all available catalogues of the individual national seismic networks and international seismological centers, all of which would need to be completed, standardized, and merged in order to obtain a homogeneous earthquake data. This article is intended to show the importance of proper data collecting from various seismic networks, as well as the need for very careful verification of partial seismic catalogues, in order to create a single set of data regarding the seismic phenomena across a large area.

2 Seismotectonics of the research area

The Carpathian Mountains are commonly known as the most seismically active area in Central Europe. The arc has an inhomogeneous distribution of earthquakes and is therefore a very interesting region for seismologists. Localization of the shocks hypocentre is very important in terms of tectonics, because of most of the earthquakes are located in a restricted area in the bending zone between the Eastern and Southern Carpathians where at least three units are in contact: the East European plate, Intra-Alpine and Moesian sub-plates [11].

As it is well known the Carpathians were formed in the Alpine–Carpathian–Pannonian (ALCAPA) region during the Alpine orogenesis. This area has very complicated tectonics. According to [12] the Carpathians arc recorded a complex tectonic history, involving extrusion of microplates, ocean closure, subduction, slab rollback, slab detachment and asthenospheric upwelling. The recent ALCAPA region consist of the Carpathian orogen and Pannonian back-arc basin [13]. Because the tectonic evolution of this region is still a matter of discussion we can distinguish two evolutionary theories. First of them explained the evolution of the ALCAPA region in terms of gravitational collapse of the continental lithosphere. Some authors confirmed this theory [14, 15]. According to the second hypotesis, the subduction of the oceanic lithosphere underneath the Carpathians is a key process during the tectonic evolution of the ALCAPA [13]. Because the processes occurring in the Vrancea zone – still active seismic zone located in the bend region in Romania are seen as the latest stage of the subduction underneath the Carpathian Mountains [16, 17] the second thesis is more commonly accepted. This interpretation is well supported by former volcanic activity of the region [13]. There is also a third theory of the tectonic evolution of this region – lithospheric delamination due to continental underthrusting and orogenic thickening [14, 18]. This model could be generated through closure of an intracontinental basin and lithospheric thickening and does not require the former presence of an ocean-floored basin, or the subduction of oceanic lithosphere [14].

3 Database

The construction of mentioned database was based on individual seismic data from the following national and international seismic networks: seismic data portal Czech-Geo operated by the Czech Geological Survey [19], Kövesligethy Radó Seismological Observatory of the Hungarian Academy of Sciences [20], National Institute for Earth Physics (NIEP) in Romania [21], Seismological Survey of Serbia [22], IRIS Data Management Center [23], the European– Mediterranean Seismological Centre (EMSC) [24] and on-line bulletins from the International Seismological Centre (ISC) [25].

We included earthquakes within the Carpathian arc from Romanian and Hungarian catalogues. Data about tremors that occurred between 1976-2017 in northern part of the arc were taken from EMSC, ISC and IRIS. Only events with a known location and strength corresponding to M_w or $M_L \geq 1{,}6$ (depending on the magnitude type given in the catalogue) were entered into our final database. Several suspected erroneous entries with incomplete data (*e.g.* date, hour, latitude, longitude, magnitude and depth) were not included in the final database.

4 Inconsistencies in the catalogues

Careful review of the particular catalogues has showed their significant inconsistencies, especially discrepancies in the location, magnitude, and completeness of events which had to be pointed out.

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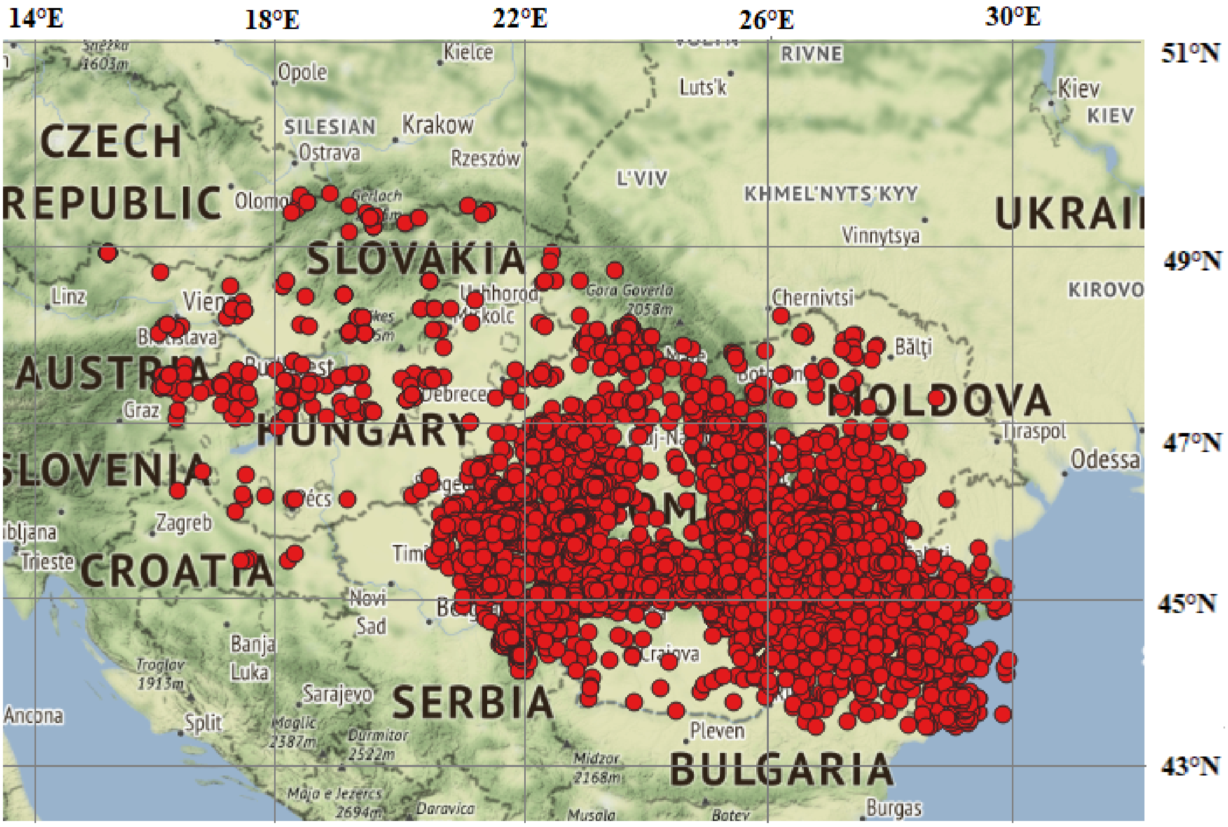

Figure 1: Epicentres map of shocks ($M_L \geq 1.6$) throughout the Carpathians arc during 1976-2017

4.1 Different time window

The first step of the analysis was to align time windows for all included catalogues. The period we considered starts from 1st January 1976 and end in 31st December 2016. We have accepted this time window due to data from the USCB which are available for this period. Firstly, the data were sorted and filtered to avoid including shocks repeated in analyzed catalogues as different shocks in the our database. All shocks that had the same date, hour, latitude, longitude, magnitude and depth were treated as one record. Secondly, some of the catalogues contained time gaps, for example the Romanian catalogue started in 1976 while the Hungarian one began in 1995. To make the final database complete in the time domain we filled up the gaps by the data taken from EMSC, ISC and IRIS.

4.2 Inhomogeneous earthquake distribution of the research area

The fact that epicentre distribution is not homogeneous throughout the entire area, tremors group mostly in the Southern part of the arc (Figure 1), consequently affects the density of the seismic network within the different parts of the Carpathians arc. It may be important for the completeness of seismic catalogues regarding weak events.

4.3 Different magnitude scales of used catalogues

Common known, the magnitude is one of the most important parameters of earthquakes and the first quantitative measure of earthquake strength.

The main problem that we had to solve in creating a complete and uniform seismic database for the Carpathian Mountains arc was the various types of magnitude given in the particular catalogues, especially m_b, M_L, and M_w magnitudes (Table 1).

5 Methods

In our merged database of seismic events from the entire Carpathian region, different magnitudes of earthquakes were unified into local magnitude for the whole study area.

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Table 1: The number of events in the Carpathians characterized by different types of magnitude.

Magnitude type	Number of earthquakes
m_b	18
M_L	363
M_w	17 541
M_w/ M_L	5 316*
all shocks	23 238

* in the Romanian catalogue, 5 316 tremors recorded since 2014 were catalogued as both M_w and M_L.

Table 2: The examples of events characterized by different types of magnitude – M_L vs. M_W above M_L >.0 in the Romanian catalogue between 2014-2017.

Date	Time	M_L	M_W	$M_L - M_W$
24.08.2014	07:12:49.66	4.6	4.2	0.4
03.04.2014	12:38:56.95	4.7	4.3	0.4
10.09.2014	19:45:57.79	4.8	4.3	0.5
24.01.2015	07:55:47.31	4.7	4.3	0.4
16.03.2015	15:49:49.14	4.7	4.3	0.4
29.03.2015	00:44:58.44	4.8	4.3	0.5
23.01.2014	06:15:04.66	4.9	4.4	0.5
29.03.2014	19:18:05.07	5	4.6	0.4
23.09.2016	23:11:20.06	5.3	4.9	0.4
27.12.2016	23:20:55.96	5.3	4.9	0.4
22.11.2014	19:14:17.11	5.7	5.4	0.3

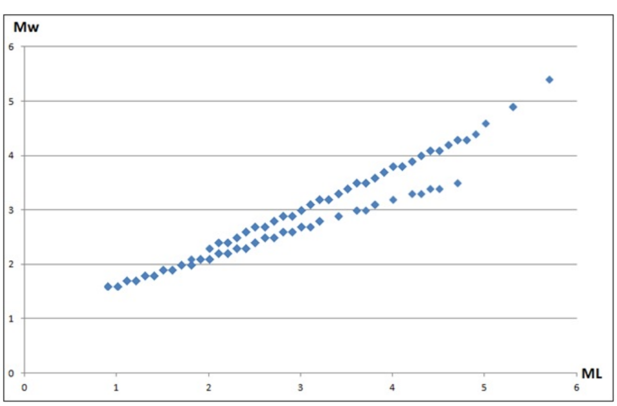

Figure 2: Regression function Mw versus ML in the Romanian catalogue

The biggest problem with the unification of catalogue was caused by the Romanian data, where magnitude M_w were given mostly. However, since 2014 the M_L value of earthquake sizes has been given together with the magnitude M_w (Table 2). For this reason we were able to compare the values of M_w and M_L from the Romanian catalogue for 5 316 tremors occurring between 2014 and 2016 (Table 1) and

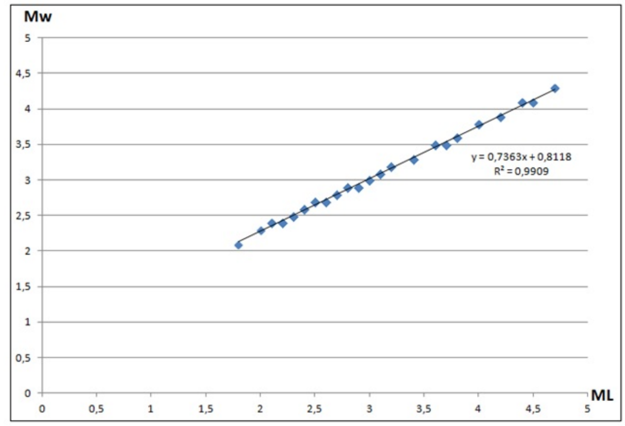

Figure 3: Regression function Mw versus ML in the Romanian catalogue for shocks occurring below 65 km of depth

subsequently to determine the regression function of M_w versus M_L. After careful analysis, it turned out that this relationship is bimodal and has two branches (Figure 2). One branch refers to shocks occurring shallowly, up to a depth of 65 km, while the other refers to tremors located deeper. We noticed that for shocks occurring below a depth of 65 km (Figure 3) the linear regression function M_w vs. M_L is done as:

$$M_L = \frac{M_W - 0.8}{0.74} \quad (1)$$

For shocks whose hypocentre depth is less than 65 km the linear regression formula is:

$$M_L = \frac{M_W - 1.12}{0.51} \quad (2)$$

In addition, regardless of the depth range, the local magnitude of strongest shocks (M_W above 4,5) presented in the Romanian catalogue can be calculated from the formula:

$$M_L = \frac{M_W - 0.29}{0.98} \quad (3)$$

These formulas (1)-(3) were used to unify the magnitudes of all the shocks from the Romanian catalogue by converting them into M_L value (Figure 3, Figure 4, Figure 5).

As one can see, the hypocentre depth range is a very important parameter to distinguish different types of magnitudes contained in the Romanian seismic catalogue. This data agrees with Kanamori's [26] suggestion that M_w can be determined for both shallow and deep earthquakes whereas M_L depends on depths of the hypocentre and the 'size' of earthquake.

Another considered problem was the different types of magnitudes listed in the Hungarian catalogue as well as the catalogues for the northern part of the Carpathians. In both catalogues the local magnitude M_L was given primarily but the magnitudes of 7 shocks (out of 209) described in

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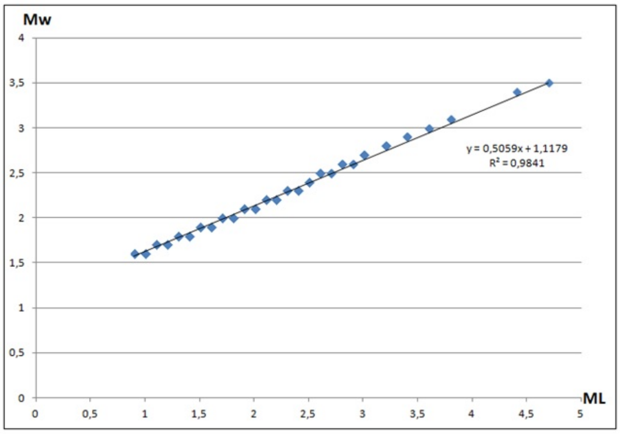

Figure 4: Regression function Mw versus ML in the Romanian catalogue for shocks whose depth is less than 65 km

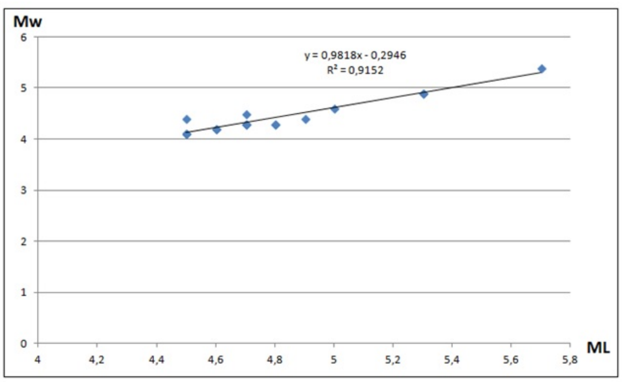

Figure 5: Regression function Mw versus ML in the Romanian catalogue of shocks for which $M_W > 4.5$

the Hungarian catalogue and 11 (out of 172) depicted in the catalogue for the northern part of the Carpathians were of the m_b type.

According to Kanamori [26] m_b is almost equal to M_L for shallow seismic events. Taking into consideration the small amount of shocks with magnitude mb in relation to the number of shocks with magnitude M_L and also a small depth range (less than 33 km of depth) of seismic events, we could attribute the m_b value to the M_L.

6 Results

Our database, which was compiled basing on the data from the aforementioned seismic catalogues, includes 23 238 events on ML ≥ 1.6 from period 1976 to 2017 that occurred in the studied area. Analysis of the database revealed an apparent incompleteness of smaller earthquakes with magnitudes less than 2 (Figure 6). For this reason, we decided to construct the Carpathian arc database for shocks with magnitudes $M_L \geq 2.0$ to obtain the relatively complete data set.

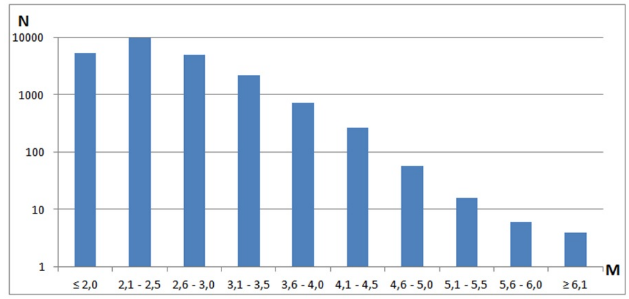

Figure 6: Histogram presenting the number of tremors for consecutive magnitude intervals: for the whole Carpathian Mountain arc area. N – number of events, M – magnitude intervals

7 Discussion and conclusions

As it is already well known, the main purpose of earthquake catalogues is to provide users with simple parameters for initial interpretations of the data. Any and every earthquake catalogue should endeavour to homogenize the given parameters, especially the magnitude, and any additional strength measure [27].

Unifying the seismic data of a huge area like the Carpathian Mountain arc (190 000 km^2) required solving a few problems, among others:

- collecting data from various available partial catalogues operated by several agencies,
- capturing and rejecting the same shocks that are repeated in different catalogues,
- sorting and filtrating the data to make correction of incorrectly described events,

The biggest problem was unification of magnitudes, because in different catalogues the various types of magnitude are given.

Grünthal and Wahlström [27] emphasize that M_L is by far the dominant magnitude in most of the used catalogues despite a heterogeneity between different local M_L scales, unknown to its extent. As Kanamori [26] wrote, a mix use of different magnitude scales (especially those determined at different periods) often causes confusion and should be avoided as much as possible. For these reasons, we have decided to unify all magnitudes to M_L, because they concern for a relatively homogeneous area which is the Carpathian Mountains arc. As a result, our methodol-

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ogy could reasonably be applied to the seismic data of all such homogenous mountain ranges.

The database we receive will be available soon to the seismological community.

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