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Which one of the three latest large earthquakes in Zagreb was the strongest – the 1905, 1906 or the 2020 one?

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Following the damaging earthquake of 22 March 2020 ($M_L = 5.5$, $M_w = 5.3$, I_{max} = VII EMS) in Zagreb, a question was raised whether this was the largest event after the Great Zagreb earthquake of 1880 (I_{max} = VIII MSK). The counter-candidates are the events of 17 December 1905 and 2 January 1906, for which relevant earthquake catalogues mostly report larger or comparable magnitudes as for the earthquake of 2020, with their maximum intensities mostly within a narrow margin between VII and VII–VIII in various intensity scales. In order to resolve the question, we have (re)analysed all available macroseismic data for the two historical events, collected readings from station bulletins, and analysed available historical seismograms. Macroseismic proxy for the local magnitude (M_{mR}) was estimated on the basis of modelled radii of isoseismals V EMS and VI EMS using the regressions derived for a set of 12 earthquakes in NW Croatia and the neighbouring areas. Macroseismic magnitude was found to be the largest for the 1906 event ($M_{mR} = 5.3$), followed by $M_{mR} = 5.1$ for the 2020 quake. Considering the magnitudes computed after Wiechert seismograms from the Göttingen (GTT) station, and from the amplitude/period readings reported from the German stations JEN and HOH for the earthquake of 1906, as well as the magnitudes calculated from broad-band records of the GTTG station and the stations of the Croatian network for the event of 2020, a unified local magnitude of $M_L = 5.3$ is found for both events. The magnitudes of the 1905 earthquake were consistently the lowest of the three. Taking the uncertainties into account, the events of 1906 and 2020 should be considered approximately equal in size. However, the strongest shaking in the centre of Zagreb was caused by the 2020 event. It occurred on the reverse North Medvednica boundary fault, while the macroseismic epicentres of earthquakes of 1905 and 1906 lie practically on the trace of the nearby strike-slip Kašina fault. That Kašina fault could have been the source of the 1906 earthquake is also hinted at by the elongated region of the strongest shaking along its strike.

Keywords: historical earthquake quantification, macroseismic magnitude, isoseismal radius, historical seismograms

Magnitudes and intensity scales mentioned in text:

M – Magnitude;
M_2 – Magnitude from other sources reported in the Croatian Earthquake Catalogue (mostly M_L);
M_{cat} – The reference magnitude in CEC. It is the average of $M_{L,CR}$ and M_2. If one of them is missing, it equals the other one;
M_L – Local magnitude;
$M_{L,CEC}$ – Final local magnitude computed here, the average of M_{mR} and $M_{L,CR}$.
$M_{L,CR}$ – Local magnitude in the Croatian Earthquake Catalogue computed using seismograms of the ZAG station (before 2000) and the median of the CR-network afterwards (Herak, 2020);
M_{LH} – Magnitude as defined by Kárnik (1969);
M_m – Macroseismic magnitude;
M_{m5} – Macroseismic magnitude computed from the radius of the isoseismal V;
M_{m6} – Macroseismic magnitude computed from the radius of the isoseismal VI;
M_{mR} – Macroseismic magnitude computed from the radii of the isoseismal lines;
M_S – Surface wave magnitude;
M_W – Moment magnitude;
EMS – European Macroseismic Scale 1998 (EMS-98), Grünthal et al. (1998);
MCS – Mercalli-Cancani-Sieberg macroseismic scale;
MS – Mercalli-Sieberg scale;
MSK – Medvedev-Sponheuer-Kárnik (MSK-78) scale with modifications from 1981 (Medvedev et al., 1964; Medvedev, 1978; Ad hoc Panel, 1981).

1. Introduction

After Zagreb, the capital of Croatia, was shaken by a destructive earthquake (M_L = 5.5, M_W = 5.3, I_{max} = VII EMS, hereafter E-2020) in the morning hours (05:24 UTC) of 22 March 2020, the media reported that it was the largest event to have occurred there in the last 140 years, *i.e.* after the Great Zagreb earthquake of 1880 (I_{max} = VIII MSK). This was often repeated in the days that followed, and was also stated in papers that followed the event (*e.g.* Bogdan, 2020; Markušić et al., 2020). However, earthquake catalogues list two strong events that occurred close to Zagreb in the time period between these two shocks. They occurred on 17 December 1905 (hereafter E-1905) and 2 January 1906 (hereafter E-1906), with magnitudes and intensities exceeding the ones of E-2020. In particular, the Croatian Earthquake Catalogue (Herak et al., 1996a; henceforth CEC) lists both events with similar epicentral intensities (VII–VIII MSK) and similar magnitudes (M_L 5.5 and M_L 5.6, see Tabs. 1 and 2) to the ones for E-2020. Tables 1 and 2 list the parameters of the two earthquakes as given in various catalogues.

The seismic activity at the turn of 1905 to 1906 started with a strongly felt event on 17 December 1905. It was followed by over 50 felt aftershocks (see Kišpatić, 1906), the last of which occurred only 5 minutes into the new year 1906 (local time). Just two days later, on 2 January 1906, another very strong event occurred. It was mostly described as much stronger than the December one, but this fact was not reflected in CEC due to the same maximum estimated intensity on which the magnitude estimate in CEC was based. The fact that a strong event was followed by another, apparently stronger one, certainly complicates interpretation of macroseismic observations after E-1906, as all damage could have been cumulative. The same is true also for E-2020, but the other way around – the mainshock was followed within an hour by a strong aftershock (M_L 4.9), so the damage became cumulative again before the effects of the mainshock could have been assessed.

The aim of this paper is to re-analyse all available sources that could help in quantification of E-1905 and E-1906. At first, we are going to analyse and compare observed macroseismic data for the three events, and derive local formulas to determine their macroseismic magnitudes (M_m) using lower intensities for which the assignment is not influenced by cumulative damage effects. Then, we shall analyse historical microseismic data (analogue seismograms and bulletin data), in order to compute instrumental magnitudes (M_L, M_{LH}) of E-1905 and E-1906.

Table 1. Parameters reported for the earthquake of 17 December 1905 in relevant catalogues.

	Author(s)	Date time (UTC)	Latitude (°N)	Longitude (°E)	Depth (km)	Epicentral intensity	M
1	Kárnik (1969)	17 Dec. 1905 22:18	45.9	16.1	–	(VIII) MS	5.6
2	Shebalin et al. (1974)	17 Dec. 1905 22:16.3	45.9	16.1	7	VII–VIII MSK	5.6
3	CEC (Herak et al., 1996a; updated 2019)	17 Dec. 1905 22:16:37	45.90	16.10	7.0	VII-VIII MCS	5.48
4	Shebalin et al. (1998)	17 Dec. 1905 22:16.18	45.9	16.1	11	VII-VIII EMS	5.6
5	Zsíros (2000)	17 Dec. 1905 22:16:33	45.82	15.98	7	VII-VIII MCS (?)	5.6
6	SHARE (Grünthal et al., 2013)	17 Dec. 1905 22:16:37.0	45.900	16.100	7	–	5.1
7	ISC-GEM suppl. (Storchak et al., 2013; 2015; Di Giacomo et al., 2018)	17 Dec. 1905 22:16:38.62	45.75	16.258	15.0	–	–
8	**This study**	**17 Dec. 1905**	**45.92**	**16.09**	**10**	**VII EMS**	**M_L 4.7 M_{LH} 5.0**

Table 2. Parameters reported for the earthquake of 2 January 1906 in relevant catalogues.

	Author(s)	Date time (UTC)	Latitude (°N)	Longitude (°E)	Depth (km)	Epicentral intensity	M
1	Kárnik (1969)	2 Jan. 1906 04:25	45.9	16.1	(10)	IX MS	6.3
2	Shebalin et al. (1974)	2 Jan. 1906 04:26.5	45.9	16.1	5	VIII MSK	6.1
3	CEC (Herak et al., 1996a; updated 2019)	2 Jan. 1906 04:26:36	45.92	16.10	5.0	VII–VIII MCS	5.64
4	Shebalin et al. (1998)	2 Jan. 1906 04:26:30	45.9	16.1	13	VIII EMS	6.1
5	Zsíros (2000)	2 Jan. 1906 04:26:36	45.92	16.10	10	VIII MCS (?)	6.1
6	SHARE (Grünthal et al., 2013)	2 Jan. 1906 04:26:36.0	45.920	16.100	0	–	5.3
7	ISC-GEM suppl. (Storchak et al., 2013; 2015; Di Giacomo et al., 2018)	2 Jan. 1906 04:26:27.25	45.386	16.521	12.0	–	M_w 5.79 ± 0.41
8	**This study**	**2 Jan. 1906**	**45.93**	**16.11**	**18**	**VII-VIII EMS**	**M_L 5.3 M_{LH} 5.5**

2. Macroseismic analyses

2.1. The earthquake of 17 December 1905 (E-1905)

The intensities for E-1905 were estimated by the authors on the basis of the extensive report by Kišpatić (1906), the articles in newspapers published in today's Austria, Croatia, Czech Republic and Ukraine (see the list of consulted newspapers at the end of the References section), the Hungarian earthquake bulletin (Réthly, 1906), the Austrian earthquake bulletin Allgemeiner Bericht (1907), and a report by Christensen and Ziemendorff (1909). We were able to estimate intensity (EMS scale) for 131 localities with intensity III EMS or larger. The largest damage occurred in the villages lying about 15–25 km to the NE from Zagreb. A brief summary of the reported earthquake effects in those settlements is as follows (see Electronic Supplement for the complete list od assigned intensities):

Čučerje: A strong earthquake; The church and the parish house got large cracks on the walls; Church tower heavily cracked (it survived the 1880 earthquake without damage); Large damage in the church's interior; Church probably damaged beyond repair (*note:* eventually, the church had been repaired; according to the information on the web-page of the Čučerje Parish (2021), the church and the bell tower were heavily damaged already in an earthquake of 1822); Large piles of rubble lay around the church; Farmers' stone-built houses were considerably damaged and in even worse condition than the church; Walls of the school also cracked in both classrooms; One badly built house was totally demolished;

Kašina: Very strong earthquake lasting about 10 s; Huge damage; Most walls on houses and on the church cracked; People spent the night in the open; Many collapsed chimneys and fallen roof tiles;

Marija Bistrica: Very strong earthquake; Objects fell to the ground, many walls had large cracks; Many stoves collapsed in farmers' houses.

Planina: The village that apparently suffered the most, the houses were almost demolished (second hand report).

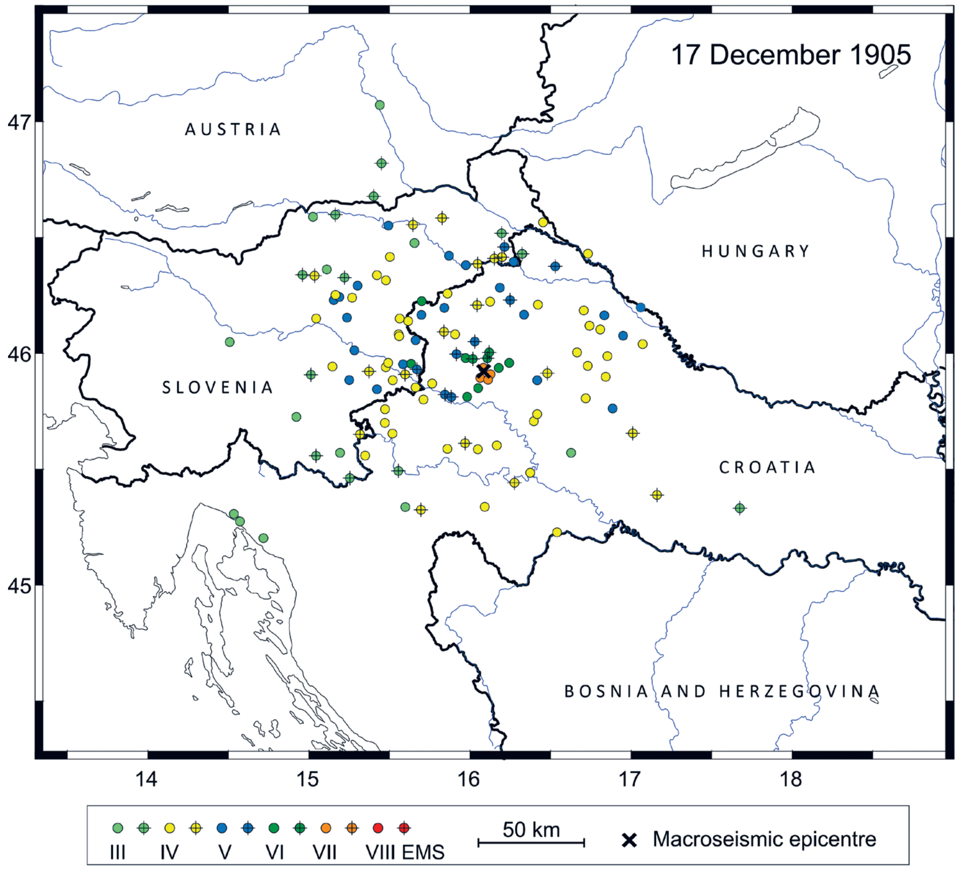

Figure 1. Intensities for the earthquake of 17 December 1905.

Stubica Gornja: On many houses chimneys collapsed and walls cracked; Much damage, especially on adobe houses. Pictures fell from the walls, items broke in cupboards. Stoves crashed in timber houses.

Vugrovec: Very strong earthquake; Pendulum clocks stopped; Walls cracked; Glasses fell to the ground; Chimneys collapsed on the parish house and on the bishop's house; Frightened people remained up all night. Roof tiles that fell from the church lay around in large piles.

In *Zagreb* the intensity is estimated as I_{ZAG} = VI EMS.

The intensity map is shown in Fig. 1. The macroseismic epicentre was determined using the program MEEP v.2.0 by Musson (2009) modified as described in detail by Herak et al. (2018, 2020). In particular, the hypocentre is found as the barycentre of 2000 bootstrap solutions with replacements using the centroid algorithm and the MEEP method. All other options remain the same as used by Herak et al. (2020). The macroseismic epicentre is located near Planina Donja (45.92 °N, 16.09 °E).

2.2. The earthquake of 2 January 1906 (E-1906)

The intensities for E-1906 were estimated on the basis of original handwritten notes and manuscripts by M. Kišpatić and A. Mohorovičić (kept in the Archives of the Department of Geophysics, and subsequently published by Mohorovičić, 1908), printed earthquake reports with detailed description of earthquake effects (Kišpatić, 1907), Hungarian (Réthly, 1907) and Austrian (Allgemeiner Bericht, 1908) earthquake bulletins, as well as a number of newspapers from todays Austria, Croatia, Hungary and Slovenia (see the list of consulted newspapers at the end of the References section). We also checked international earthquake catalogues and bulletins (*e.g.* Scheu, 1911).

For a total of 429 settlements intensities were determined ranging from II EMS to VII–VIII EMS. As noted in the Introduction, in the pleistoseismal area only cumulative effects of E-1905 and E-1906 (that occurred only 16 days apart) could have been observed. The largest damage was seen in the same area as for the E-1905 (see above), and the most affected were the following settlements (see Electronic Supplement for the complete list of assigned intensities):

Vugrovec: Terrible, violent earthquake, stronger than the 1880 one (!), lasting 15–20 s; Huge damage; Church almost ruined, walls show openings; Plaster fell off the walls, half of the walls cracked and moved; People were in despair; A crack appeared in the ground on the hill where the bishop's house is situated.

Čučerje: The church that was damaged by E-1905, was in ruins with large openings in the walls. A large pile of bricks that fell from the tower was found in front of the main gate. Large damage occurred also inside the church; The road towards Gora cracked in three places; The school sustained damage, as well as many stone houses, whose walls partly collapsed, and partly cracked. It was no longer possible to stay in many houses.

Kašina: Very strong shock, with terrible thunder-like noise, lasting for 15 s; People considered this earthquake to be much stronger than the 1880 one (!); All adobe houses were destroyed from the inside, and external walls cracked to the foundation; Cracks in the ground occurred near the parish house.

Moravče: Terrible shock that lasted about 15 s; Much damage to the church and the parish house; Firewalls collapsed, and many tiles cracked and fell from the roof. Nearly all masonry houses cracked heavily, some walls fell down.

Stubica Donja: Forceful earthquake that caused considerable damage; many chimneys and stoves collapsed, and cracks – large and small – are visible on every house. People fled their houses in great fear.

Stubica Gornja: Cracks on the adobe houses appeared that were so large it was a miracle the houses did not collapse; The church and the school were so damaged that they had to be closed; This event caused more damage than the one of 1880 (!).

Marija Bistrica: Severe earthquake which caused much damage to the famous church; Every house in the village was affected by the earthquake. School building was so damaged that the teacher's apartment had to be evacuated.

Zelina Donja: Severe, vertical earthquake, lasting for about 15 s; People were seized with terror; Farm animals got upset; The earthquake was as forceful as the 1880 one, but of shorter duration; Bottles fell from the cupboard whose doors opened and files fell out; Chimneys fell from the new parish house; The Chapel of St. Jana was quite cracked; In the St. Nicholas church the vault fractured, and a wall broke down on the tower. Four pipes fell off the organ.

Our estimate of intensity in *Zagreb* is I_{ZAG} = VI–VII EMS.

The intensity map is shown in Fig. 2. The macroseismic epicentre calculated in the same way as for the E-1905 is also located near Planina Donja (45.93 °N, 16.11 °E). A peculiar feature, noted and described already by Scheu (1911), is that isoseismals are apparently not concentric, but separated into two groups – one that surrounds the epicentre in a cross-like shape, and another one north of the Drava river, in Hungary, where intensities as far as 150 km away reached VI on an unspecified 12-degree scale[1]. Based on contemporary data Gorjanović-Kramberger (1907)[2] and Scheu (1911) put the epicentre near Planina. This agrees with our location. Szirtes (1910) reported the coordinates as 45.97 °N, 16.10 °E.

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[1] The largest intensity estimated in Hungary by Réthly (1907) was VI–VII on the Forel-Mercalli scale; see Fig. 2 with our estimates.

[2] D. Gorjanović-Kramberger also identified the major faultlines in the vicinity of Zagreb and Medvednica. In a map within his paper from 1907 three faults (*'Bruchlinien'*) are presented: the Planina fault (striking NNW–SSE, corresponding to the Kašina fault), and two faults striking SW–NE: the Bistra fault (corresponding to the North Medvednica boundary fault), and the Zagreb fault (running from Podsused to Sv. Ivan Zelina). See also Fig. 4 below.

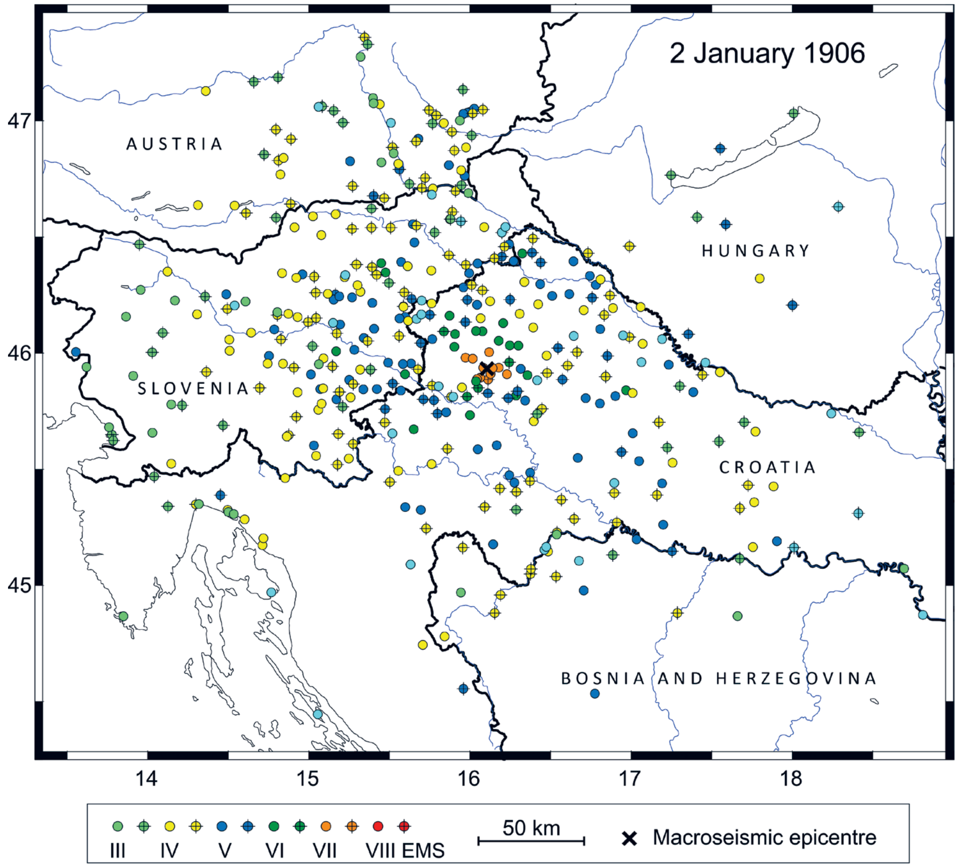

Figure 2. Intensities for the earthquake of 2 January 1906.

2.3. The earthquake of 22 March 2020 (E-2020)

Macroseismic data for the 2020 event were collected by the Croatian Seismological Survey (personal communication, 2020) for the Croatian territory, and by the Slovenian Environment Agency for Slovenia. For some localities in Croatia, and for Austria, Bosnia and Herzegovina, and Hungary intensities were estimated after the testimonies available at the web-page of the European-Mediterranean Seismological Centre (EMSC, 2020). The merged intensity dataset is presented in Fig. 3.

In Zagreb this event caused heavy damage. Preliminary estimates of total damage to buildings are in excess of 1.2 billion EUR, with the estimated cost for reconstruction between 5.6 and 10 billion EUR (Šavor Novak et al., 2020).

The intensity in Zagreb shown on the preliminary map by the Croatian Seismological Survey of I_{ZAG} = VII EMS agrees with our estimate. It is consider-

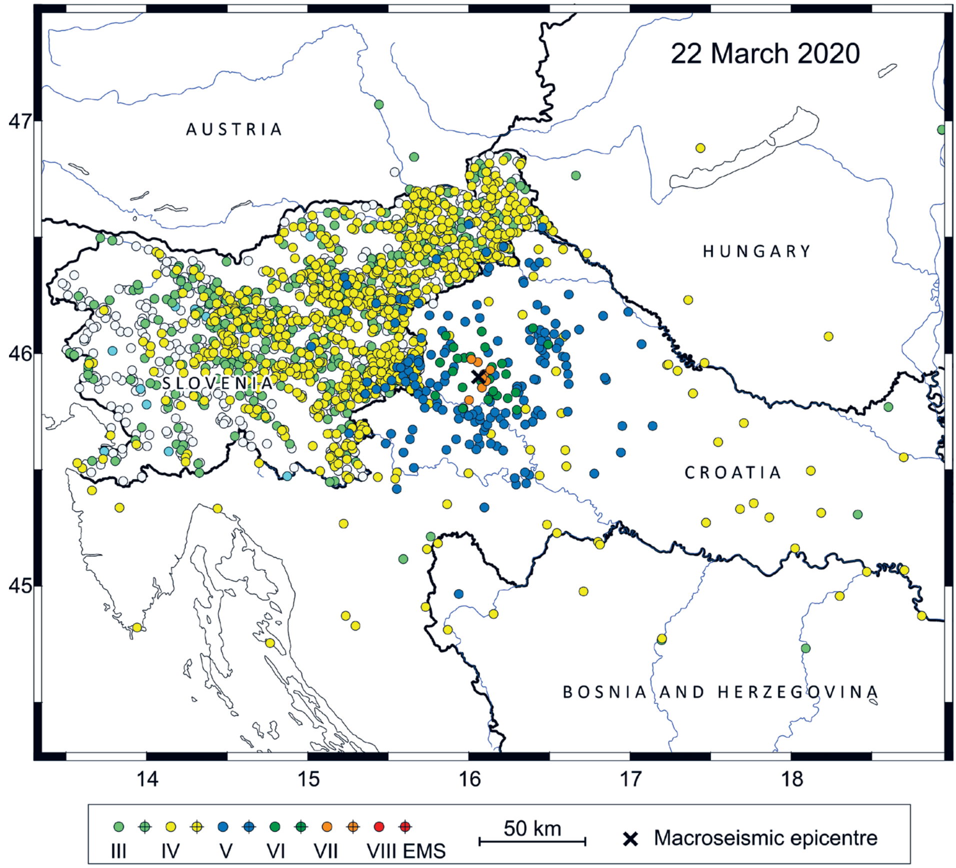

Figure 3. Intensities for the earthquake of 22 March 2020. Only localities with estimated intensity III EMS or above are shown. Data from the Croatian Seismological Survey and the Slovenian Environment Agency. Some data were also estimated after the European-Mediterranean Seismological Centre online testimonies (EMSC, 2020).

ably larger than I_{ZAG} = VI MM (corresponding to about VI EMS, Musson et al., 2010) proposed by Markušić et al. (2020) for the residential area of Zagreb.

The macroseismic epicentre lies near Čučerje (45.90° N, 16.06° E) about 4 km to the NE from the instrumentally computed epicentre close to Markuševec.

2.4. Macroseismic magnitudes

The comparison of the intensity fields presented in Figs. 1–3 clearly suggests that E-1905 was the smallest of the three analysed events. However, comparison of Figs. 2 and 3 is not conclusive. Overall, estimates are clearly more consistent for E-2020 than for the E-1906, where different intensities are often found close one to another, or at the distances where the estimated values are not expected (see above; also Fig. 2). This is due to the data-quality mostly related to the newspaper sources and their reliability (especially for lower intensities) for E-1906, as well as to the experience of seismologists who collected and interpreted data after E-2020. The two pleistoseismal areas seem to be of similar sizes, whereas intensity V EMS was reported further away for E-1906 than for the E-2020.

Macroseismic magnitudes are most often computed from the epicentral intensity (I_0) and the (macroseismic) focal depth (h). For estimation of I_0 and h probably the most used is the Kövesligethy-Jánosi intensity attenuation model (Kövesligethy, 1906, 1907; Jánosi, 1907):

$$I = I_0 - k \log (r/h) - k \, \mu \, \alpha \, (r - h), \qquad (1)$$

where I is the observed intensity at hypocentral distance r, k is the isoseismal coefficient (with a value between 2 and 4, usually around 3, *e.g.* Musson, 2009) which controls the separation of isoseismals, α is the intensity attenuation coefficient, and $\mu = \log(\mathrm{e}) = 0.43429$. In the case of E-1905 and E-1906, both I_0 and h are poorly constrained due to unknown local effects, source effects, and uneven data quality. Musson (2005) discussed the problems when I_0 is used as a substitute for magnitude.

An alternative approach is to use observed isoseismal area A_n of intensity I_n (or, equivalently, radius of the circle of the same area, R_n) to estimate the magnitude. Most often it is done using local or regional empirical equations linking magnitude (M) and the logarithm of A_n or R_n (*e.g.* Musson, 1996, 2005; Michael-Leiba, 1989; Živčić and Cecić, 1998). This approach is often more robust, as the areas of isoseismals are less sensitive than I_0 to small variations of depth and to the local (de)amplification close to the epicentre, especially if I_n is smaller than I_{max} by two or more. In order to use this method, we first attempt to determine the parameters a and b in expressions of the form

$$\mathrm{M_L} = a \log(R_n) + b, \qquad (2)$$

which would be applicable to the Zagreb area, by applying appropriate regressions to observed pairs (M_L, R_n) for a set of calibration earthquakes. $\mathrm{M_L}$ was taken from CEC, and radii R_n had to be determined for each selected earthquake. The calibration earthquakes had to satisfy the following restrictions:

- Epicentres must be in NW Croatia or in adjacent regions of Slovenia and Hungary;
- Maximum observed intensity must must be larger than V EMS;
- Earthquakes must have occurred in the instrumental era, *i.e.* they must have instrumentally determined $\mathrm{M_L}$ assigned in CEC;
- There must be enough observed intensity points to warrant reasonably reliable construction of isoseismals.

Inspection of relevant databases and catalogues revealed that only 12 earthquakes satisfy these conditions. They are shown in Fig. 4 and listed in Tab. 3. For all of them except for the event of 1990, digitized data points were either taken from the Croatian Macroseismic Database (Sović, 1999) or from the corresponding database of the Slovenian Environment Agency, or were digitized from the macroseismic analogue maps in the framework of this study. For the

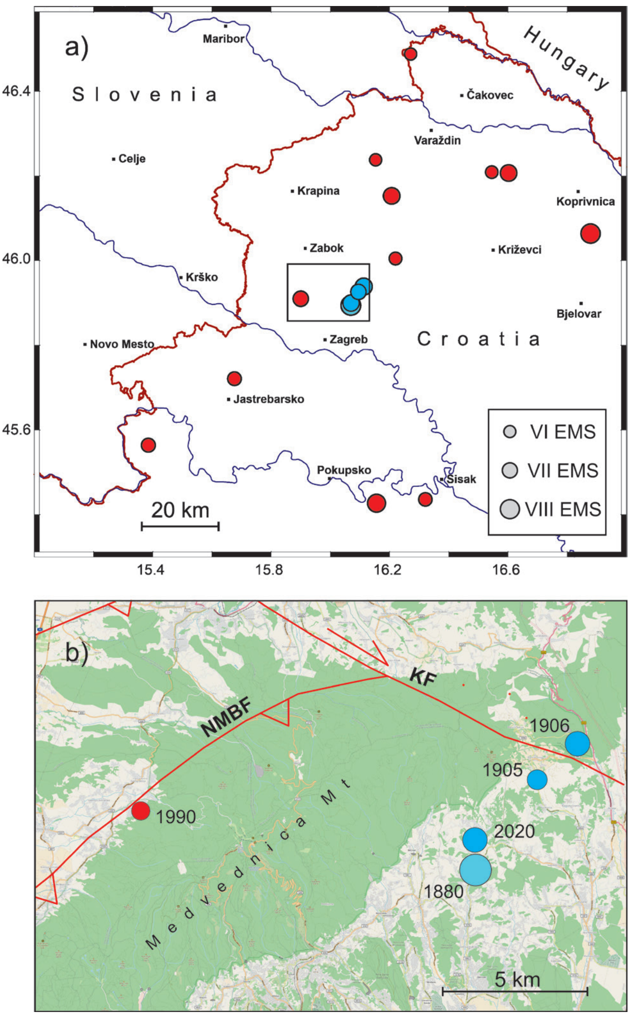

Figure 4. *a*) Macroseismic epicentres of earthquakes considered. Red circles – 12 calibration events used in regressions of M_L *vs*. log(R); Blue circles – events of 1880 (pale blue), 1905, 1906 and 2020. *b*) Zoom into the Zagreb epicentral area (rectangle in part *a*). Red lines are the main faults: North Medvednica boundary fault (NMBF) and the Kašina fault (KF) (modified after Tomljenović and Czontos, 2001).

*Table 3. Calibration earthquakes chosen to define relationships $M(R_n)$, expression (2). Lat., Lon. – coordinates of the macroseismic epicentre; h – macroseismic depth; I_{max} – maximum observed intensity; $M_{L,CEC}$ – local magnitude from CEC (see Herak, 2020). R_5, R_6 – radii of circles having the same area as the modelled isoseismals V and VI EMS; σ_M – assigned standard error of the magnitude; $\sigma(\log R_5)$, $\sigma(\log R_6)$ – assigned standard errors of the logarithms of R_5 and R_6. For detail on assigning individual errors, see the Appendix. *Isoseismals digitized from the map.*

Date (DD-MM-YYYY)	Time (hh:mm)	Lat. (°N)	Lon. (°E)	h (km)	I_{max} EMS	$M_{L,CEC}$	σ_M	R_5 (km)	$\sigma(\log R_5)$	R_6 (km)	$\sigma(\log R_6)$
08-10-1909	09:59	45.43	16.16	12	VIII	**5.80**	0.30	**89**	0.14	**65**	0.14
27-03-1938	11:16	46.06	16.88	14	VIII	**5.60**	0.30	**102**	0.14	**67**	0.14
11-06-1973	03:15	46.24	16.15	5	VI	**4.00**	0.30	**20**	0.17	**9**	0.17
16-02-1977	19:34	46.01	16.22	4	VI	**4.00**	0.30	**15**	0.14	**7**	0.14
16-03-1982	13:52	46.15	16.21	7	VII	**4.45**	0.30	**39**	0.10	**17**	0.12
28-05-1982	21:08	46.21	16.55	6	VI	**4.00**	0.30	**11**	0.17	–	–
03-09-1990*	10:48	45.91	15.90	5	VII	**5.00**	0.25	**35**	0.17	**20**	0.17
21-09-1992	20:47	46.49	16.27	4	VI	**3.45**	0.25	**10**	0.17	–	–
29-05-1993	08:43	45.56	15.39	5	VII	**4.20**	0.25	**22**	0.12	**9**	0.14
01-06-1993	19:51	46.21	16.60	9	VII	**4.70**	0.25	**50**	0.10	**23**	0.12
10-09-1996	05:09	45.44	16.32	17	VI	**4.50**	0.25	**44**	0.17	**16**	0.17
28-10-2006	13:55	45.72	15.68	2	V–VI	**4.11**	0.20	**12**	0.14	**4**	0.17

earthquake of 3 September 1990, we were only able to digitize isoseismals from the analogue intensity map of low resolution.

This rather limited dataset forced us to make compromises regarding the choice of isoseismals considered. Inspection of data revealed that in many cases intensities IV and below are not completely reported, so it was impossible to realistically asses their radii. On the other hand, as strong earthquakes are rather rare, there was not enough cases with well defined isoseismals VII or above to perform meaningful regressions. We thus decided to use isoseismals V and VI, for which the corresponding radii (R_5 and R_6) could have been estimated in most of the cases and cumulative effects of two strong earthquakes are minimal.

The process of determination of R_n may be done in two ways. Given the intensity points, the first one includes drawing isoseismals in a usual way (*e.g.* Cecić, 1990), and then determining their areas and equivalent radii. A big drawback is that this is always a subjective process, and intensity distribution (and thus also the isoseismals) can be heavily distorted by the influence of local site conditions and attenuation properties. Alternatively, one could define an objective procedure that will yield comparable results over different data-sets. Natural candidates are established algorithms for interpolation and smoothing of 2D

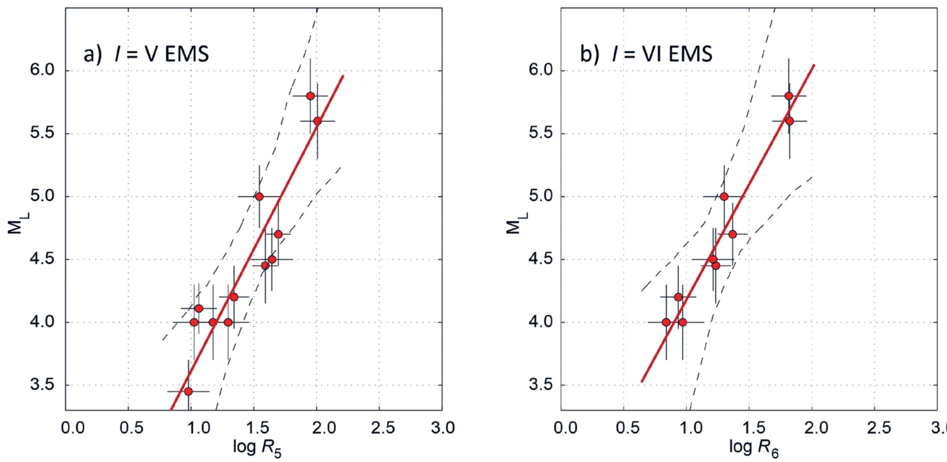

Figure 5. Observed magnitudes M_L and estimated radii (log $R_{5,6}$) of isoseismals V EMS (*a*) and VI EMS (*b*). The corresponding estimated individual errors are given by the horizontal and vertical error bars, respectively (see Tab. 3). The full red lines are the regressions (3) and (4), and the dashed lines bound the 3σ confidence region for the regression lines.

data (*e.g.* kriging), but difficulties arise in practice when one has to deal with local (de)amplification, large areas with missing data, etc. This may be largely avoided if a physically sound model of macroseismic field is fit to the data, and isolines of the modelled field are used as proxies for the areas shaken with a chosen intensity. This is the approach we follow here, and choose the modified Kövesligethy-Janosi formula (1) to describe the observed intensity dataset. With errors present in both variables (M_L and R_n) in (2), our regression method of choice was the York regression (York et al., 2004), an orthogonal regression algorithm that allows individual standard errors in both variables. Detailed description of the modification to (1), the regression used, definition of the weights given to data, and the procedures followed, are given in the Appendix.

The regressions resulted in (see Fig. 5):

$$M_{m5} = (1.938 \pm 0.350) \log(R_5) + (1.675 \pm 0.522); \quad r^2 = 0.85; \; s = 0.28, \tag{3}$$

$$M_{m6} = (1.835 \pm 0.395) \log(R_6) + (2.345 \pm 0.523); \quad r^2 = 0.94; \; s = 0.16, \tag{4}$$

where M_{m5} and M_{m6} are macroseismic magnitudes estimated from the radii R_5 and R_6, respectively, r^2 is the coefficient of determination, and s is the standard error of regression.

The two regressions (3) and (4) explain 85% and 94% of observed variance, respectively, they have similar slopes, and yield magnitudes with the standard error below 0.3. Some of the variance inevitably comes from the influence of focal depth which was not accounted for due to large uncertainties associated with macroseismic depth estimates (but note that larger inherent error was assumed for isoseismals close to the epicentre, where the depth influence is the largest – see the Appendix). These expressions can be used to asses macroseismic magnitudes for earthquakes in NW Croatia and the surrounding areas. We define the magnitude M_{mR} as the average of the magnitudes M_{m5} and M_{m6}. The standard error of M_{mR} is then $s(M_{mR}) = [0.5\, s^2(M_{m5}) + 0.5\, s^2(M_{m6})]^{1/2} = 0.23 \approx 0.2$.

Now we can estimate macroseismic magnitudes for the events E-1905, E-1906 and E-2020 using expressions (3) and (4) and the radii R_5 and R_6 that were measured as described in the Appendix for the 12 calibration earthquakes. In addition, we'll also compute macroseismic magnitude for the Great Zagreb earthquake of 1880 after the intensity data points from the Croatian Macroseismic Database (Sović, 1999). Table 4 presents macroseismic magnitudes for the four events.

Macroseismic analyses thus resulted in revised hypocentral locations and macroseismic magnitudes for the four largest events in the Zagreb epicentral area since 1880. As shown in Fig. 4b, the macroseismic epicentres of all four events lie within a circle of 5 km in diameter, *i.e.* mostly within each other's respective 1σ confidence region. The macroseismic epicentres of E-1905 and E-1906 lie very close to the nearby strike-slip Kašina fault (KF in Fig. 4b) which is traditionally assumed to have caused the 1880 event (*e.g.* Prelogović and Cvijanović, 1981). The elongation of the most-shaken area of E-1906 in the SE–NW direction (I ≥ VI EMS, Fig. 2) also speaks in favour of KF as the source of these two events. For E-2020 it was suggested that it occurred on the system of the reverse North Medvednica boundary fault (NMBF in Fig. 4b; Tomljenović, 2020; Šavor Novak et al., 2020). Given the proximity of the other three epicentres, and the fact that the instrumentally confirmed activity of NMBF is considerably larger than the activity of KF, we cannot exclude the possibility that NMBF was also responsible for the three earlier earthquakes.

The macroseismic magnitude based on isoseismal radii of the 1880 earthquake ($M_{mR} = 6.1 \pm 0.2$) agrees well with the local magnitude estimated on the basis of

*Table 4. Hypocentral parameters (Date, Time, Lat., Lon., h; focal coordinates determined by the modified MEEP v2.0 program as decribed in section 2.1) maximum intensity I_{max} and radii R_5 and R_6 for the three historical earthquakes and for E-2020, and their macroseismic magnitudes M_{m5} and M_{m6} according to expressions (3) and (4). M_{mR} is the mean macroseismic magnitude computed from isoseismal radii. *Standard errors of the macroseismic depth h are equal or larger than the corresponding error in epicentral coordinates*

Date	Time (hh:mm)	Lat. (°N)	Lon. (°E)	h* (km)	I_{max} EMS	R_5 (km)	R_6 (km)	M_{m5}	M_{m6}	M_{mR}
09-11-1880	06:34	45.89 ± 4 km	16.06 ± 5 km	17	VIII	194	120	6.1	6.2	6.1 ± 0.2
17-12-1905	22:16	45.92 ± 5 km	16.09 ± 6 km	10	VII	50	22	5.0	4.8	4.9 ± 0.2
02-01-1906	04:26	45.93 ± 6 km	16.11 ± 6 km	18	VII–VIII	85	36	5.4	5.2	5.3 ± 0.2
22-03-2020	05:24	45.90 ± 6 km	16.06 ± 6 km	5	VII	61	29	5.1	5.0	5.1 ± 0.2

I_{max} (or I_0), which is usually reported for this event (M_L = 6.2 is given in CEC). Judging from M_{mR} for the events of 1905, 1906 and 2020 (Table 4), the smallest among them was E-1905, and the largest one was E-1906. However, given the standard errors of ± 0.2 magnitude units, it is only clear that most probably E-1905 was the weakest one. In the centre of Zagreb, however, E-2020 was the most strongly felt one (I_{ZAG} = VII EMS) because its epicentre was closer to the city than the epicentres of E-1905 (I_{ZAG} = VI EMS) and E-1906 (I_{ZAG} = VI–VII EMS).

3. Microseismic analyses

3.1. Seismograms

The earthquakes E-1905 and E-1906 were instrumentally recorded by the majority of seismographic stations operating in Europe at that time, 22 of which provided their phase readings as reported by Szirtes (1909, 1910). Unfortunately, the amplitude and period readings were not included in these compiled reports.

EuroSeismos-SISMOS web portal (INGV, 2021), which was established in the framework of the EuroSeismos and SISMOS projects (Ferrari and Pino, 2003; Ferrari, 2016), hosts thousands of scanned historical seismograms from the European observatories. From the seismograms retrieved from there only the seismograms from the Göttingen (GOT) station in Germany were usable. Emil Wiechert, who was the director of the Institute of Geophysics in Göttingen constructed three modern mechanical seismographs with air damping that enabled more reliable retrieval of true ground motion. His astatic horizontal seismograph with the mass of 1200 kg was built in 1900, but started operating in 1902, and the vertical Wiechert seismograph (1300 kg) was installed and put to service in 1905. The first recordings of the short period 17000 kg pendulum (NS component only) were obtained already in 1905, but the instrument started regular operation only in 1907. The EW component was added in 1932 (Steffen et al., 2014).

The earthquake E-1905 was well recorded by the vertical Wiechert instrument with the mass of 1300 kg (Fig. 6a). To the best of our knowledge, this is the earliest preserved seismogram of a Croatian earthquake recorded by the instrument with a damping device![3]

The event E-1906 was also well recorded on Wiechert seismographs in Göttingen. Four seismograms have been preserved – two horizontal components on a

[3] In addition to high-resolution scans of GTT seismograms, the photographs of the Vicentini seismograms from Sarajevo (for both E-1905 and E-1906) exist in the Archive of the Department of Geophysics in Zagreb, but without indication of the scale, and the amplitudes of E-1906 have been clipped. Moreover, the damping on the Vicentini instruments was very weak and nonlinear (see *e.g.* Herak et al., 1996b), provided only by friction, so retrieving the ground amplitudes is highly unreliable.

Table 5. Constants of the GTT Wiechert seismograph at the end of 1905 and the beginning of 1906, and of the Omori-Bosh seismograph in Hohenheim (HOH; after Mack, 1907). T_0 is the free period of oscillations, V_0 is the static magnification, and ε is the damping ratio, i.e. the ratio of successive free swings' amplitudes of the recording stylus during the calibration procedure, with damping active. The interval of values is given in brackets.

Instrument	Component	T_0 (s)	V_0	ε (A_1/A_2)	Drum speed (mm/min)
GTT Wiechert 1200 kg	NS	13 [12–14]	160 [150–170]	5 [5–6]	10
GTT Wiechert 1200 kg	EW	13 [12–14]	160 [150–170]	5	10
GTT Wiechert 1300 kg	Z	6 [5-7]	165 [160–170]	4	10
GTT Wiechert 17000 kg	NS	[1.4–2.2]	[2000–2200]	8	60
HOH Omori-Bosch	EW	6	36	[4-6]?	15

1200 kg instrument, vertical component (1300 kg), and short-period NS-component (17 tons). Three examples of unprocessed seismograms are shown in Fig. 6.

The constants of the GTT seismographs have been taken from the Göttingen bulletins (Wiechert, 1906; Zoeppritz, 1908), Allegretti et al. (2000; after Duda et al., 1990), Bormann (2012), or the web-site of the Wiechert'sche Erdbebenwarte Göttingen (2021), and are given in Tab. 5.

The original seismograms were further processed by manually cleaning the scans of dust, scratches and other blemishes, and by image corrections in order to rectify the curved movement of the styluses. All cleaned and rectified seismograms used are shown in the same time scale in Fig. 7.

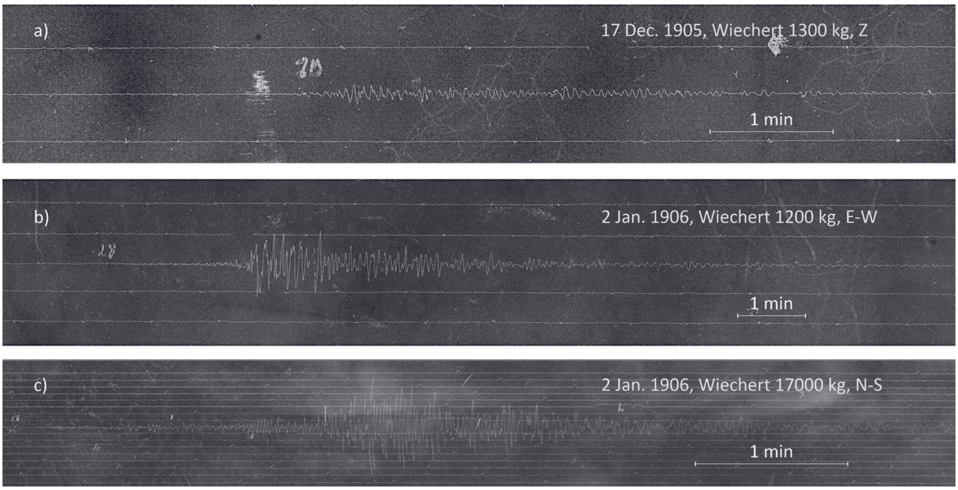

Figure 6. Examples of scans of Wiechert seismograms of E-1905 and E-1906 recorded at Göttingen (GTT, Germany). *a*) Vertical component, 17 December 1905; *b*) EW component, 2 January 1906; *c*) short period NS component, 2 January 1906.

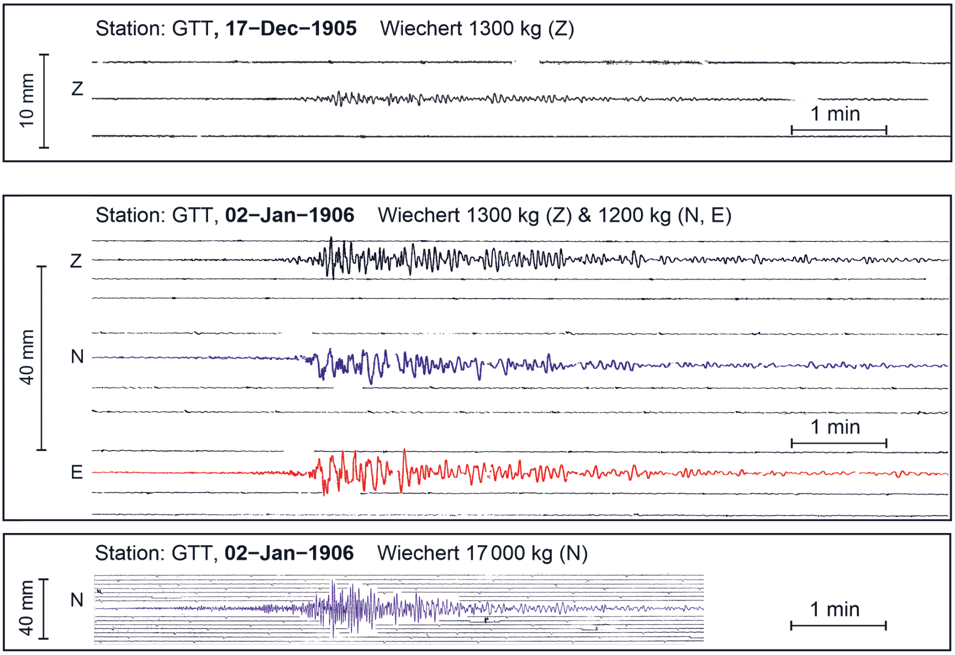

Figure 7. Processed images of the GTT seismograms of the Zagreb earthquakes of 1905 and 1906. The seismograms are in the common time scale. They are not scaled to the same magnification (see individual amplitude scales on the left).

3.2. Bulletin data

Bulletin of the Göttingen station lists maximum amplitudes of horizontal ground motions after the recordings of the 1200 kg instrument for E-1905 (the corresponding seismograms are not available): $2A_N = 7.4$ µm ($T = 4$ s), $2A_E = 7$ µm ($T = 5$ s).

Besides Göttingen, E-1906 was recorded on two more German stations – Hohenheim (HOH) and Jena (JEN). In Hohenheim, the Omori-Bosch seismograph with a horizontal pendulum and air-damping device was in use by the end of 1905 and in the beginning of 1906 (Wieland and Schick, 1997). Mack (1907) gives the maximum recorded amplitude on the EW component for E-1906 as $A_E = 1.5$ mm at the period of $T = 4$ s. The constants of the instrument in Tab. 5 are also given after Mack (1907) (except for the damping ratio ε that we assumed to be between 4 and 6), which enabled us to get the ground motion amplitude.

The Wiechert horizontal seismograph (1200 kg) was also installed in Jena (Szirtes, 1910; Unterreitmeier, 1997). It recorded both earthquakes. The Jena monthly bulletins (Eppenstein 1906a?, 1906b?), list periods and peak-to-peak maximal displacement amplitudes in µm. For E-1905 they are: $2A_E = 10$ µm ($T = 4$ s), $2A_N = 14$ µm ($T = 3$ s); and for E-1906: $2A_E = 44$ µm ($T = 4$ s), $2A_N = 70$ µm ($T = 6$ s).

3.3. Instrumental magnitudes

Epicentral distances of E-1905 and E-1906 are about 605 km, 650 km, and 770 km for the three German stations JEN, HOH, GTT, respectively. Therefore, the only magnitudes that can be computed are local magnitudes (M_L), and the magnitude M_{LH} as proposed by Kárnik (1969):

$$M_{LH} = \log(A_H/T_H)_{\max} + \sigma(\Delta°) + \delta M^s \tag{5}$$

Here $(A_H/T_H)_{\max} = [(A_N^2/T_N^2)_{\max} + (A_E^2/T_E^2)_{\max})]^{1/2}$, A_N/T_N and A_E/T_E are maximum amplitude/period ratios on two horizontal components in μm/s, $\sigma(\Delta°)$ is the calibrating function, $\Delta°$ is the epicentral distance in degrees, and δM^s is the station correction. The calibrating function $\sigma(\Delta°)$ is $\sigma(\Delta°) = \sigma_{LH}(\Delta°) = 1.66 \log(\Delta°) + 3.3$ for $1° < \Delta° < 160°$, and periods $T_H > 3$ s. For $1° < \Delta° < 6°$, and periods $T_H \leq 3$ s, $\sigma(\Delta°) = \sigma_{LgH}(\Delta°)$ is given by tabulated values in Kárnik (1969; Tab. 3, p. 39).

$(A_H/T_H)_{\max}$ in (5) is computed as the vectorial sum only if the maxima on both components correspond to time difference less than the corresponding predominant period. If the difference is larger, one measurement is used and +0.1 is added to the computed M_{LH}. Kárnik (1969) does not state which component is used in this case. Our interpretation is to take the larger one[4], which is how all M_{LH} are computed below. Vertical components are not used.

Local magnitude that is eligible is *e.g.* the one used in Croatia, originally defined by the Croatian team members (D. Cvijanović, B. Makjanić and D. Skoko) of the UNDP/UNESCO project *Survey of the Seismicity of the Balkan Region* (Shebalin et al.,1974) as:

$$M_{L,CR} = \log(A_{max}) + 2.094 \log(\Delta°) + 2.19. \tag{6}$$

A_{max} is the average maximum amplitude on the two horizontal components (in μm). The formula was derived using recordings of the horizontal 1000 kg Wiechert instrument in Zagreb, which is of the same construction as the GTT 1200 kg instrument. Being displacement-based, it is not applicable to recordings of the short-period seismographs (see discussion of this issue in Herak, 2020). After 1982, A_{max} was replaced by the maximum of the velocity-proportional seismograms (V_{max}), and vertical component was included into calculations. Its use and possible inhomogeneity before and after 1982 were discussed by Herak (2020).

The magnitudes for the events E-1905 and E-1906 computed from the scanned GTT seismograms and the data on the amplitudes and periods published in station bulletins are presented in Tab. 6. The station correction of $\delta M^s = +0.1$ has been added to GTT magnitude M_{LH} as suggested in Kárnik (1969) for the

[4] The vectorial sum of two ratios A_1/T_1 and A_2/T_2 is always larger than $\max(A_1/T_1, A_2/T_2)$. It thus seems reasonable to compensate this by adding 0.1 magnitude units to the magnitude computed using $\max(A_1/T_1, A_2/T_2)$.

*Table 6. Amplitudes (A), periods (T), epicentral distance (Δ), station corrections (δM^s), and computed magnitudes. Final values (bold print) of $M_{L,CR}$ are computed using the average amplitudes on two components, final M_{LH} is the larger of the magnitudes corresponding to the two components (see text above). *Bulletin data; [a] Croatian Seismic Network, DOI: 10.7914/SN/CR; [b] Not applicable for a short-period seismograph; [c] The predominant period of T = 1.0 s is too low to be considered for M_{LH}.*

Station/Network	Instrument	Component	*A* (mm)	*A* (μm)	*T* (s)	Δ (km)	δM^s	$M_{L,CR}$	M_{LH}
E-1905 (17 December 1905)									
GTT*	WIE 1200	NS		3.7	4	770	0.1		4.9
		EW		3.5	5	770	0.1		4.7
		Average		3.6				4.5	
		Z	0.85	4.3	3.4				
JEN*	WIE 1200	NS		5	4	650	–		4.8
		EW		7	3	650	–		5.0
		Average		6.0				4.6	
E-1906 (2 January 1906)									
GTT	Wiechert 1200	NS	3.6	21.4	6.1	770	0.1		5.4
		EW	4.5	26.8	5.4	770	0.1		5.6
		Average	4.1	24.1				5.3	
		Z	4.8	21.7	4.5				
	Wiechert 17 t	NS	19.0	8.8	1.0	770		–[b]	–[b,c]
HOH*	Omori-Bosch	EW	1.5	33.9	4	605	–	**5.3**	**5.6**
JEN*	WIE 1200	NS		22	4	650	–		5.4
		EW		35	6	650	–		5.4
		Average		28.5				5.3	
E-2020 (22 March 2020)									
GTTG	BB displacement	NS		54	6	770	0.0		5.8
	BB displacement	EW		40	5	770	0.0		5.7
		Average		47				5.6	
CR[a] – N,E comp. stations, $\Delta° > 1°$	BB displacement	Median						5.4	5.4 ± 0.2

period 1903–1906. For JEN and HOH no correction is added as they are not listed in Kárnik (1969) for the years 1905 and 1906. The magnitude M_{LH} for the broad-band station GTTG (practically collocated with the former GTT) is computed for the displacement seismogram obtained by integration of the velocity record. For the Croatian network (CR), $M_{L,CR}$ and M_{LH} are the medians of individual station magnitudes, also computed using horizontal BB-seismograms.

Instrumental magnitudes for E-2020 are on the average larger by 0.1–0.2 magnitude units than the corresponding magnitudes for the E-1906. Again, E-1905 is clearly the smallest of the three events. As only vertical seismogram for E-1905 is available at GTT, it could not have been used for direct magnitude estimation. However, the quotient of amplitude/period ratios of the vertical components at GTT (1300 kg vertical instrument) for E-1905 and E-1906 of 3.8 corresponding to the difference of magnitudes of about 0.6, is in reasonable agreement with the values shown in Tab. 6 for the horizontal components.

4. Conclusions

Using available macroseismic information as well as microseismic (instrumental) data (bulletin reports and seismograms), we were able to revise the macroseismic locations and magnitudes for the two Zagreb earthquakes of 1905 and 1906. The results are summarized in Tab. 7. The final values of $M_{L,CR}$ and M_{LH} are computed as weighted averages of the values given in Tab. 6, where magnitudes computed from seismograms with two horizontal components were given weights of 2.0, whereas magnitudes based on the single-component records and bulletin data were given weights of 1.0. M_{mR} were taken from Tab. 4.

Instrumental magnitudes computed here for E-1905 and E-1906 may be compared to their counterparts listed in CEC and in Kárnik (1969) (see Tables 1 and 2). CEC lists magnitudes M_{cat}, $M_{L,CR}$, and M_2 (see the list of magnitudes at the beginning of the paper). For E-1905 and E-1906, M_{cat} = 5.48 and M_{cat} = 5.64 are reported, respectively. These are compared with $M_{L,CEC}$ = 4.7 and $M_{L,CEC}$ = 5.3 for these two events, obtained here (Tab. 7). The M_L magnitudes for E-1905 differ by about 0.8 magnitude units (m. u.), and we may confidently state this magnitude is significantly overestimated in CEC, and should be revised. The magnitude of E-1906 in CEC also seems to be overestimated by more than 0.3 m. u. These overestimations are caused by exaggerated epicentral intensity for E-1905, and by apparently too large values of M_2 adopted in CEC.

The M_{LH} magnitudes in the Kárnik (1969) catalogue (M_{LH} = 5.6 for E-1905, and M_{LH} = 6.3 for E-1906, Tabs. 1 and 2) are based on data from two stations for E-1905, and four stations for E-1906. The stations used are not specified. These magnitudes are considerably higher than M_{LH} = 5.0 and M_{LH} = 5.5 estimated here for these two events (Tab. 7). The reasons for this discrepancy are not clear.

Table 7. Summary of macroseismic locations of hypocentres and estimated magnitudes for the earthquakes considered. $M_{L,CEC}$ is the average of the two proxies for the M_L as estimated here: $M_{L,CEC} = (M_{mR} + M_{L,CR})/2$.

Date	Time (hh:mm)	Latitude °N	Longitude °E	Depth km	I_{max} EMS	M_{mR}	$M_{L,CR}$	$M_{L,CEC}$	M_{LH}
09-11-1880	06:34	45.89 ± 4 km	16.06 ± 4 km	17	VIII	**6.1**	–	**6.1**	–
17-12-1905	22:16	45.92 ± 5 km	16.09 ± 6 km	10	VII	**4.9**	**4.5**	**4.7**	**5.0**
02-01-1906	04:26	45.93 ± 6 km	16.11 ± 6 km	18	VII–VIII	**5.3**	**5.3**	**5.3**	**5.5**
22-03-2020	05:24	45.90 ± 6 km	16.06 ± 6 km	5	VII	**5.1**	**5.5**	**5.3**	**5.6**

As the Kárnik (1969) catalogue is the reference for many of the strong European earthquakes from the first half of the 20th century, it is worth checking the magnitudes for important events whenever the seismograms recorded by well-calibrated instruments are available.

All three studied events were recorded only at the Göttingen station (GTT and GTTG), which enables relative comparison of their size. The Göttingen M_{LH} magnitudes for E-1905 (M_{LH} = 4.9), E-1906 (M_{LH} = 5.6) and E-2020 (M_{LH} = 5.8) (see Tab. 6) confirm, within the error of magnitude estimation, relative instrumental magnitude scaling of the three events as estimated above.

The answer to the question posed in the title: "Which of the three events was the strongest – E-1905, E-1906, or E-2020?", turns out not to be a straightforward one. With E-1905 undoubtedly identified as the weakest one, we find that the maximum intensity was larger, and macroseismic effects seem to have been more widespread for E-1906 than for E-2020, hence the former earthquake had larger macroseismic magnitude M_{mR} by 0.2. On the other hand, comparison of instrumental magnitudes for the two events, suggests that E-2020 was larger than E-1906 by about 0.1–0.2 magnitude units. Both conclusions may be challenged. Firstly, the ambiguity of historical data and perhaps uneven data quality for the two earthquakes may have significantly influenced their macroseismic magnitudes. Secondly, one could argue that instrumental magnitudes for E-1906 are available only for a very narrow backazimuth interval and only for few stations and may thus not be representative of its true magnitudes. This point could be even more important if the focal mechanisms of E-1906 and E-2020 (strike-slip *vs.* pure reverse faulting) were indeed so different. Considering both macroseismic and microseismic analyses, a unified local magnitude of $M_L = M_{L,CEC} = 5.3$ is found for both events.

However, if "the strongest earthquake in Zagreb since the Great one of 1880" is understood as the one that produced the largest effects in the centre of the city of Zagreb itself, then the shaking in 2020 was somewhat stronger than what the same city area experienced in 1906, in part probably due to larger hypocentral distance of E-1906.

The magnitudes of events E-1905 and E-1906 as currently listed in most of the relevant catalogues are considerably overestimated. Unless corrected, this fact may adversely influence seismic hazard estimates for the greater Zagreb area.

While it is proposed that the E-2020 earthquake occurred on the reverse North Medvednica boundary fault (NMBF, Fig. 4b), the locations of E-1905 and E-1906 in the immediate vicinity of the SE–NW striking Kašina fault (KF in Fig. 4b), as well as the area of the largest intensities for E-1906 being elongated in the same direction (Fig. 2), indicate that KF could have been the causative fault in that case.

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SAŽETAK

Koji je od tri posljednja velika potresa kod Zagreba bio najjači – onaj iz 1905., 1906. ili 2020. godine?

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Nakon jakog potresa 22. ožujka 2020. u Zagrebu ($M_L = 5.5$, $M_w = 5.3$, I_{max} = VII EMS), postavljeno je pitanje je li to bio najjači potres nakon Velikog zagrebačkog potresa 1880. godine (I_{max} = VIII MSK). Protukandidati su potresi od 17. prosinca 1905. i 2. siječnja 1906. za koje relevantni katalozi potresa uglavnom navode veće ili usporedive magnitude kao za potres 2020. g., i čiji su maksimalni intenziteti uglavnom unutar između VII i VII–VIII prema raznim makroseizmičkim ljestvicama. Kako bismo odgovorili na to pitanje, ponovno smo analizirali sve dostupne makroseizmičke podatke za dva povijesna potresa, prikupili očitanja iz raznih seizmoloških biltena, te smo analizirali dostupne seizmograme ta dva potresa. Makroseizmički određena lokalna magnituda (M_{mR}) procijenjena je na temelju modeliranih polumjera izoseista V EMS i VI EMS koristeći regresije izvedene za skup od 12 potresa u SZ Hrvatskoj i susjednim područjima. Utvrđeno je da je makroseizmička magnituda najveća za potres iz 1906. (M_{mR} = 5.3), a slijedi je M_{mR} = 5.1 za potres 2020. Uzimajući u obzir magnitude izračunate na temelju seizmograma s Wiechertovih instrumenata na postaji u Göttingenu (GTT) i iz objavljenih vrijednosti najvećih omjera amplitude i perioda za njemačke postaje JEN i HOH za potres 1906. godine, kao i magnitude izračunate prema širokopojasnim seizmogramima postaje GTTG i postaja hrvatske seizmografske mreže za potres 2020., za oba potresa određena je unificirana lokalna magnituda M_L = 5.3. Magnitude potresa 1905. bile su sustavno najniže. Uzimajući u obzir nepouzdanosti magnituda, potrese iz 1906. i 2020. godine treba smatrati približno jednakima. Ipak, najjaču trešnju u središtu Zagreba izazvao je potres 2020. godine. Taj se potres dogodio na reversnom Sjevernom rubnom medvedničkom rasjedu dok makroseizmički epicentri potresa 1905. i 1906. godine leže praktički na površinskom tragu obližnjeg Kašinskog rasjeda s pomakom po pružanju. Da bi Kašinski rasjed mogao biti uzročni rasjed potresa 1906. godine, sugerira i elongacija područja najvećeg intenziteta duž njegova pružanja.

Ključne riječi: kvantificiranje povijesnih potresa, makroseizmička magnituda, polumjer izoseista, seizmogrami povijesnih potresa

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Appendix – Regression procedure

In order to model theoretical macroseismic fields, we have fit the modified Kövesligethy-Jánosi formula (1) to the observed set of intensities for each calibration earthquake (Tab. 3). The modification consists of formally allowing elliptical anisotropy of the attenuation coefficient α in the epicentral region which enables modelling of the often-observed elongation of innermost isoseismals. This anisotropy is defined by the elliptical distribution of the attenuation coefficient (with the values α_a and α_b along the long and short axes, respectively), the azimuth (φ) of the long axis, and the epicentral distance (D_α) after which the medium is considered isotropic (α_b linearly tends to α_a as epicentral distance tends to D_α). The modified expression (1) is then:

$$I = I_o - k \log (r/h) - k\,\mu\,\alpha(\alpha_a, \alpha_b, \varphi, D_\alpha)\,(r - h), \qquad \text{(A1)}$$

The procedure we followed consists of the following steps:

1. Given the intensity dataset I_i, find the macroseismic epicentral coordinates using the MEEP-program as described in Herak et al. (2018, 2020).
2. Using grid-search find the parameters I_0, h, k, α_a, α_b, φ, D_α in (A1) that best fit the intensity data-points (IDP) dataset. Please note here that we do allow a wide range of those parameters and ignore possible trade-offs between them, as we do not aim to obtain the inter-earthquake consistency of parameters (*e.g.* regional k and α), but are simply looking for the set of parameters (I_0, h, k, α_a, α_b, φ, D_α) that result in the best fit to the data (r_i, I_i).
3. We define the n-th isoseismal proxy as the ($n - 0.5$)-isoline of the modelled field I_c. In this way, for instance, R_6 corresponds to the equivalent distance of isoline 5.5, which is close to what isoseismal VI EMS represents in practice.
4. Residuals $\Delta I_i = I_i - I_{ci}$ are computed between observed (I_i) and modelled (I_{ci}) intensities. In order to reduce the influence of local conditions, for each IDP we average all residuals within the 20-km distance around it, and then correct it by subtracting the average ΔI_i, thus hopefully reducing that observation to the average soil. The choice of 20 km was found by trial and error to be optimal for our dataset – for larger values local effects were mostly averaged out, whereas for the lower ones the results were overcorrected and approached the modelled field itself.
5. With IDP-s reduced to the average soil, we perform steps 1.–3. again, with I_i replaced with their reduced values, and adopt 4.5 and 5.5 isolines (ellipses) as representative proxies for isoseismals V and VI EMS. After computing areas of these ellipses (A_5 and A_6), the radii R_5 and R_6 are computed as radii of the circles with the areas A_5 and A_6, respectively.

Such a procedure proved rather robust and insensitive to reasonable variations in input parameters guiding the grid-search. Quite stable results were obtained even in cases when large azimuthal gaps existed in data, or when data were spatially limited (*e.g.* within national borders). An example is given for the earthquake of 27 March 1938 in Fig. A1.

In Fig. A1a only data from part of Croatia between the Sava river and Hungary are used to derive the radii R_5 and R_6, and Fig. A1b shows the fitted isoseismals for the case when also data from Hungary are considered. The difference in results is about 5% for R_6 and 8% for R_5, which is practically negligible as logarithms of the radii are relevant in the context of expression (2).

The above procedure yielded for each of the 12 calibration events the radii R_5 and/or R_6, presented in Table 3. Together with their magnitudes M_L they form pairs (R_5, M_L) and (R_6, M_L), which are used to calibrate expressions:

$$M_L = a_5 \log(R_5) + b_5$$

$$M_L = a_6 \log(R_6) + b_6, \qquad \text{(A2)}$$

where the parameters $a_{5,6}$ and $b_{5,6}$ must be found by regression of R_5 and M_L (or R_6 and M_L). As both variables have errors, an ordinary least-squares regression is not applicable. We therefore chose to perform the York regression (York et al.,

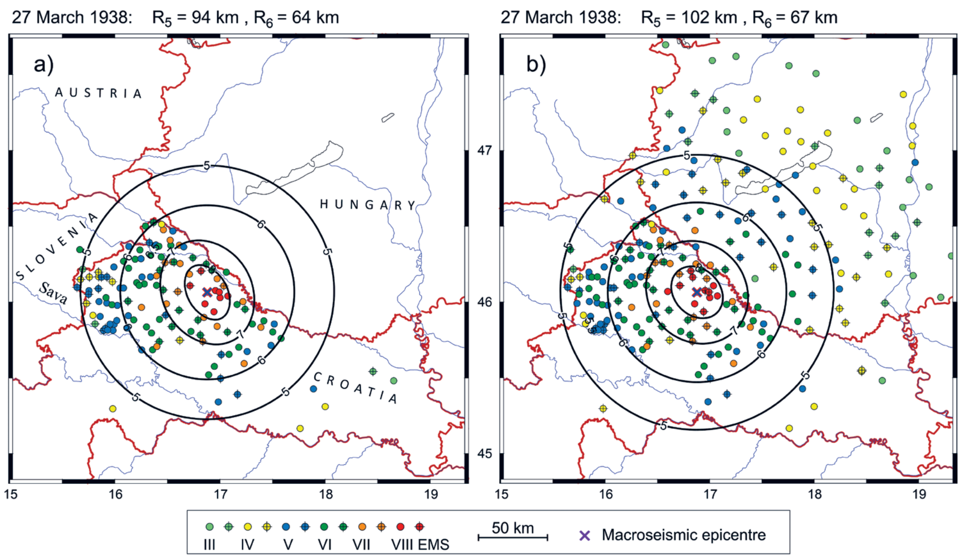

Figure A1. Intensities for the Bilogora Mt. earthquake of 27 March 1938, observed in part of Croatia (*a*), and with Hungary dataset (CSFK-GGI, 2020) merged (*b*). Modelled isoseismals V, VI, VII and VIII are shown as black ellipses/circles and the results for the radii *R*5 and *R*6 are given above the figures.

2004), a general orthogonal regression algorithm that allows specifying individual standard errors in both variables (Matlab program by T. Wiens, 2010). As standard errors of individual magnitudes (σ_M) are not specified in CEC, we made an educated guess (see also Herak, 2020), as presented in Table 3. The errors of the $\log(R_{5,6})$ also had to be assumed based on experience and the quality of input data (see Table 3). To make the choice reproducible we conservatively defined $\sigma(\log R_n)$ (with n = 5 or 6) as:

$$\sigma(\log R_n) = 0.1(1 + 0.2q_1)\,(1 + 0.2q_2)\,(1 + 0.2q_3). \qquad \text{(A3)}$$

Here:

For $n = 5$: $q_1 = 2$ for $N_5 < 20$, $q_1 = 1$ for $20 \le N_5 < 50$, $q_1 = 0$ for $N_5 \ge 50$; N_5 – number of intensities $I_i \ge$ IV–V EMS;

For $n = 6$: $q_1 = 2$ for $N_6 < 10$, $q_1 = 1$ for $10 \le N_6 < 25$, $q_1 = 0$ for $N_6 \ge 25$; N_6 – number of intensities $I_i \ge$ V–VI EMS;

$q_2 = 1$ if $(I_{max} - n) < 2$, $q_2 = 0$ if $(I_{max} - n) \ge 2$;

$q_3 = 2$ for years before 1950, and $q_3 = 0$ afterwards.

q_1 assumes better confidence for more numerous datasets, q_2 gives more weight to isoseismal radii corresponding to intensities away from the meisoseismal area (and thus less influenced by the focal depth), whereas q_3 prefers more recent datasets, *i.e.* those with hopefully more data based on direct evidence from field work, available questionnaires, *etc.* In this way the least *a priori* standard error $\sigma(\log R_n) = 0.10$ (corresponding to the uncertainty in the radius of about 25%) is assumed for strong earthquakes ($I_{max} \ge$ VIII EMS), that occurred after 1950, and the number of IDPs is high. The largest standard errors $\sigma(\log R_n) = 0.17$ (corresponding to the uncertainty in the radius of about 50%) are assigned to weak events with few data.

The regressions resulted in [expresions (3) again, see also Fig. 5]:

$$\mathrm{M}_{m5} = (1.938 \pm 0.350)\log(R_5) + (1.675 \pm 0.522); \quad r^2 = 0.85; \; s = 0.28, \qquad (3)$$

$$\mathrm{M}_{m6} = (1.835 \pm 0.395)\log(R_6) + (2.345 \pm 0.523); \quad r^2 = 0.94; \; s = 0.16. \qquad (4)$$