Assessing the completeness of historical and instrumental earthquake data in Austria and the surrounding areas

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Abstract

In regions with long historical earthquake records, seismic hazard assessments are additionally challenged by the large uncertainties related to the available pre-instrumental data. A major source of uncertainty is the incompleteness of historical earthquake records. Therefore, an important step in seismic hazard assessment is the check of completeness for different intensity levels and the removal of aftershock sequences. Mainly two different approaches have been proposed for checking the completeness of seismic catalogues: the temporal course of earthquake frequency (TCEF), and a completeness check based on statistical analysis of the mean earthquake recurrence interval for varying time windows. We systematically compared the effects of the different methods on the Gutenberg-Richter relation (GR-relation), as well as the influence of removing fore- and aftershocks.

For that purpose we created and declustered a new composite catalogue for Austria, the Vienna Basin and a 100 km wide region outside the boundaries of Austria and Vienna Basin based on four different earthquake catalogues. We can show that the a- and b-values for the GR-relations derived from different completeness analyses depend on the correction method used. Corrections with the TCEF seem to produce lower a- and b-values. The Stepp method, on the other hand, excludes the highest intensity class (I_0 =X) and tends to calculate lower a- and b-parameters. Based on these results, we prefer the latter.

Both completeness methods have further been applied to a subset of the composite catalogue corresponding to a source zone including the active Vienna Basin fault system. Comparison shows that completeness of the entire dataset is apparently overestimated.

Die Unvollständigkeit von historischen Erdbebenaufzeichnungen ist ein wesentlicher Unsicherheitsfaktor bei der Bestimmung der Erdbebengefährdungen in Regionen, in denen der größte Teil der aufgezeichneten Erdbeben aus historische Daten stammt. Ein wichtiger Schritt der Gefährdungsanalyse ist daher die Abschätzung der Vollständigkeit der vorhandenen Erdbebenaufzeichnungen für einzelne Intensitätsklassen. In den meisten Fällen wird die Vollständigkeit der Erdbebenkatalogen mit einer der zwei folgenden Methoden bewertet: der TCEF-Methode (Temporal Course of Earthquake Frequency; kumulative Anzahl der Erdbeben pro Intensitätsklasse), und dem Stepp Test, eine statistische Überprüfung der Vollständigkeit auf Basis der mittleren Wiederholungsintervalle von Erdbeben für unterschiedliche Zeitfenster. Unser Artikel enthält einen systematischen Vergleich der Ergebnisse der beiden Tests und ihrer Anwendung für die Erstellung einer Gutenberg-Richer-Funktion (GR). Weiters wird der Effekt der Entfernung von Vor- und Nachbeben aus dem Erdbebendatensatz untersucht.

Bei diesem Vergleich verwenden wir einen neu zusammengestellten Erdbebenkatalog, der Österreich, das Wiener Becken außerhalb Österreichs, und eine 100 km breite Zone um diese Region erfasst. Vor- und Nachbeben wurden aus dem Datensatz manuell eliminiert. Wir können zeigen, dass die Korrektur der Unvollständigkeit der Erdbebendaten nach Anwendung des TCEF-Tests und des Stepp Tests zu GR-Funktionen mit unterschiedlichen a- und b-Werten führt. Aus der TCEF-Korrektur ergeben sich kleinere a- und b-Werte. Der Stepp Test führt zu tendenziell höheren a- und b-Werten, da die höchste Intensitätsklasse (I_0 =X) durch den Test als unvollständig kategorisiert und somit nicht berücksichtigt wird. Aufgrund des durchgeführten Vergleichs bevorzugen wir die letztgenannte Korrekturmethode.

Beide Korrekturen werden in einem zweiten Schritt auf ein Teilgebiet des Gesamtdatensatzes angewandt, das der seismischen Quellzone des Wiener Becken-Störungssystems entspricht. Der Vergleich der Vollständigkeit der Daten aus diesem Teilgebiet zeigt, dass beide Analysemethoden die Vollständigkeit des Gesamtdatensatzes überschätzen.

1. Introduction

Earthquake catalogues are the most important seismological product in regions such as Central Europe, where earthquake hazard assessments exclusively rely on the analysis of historical and instrumental earthquake data (Lenhardt, 2007; Grünthal et al., 1998; 1999). Catalogues of historical and instrumental data are used for estimations of the mean annual rate of seismic activity and the determination of seismicity parameters, such as the magnitude-frequency relation coefficients (a- and b-values) in the corresponding Gutenberg-Richter relation.

Due to various reasons, historical and even instrumental data ,records are by their nature incomplete. It is therefore important that seismic hazard analysis accounts for this deficiency. The reasons for incomplete historical earthquake data are discussed by Gutdeutsch and Hammerl (1997, 1999), who defined a record threshold for historical earthquakes. For historical times, this threshold depends on the local intensity of a historical event as well as on a various other factors such as the past population density, the presence, interest and motivation of chronologists who could take note of the event, as well as social and political circumstances and other natural disasters distracting attention from earthquakes. The incompleteness of instrumental data may be due to the geometry and coverage of the seismic network, or malfunction of seismic stations. An example is the destruction of the seismographs installed at the ZAMG in Vienna during the Second World War (Hammerl et al., 2001). A thorough assessment of the data completeness is therefore a prime prerequisite for any hazard evaluation.

Several methods have been proposed to assess the intensity/magnitude above which an earthquake catalogue can be considered as reasonably complete, or alternatively to assign time intervals in which a certain intensity/magnitude range is likely to be completely reported (Stepp, 1972; Mulargia and Tinti, 1987; Grünthal et al., 1998; Stucchi et al., 2004; Wössner and Wiemer, 2005). These assessments are used for determining the completeness of the analyzed catalogues and for estimating corrected occurrence rates for earthquakes of different intensity/magnitude classes, which are then used to define intensity/magnitude-frequency relations.

Accordingly, the purpose of the study presented here is twofold. Firstly, we evaluate the completeness of earthquake records in the Central European region covering Austria and the Vienna Basin. For that, we use firstly the TCEF method (temporal course of earthquake frequency) because it is the most commonly used in Germany and Austria (e.g. Lenhardt., 1996). For comparison, we additionally assess the completeness of this data set by using the statistical approach proposed by Stepp (1972). Secondly, we use these new data to determine the effects of different correction methods on intensity-frequency relations. The results of this sensitivity study will be presented in terms of a- and b-parameters of Gutenberg-Richter relation. Finally, we compare the results of completeness analyses derived from the regional dataset (Austria, the Vienna Basin including its extension into the Czech Republic and

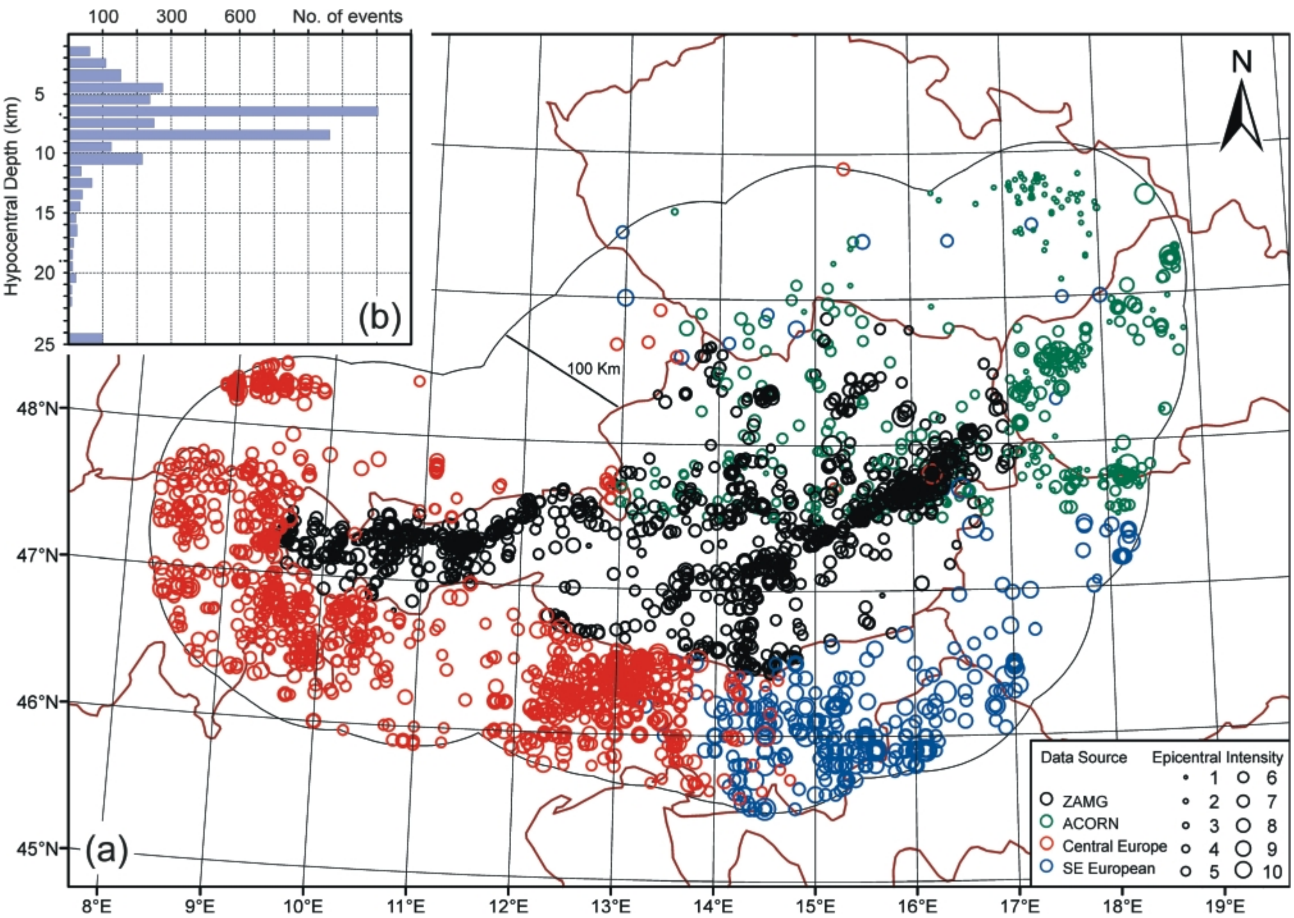

FIGURE 1: 1a. Compiled catalogue for Austria, the Vienna Basin and a 100 km wide region outside the boundaries of Austria and Vienna Basin (1048 -2009 AD). The intensity range is from II – X. Colours indicate the coverage of the different earthquake catalogues used for this study. (Black) ZAMG Catalogue of Felt Earthquakes (1201- 2009 AD). Data cover the area within the boundary of Austria. The intensity range is from III - IX (ZAMG, 2010); (Green) ACORN Earthquake Catalogue (1267 – 2004 AD) with an intensity range from II - VIII (Lenhardt et al., 2007); (Red) European Earthquake Catalogue for Austria and a 100 km buffer area outside the boundary of Austria (479BC - 1981 AD). The intensity range is from III - X (Van Gils and Leydecker, 1991). (Blue) Southeast European Earthquake Catalogue (342BC – 1990AD). The intensity range is from III – IX (Shebalin and Leydecker, 1998). 1b. Hypocentral depth of the region under consideration which is characterized by shallow seismicity with 90% of all events occurring in the upper crust at hypocenter depths above 12 km.

Slovakia, and a 100 km wide bounding region) to completeness analyses of a sub-sample of the region. The sub-sample has the size of a typical seismic source zone used in seismic hazard assessment and corresponds to a source zone, which may be defined for the active Vienna Basin Fault System.

2. Database: Composite earthquake catalogue

Seismicity in Austria and most of the surrounding areas is dominated by earthquakes of small to medium intensity. Earthquakes with intensities as low as I_0 =IV must be therefore taken into account for the assessment of the seismic potential and finally the seismic hazard of this region. Existing compilations of trans-national earthquake catalogues (Van Gils and Leydecker, 1991; Grünthal et al., 2009) do not meet these specific requirements. The CENEC catalogue (Grünthal et al., 2009) only lists earthquakes with Mw ≥ 3.5. Following the conversions from the originally given epicentral intensity (I_0) into moment magnitude (Mw) used by the authors, events with an epicentral intensity I_0 ≤IV-V would be associated with magnitudes in the range of 2.9 ≤ Mw ≤ 3.9, considering hypocentral depths down to 25 km (see Fig. 1b). Therefore, most events within this intensity class are eliminated in the CENEC catalogue. At this background it was decided to compile a new database, which includes all events recorded in the area of interest.

The composite catalogue used for further analyses includes Austria, a 100 km wide region beyond the national borders and the Vienna Basin Fault System in the Czech and Slovak Republic (Fig. 1a). It is compiled from four different catalogues (ZAMG, 2010; ACORN, 2004; Van Gils and Leydecker, 1991; Shebalin and Leydecker, 1998). In these catalogues the quality of entries for different areas and time periods varies significantly with respect to completeness, reliability of intensity/ magnitude, homogeneity and location accuracy.

The ZAMG (2010) catalogue of felt earthquakes includes earthquakes within the national boundaries of Austria (black circles in Fig. 1a). This catalogue contains 2089 earthquakes covering the period from about 1000 until 2009 AD. The minimum intensity is III and maximum intensity is IX. This catalogue is the most complete available and includes results of careful systematic historical investigations (Hammerl et al., 2002; Hammerl, 2007). The events included in the composite earthquake catalogue within Austria are almost entirely based on the ZAMG catalogue.

The ACORN catalogue covers a rectangular region encompassing the Eastern Alps, West Carpathians and the Bohemian Massif (Czech Republic, Slovakia, Hungry and Austria; Lenhardt et al., 2007). The data set includes 1105 earthquakes from the time period between 1600 to 2004 AD. The compiled catalogue includes 607 events from ACORN, which are located in the area of interest outside of Austria (i.e., mainly the NE part of the Vienna Basin). The intensity range is from II to IX. Earthquakes from this catalogue are shown as green circles in Fig. 1a.

Earthquake data in the adjacent region of 100 km outside of the Austrian territory in Germany, Switzerland and Italy are taken from the catalogue for European countries (Van Gils and Leydecker., 1991). The catalogue is used regardless of its known inherent inaccuracies as no other suitable data be-

(a) Examples of duplicate removed from the composite earthquake catalogue

Year	Mon	Day	Hour	Min	Sec	Lat.	Long.	Z	M	I_0	Epicenter	Country	Catalogue
1979	5	1	23	32	0	47.26	11.53	6	2.90	5	Tulfes/Innsbruck	A	ZAMG
1979	5	2	0	32	0	47.20	11.55	6	2.90	5	Tyrol	A	European
1980	11	10	23	58	0	47.26	11.43	4	1.80	4	Innsbruck	A	ZAMG
1980	11	11	0	58	0	47.25	11.40	4	1.80	4	Tyrol	A	European
1981	4	12	23	18	47	47.79	16.35	4	1.80	4	Burgenland	A	ZAMG
1981	4	13	0	18	47	47.80	16.30	4	1.80	4	Burgenland	A	European
(b) Earthquakes on Austrian territory from Van Gils and Leydecker (1991)													
1468	2	0	0	0	0	47.80	16.20	10	5.20	8	Lower Austria	A	European
1907	7	21	22	42	0	47.70	15.20	-	3.33	5	Styria	A	European
1917	11	2	22	5	0	47.30	11.50	-	3.33	5	Tyrol	A	European
1928	2	19	0	30	0	47.60	15.80	-	2.67	4	Styria	A	European
1945	12	25	21	25	0	47.20	11.40	-	3.33	5	Tyrol	A	European

Table 1: (a) Examples of duplicate earthquakes listed in the ZAMG earthquake catalogue and European earthquake catalogue. In the composite catalogue priority is given to the data provided by ZAMG. The grey shaded events have been removed from the composite catalogue. (b) Earthquakes on Austrian territory from the catalogue by Van Gils and Leydecker (1991). The events are considered in the completeness analysis.

came available. The database lists events for the years 479 BC - 1981 AD with intensities equal or higher than IV. The maximum intensity is X. In total, 1950 events were taken from this catalogue (red circles in Fig. 1a).

The earthquake catalogue for Central and Southeastern Europe (Shebalin and Leydecker, 1998) served as a base for compiling the seismicity in the 100 km bounding area around Austria in Slovenia, Croatia and Hungary. Seismic events from this catalogue are shown as blue circles in Fig. 1a. The catalogue covers the time period from 342 BC to 1990 AD. The compiled dataset includes 472 data from that catalogue with intensities between III and IX.

During the compilation of the regional dataset, the following priority has been given to the source data: ZAMG earthquake catalogue followed by the ACORN database, the European earthquake catalogue and the SE-European earthquake catalogue. Combining the listed earthquake catalogues resulted in some duplicate events, which have been removed manually. Events which are listed with same longitude, latitude and intensity but with a time difference of one hour in the ZAMG/ ACORN and European catalogues were also considered as duplicates and removed. Examples of such events are shown in Table 1a. In those cases, priority is given to the ZAMG and ACORN catalogues. From European and SE-European earthquake catalogues, five events have been taken for the Austrian territory, which are not listed in the ZAMG or ACORN catalogues (Tab. 1b).

The regional compilation for Austria, the Vienna Basin including its extension into the Czech Republic and Slovakia, and a 100 km wide bounding region resulted in a database of 5616 earthquakes with intensities between III to X between 1048 and 2009 AD. The distribution of seismicity and the temporal distribution of earthquake records according to the composite clustered catalogue are shown in Fig. 1a and 2, respectively.

3. Catalogue Declustering

The recognition and removal of fore- and aftershocks from the raw catalogue is a prerequisite for assessing catalogue completeness because of the general assumption that earthquakes are Poissonian-distributed and therefore independent of each other (e.g. Gardner and Knopoff, 1974; Shearer and Stark, 2011). Declustering removes dependent events such as foreshocks, aftershocks and swarm events except for the largest event in each swarm. Including these events in the database otherwise leads to major deviation from a Poissonian distribution (Gardner and Knopoff, 1974; Keilis-Borok et al., 1982; Molchan and Dmitrieva, 1992; Öncel and Alptekin, 1999).

The number of events removed by declustering is affected by the size of the main shock (Omori, 1900, Utsu et al., 1995). Typically, events that occur within a given time interval and a

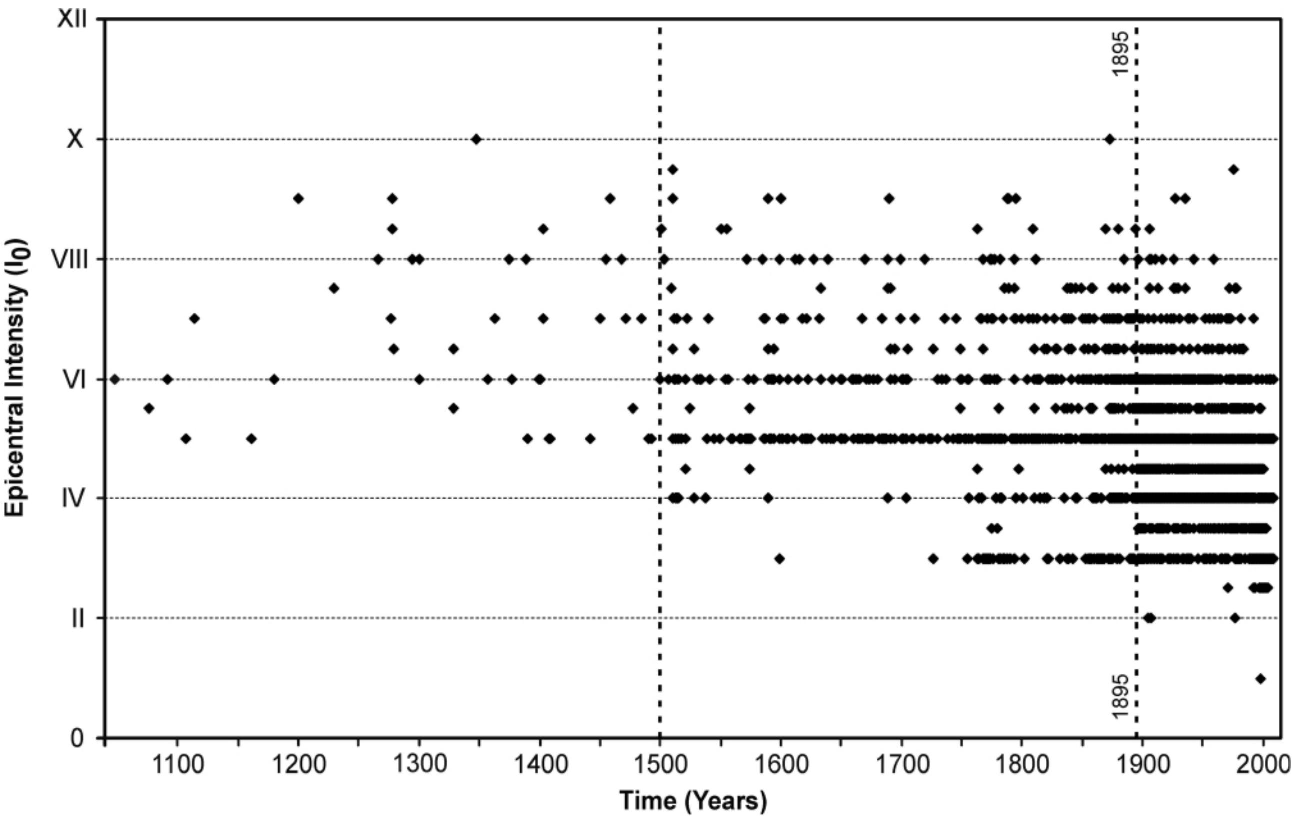

Figure 2: Intensity vs. time plot of the earthquakes listed in the clustered composite catalogue (1048 – 2009, Fig. 1a). Note the apparent increase of records around 1500, which is due to the increased number of historical chronicles available from that time onwards (Rohr, 2007, p. 118), and the major increase of earthquake records at about 1900 related to the start of systematic macroseismic data collection in the former Austro-Hungarian empire after the earthquake of Ljubljana (1895) and the installation of Wiechert seismographs (1903, 1905).

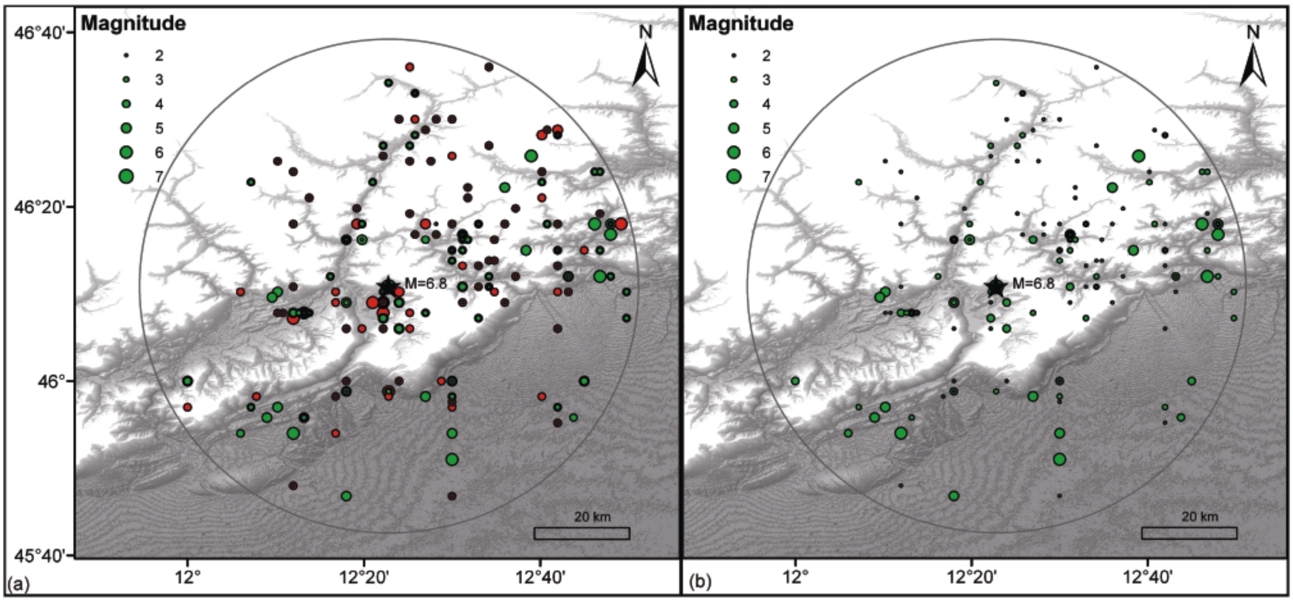

Figure 3: Determination of aftershocks of the 1873 Belluno M = 6.8 earthquake. The epicenter of the main shock is marked with star symbol. The largest distance of potential aftershocks from the mainshock is about 40 km (grey circle; see also Tab. 2). Background image is showing the DEM of the region. (a) Clustered catalogue. Aftershocks of the 1873 Belluno M = 6.8 earthquake are marked in red. (b) Declustered composite catalogue within the spatial window of the 1873 Belluno M = 6.8 main shock. The remaining events occurred outside the aftershock time window (see Fig. 4).

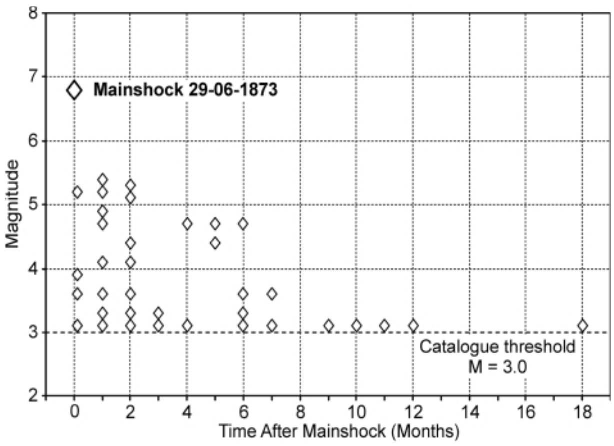

Figure 4: Aftershock sequence of the 1873 Belluno M = 6.8 main shock in the temporal window defined by the algorithm of Gardner and Knopoff (1969). The aftershock sequence of this earthquake lasted for about 18 months and includes 72 events.

Magnitude	Radius (km)	Time (days)
4.5	10	83
5.0	10	155
5.5	10	290
6.0	12	510
6.5	26	790
7.0	54	915

Table 2: Magnitude-dependent time (days after the main shock) and space windows (radius of a circle around the epicentre) used for the identification of aftershocks. Space windows follow the equation Log (Radial Distance in km) = (M - 4.32)/1.54 (Wells and Coppersmith, 1994) with a minimum radius set to 10 km. The duration of the time window is taken from Gardner and Knopoff (1969).

given distance of a larger event are regarded as dependent, where the time interval and distance vary with magnitude (Gibson and Brown, 1999). Fore- and aftershock identification in our study applies the spatial and temporal windows shown in Table 2. Both, the epicentral distance from the main shock and the time (days after/before main shock), are scaled according to the main shock moment magnitude taken from the corresponding original catalogue. The maximum epicentral distance of fore- and aftershocks from the main shock is derived from Wells and Coppersmith (1994). For historical events, the epicentral distance was increased by a factor of two in order to account for inaccurate epicenter locations. For the same reason, the minimum distance is fixed to 10 km, being the approximate hypocenter uncertainty for pre-instrumental earthquakes during the 20th century (Gangl and Decker, 2011). The duration of fore- and aftershock sequences is taken from Knopoff and Gardner (1969). All earthquakes within the defined spatial and temporal windows were identified as fore- and aftershocks and manually removed from the composite catalogue.

The 1873 Belluno earthquake (I_0 =X, M =6.8) is shown as an example of the declustering procedure. Fig. 3 shows the radial length of aftershock sequence from the main shock according to Table 2 (about 40 km for M =6.8), while the duration of the aftershock sequence of about 18 months is shown in Fig. 4. In total, 72 events have been identified as aftershocks including four events with VII< I_0 ≤VIII and seven earthquakes with VI< I_0 ≤VII (catalogue data from Van Gils and Leydecker, 1991). The analysis of the 1873 Belluno earthquake sequence further shows that its aftershock sequence accounts for about 20% of the seismicity recorded in the entire area. In total, 161 out of 373 earthquakes in this area have been identified as aftershocks of larger earthquakes, accounting for more than 40% of the recorded seismicity. This example demonstrates the large influence of strong single events and their fore- and aftershocks on the seismicity of regions of low and moderate seismicity, and Austria in detail.

Manual declustering of the raw catalogue resulted in the removal of 1633 events with intensities between III and VIII. The declustered catalogue, cleaned of aftershocks and foreshocks, is used for completeness assessments of the regional seismicity parameters.

4. Assessing Catalogue Completeness

Two completeness analyses are performed on the composite and declustered catalogues in order to assess the differences resulting from both methodological approaches in terms of recurrence intervals and GR parameters. In order to avoid ambiguities arising from different intensity-magnitude conversions the following computations and comparisons are made for intensity. The use of intensity data in Gutenberg-Richter plots appears to be justified by the fact that the region under consideration is characterized by shallow seismicity with 90% of all events occurring in the upper crust at hypocenter depths above 12 km (Fig. 1b). Even if the depth determination for historical earthquakes might not be very accurate, the instrumentally recorded earthquakes show similar depth distribution and underscore our assumption.

4.1 Temporal course of earthquake frequency (TCEF)

TCEF is a common method applied in Central Europe to check the completeness of records for single intensity classes (e.g. Lenhardt, 1996). Data completeness levels are estimated from the earthquake catalogue using plots of the cumulative number of events of a certain intensity class versus time. Slope changes in the graphs indicate changes of the completeness of the catalogue. It is commonly assumed that the most recent change in slope occurs when the data became complete for each intensity class (Gasperini and Ferrari, 2000). Recurrence intervals are computed for the time interval corresponding to the linear segments of the curves, whose corresponding epicentral intensity data are considered complete.

Representation of the TCEF for single intensity classes in Austria and surrounding Central Europe is shown in Fig 5. Inspection of the curves shows significant increases of slopes for earthquakes with I_0<VII around 1900. This dramatically in-

TCEF Declustered Catalogue

I_0	T (years)	N	No
III < I_0 = IV	114	1357	21999
IV < I_0 = V	152	1178	10548
V < I_0 = VI	155	360	3093
VI < I_0 = VII	191	130	858
VII < I_0 = VIII	242	38	204
VIII< I_0 = IX	247	12	53
IX < I_0 = X	662	4	6

Table 3: Rate of earthquake occurrence for different intensity classes using the TCEF completeness check for the declustered composite catalogue. T: time period (completeness period) for which the catalogue is considered to be complete for an intensity class. N: number of recorded earthquakes of an intensity class within the completeness period T. No: cumulative number of earthquakes with intensities ≥ I_0 extrapolating the recurrence intervals derived for the completeness time period T to the total length of the catalogue (962 years between the first data entry and 2010).

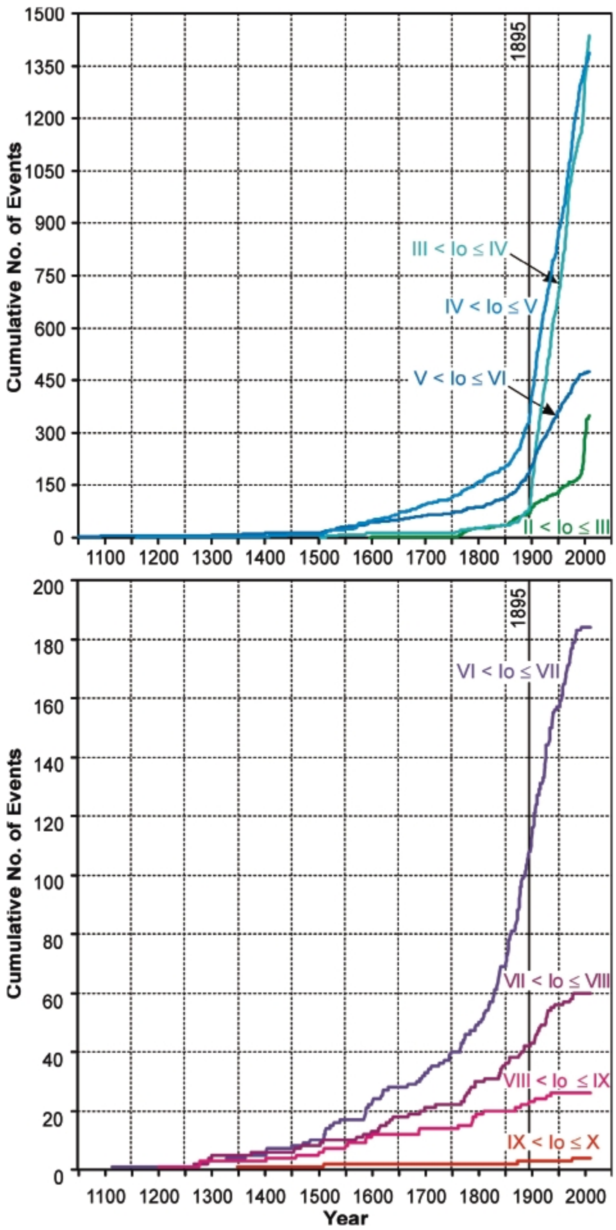

Figure 5: Temporal course of earthquake frequency (TCEF) for different intensity classes of the declustered composite catalogue. Recurrence intervals are computed for the time interval corresponding to the steepest slope of the curves. Note the significant increase of the record rate for events with I_0 = IV to VI subsequent to the earthquake of Ljubljana, 1895. Apparent plateaus of the graphs after 1990 are related to the different record lengths of the source catalogues. Note the different scales of cumulative event numbers on the upper and lower panel.

creased recording is related to the start of systematic macroseismic documentation in the former Austrian-Hungarian Empire after the earthquake of Laibach/Ljubljana in 1895 (I_0 =VIII-IX; Suess, 1887). The earthquake led to the appointment of a committee for seismology in 1895 (Erdbebenkommission der

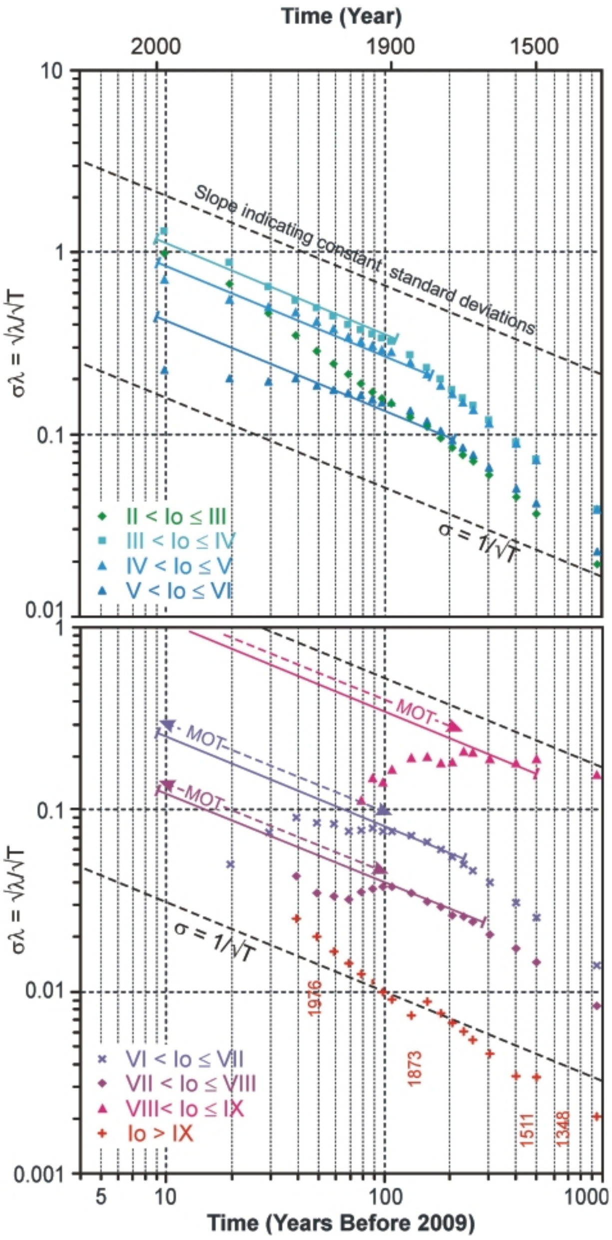

Figure 6: Completeness periods for different intensity classes determined by the method of Stepp (1972). The Stepp Test investigates the stability of the mean rate of occurrence (λ) of events in a series of time periods (T). If λ is constant, then the standard deviation (σ) varies as 1/√T, if λ is not stable, σ deviates from the straight line of the 1/√T slope. The length of the time interval at which no deviation from that straight line occurs defines the completeness period for the given intensity range. Dashed arrows in the lower diagram indicate the minimum observation time (MOT) required for deriving reliable average recurrence intervals for the intensity class indicating that ~100 years observation are required for VI < I_0 ≤ VIII and ~250 years for VIII < I_0 ≤ IX. For the intensity class I_0 > IX only four events are reported (Friuli/"Villach", 1348; Slovenia, 1511; Belluno, 1873; Friuli, 1976). A completeness time period with stable σ cannot be determined for the intensity class I_0 = X.

Kaiserlichen Akademie der Wissenschaften) and the installation of the first national seismographs in Pribram (1903) and Vienna (1905; Hammerl et al., 2001). Apparent plateaus of the curves in the last years, especially for smaller intensities, are related to the different recording lengths of the used catalogues. The earthquake recurrence intervals for different intensity classes are derived for the time interval of the graph showing the steepest slope (Table 3, Fig. 5). Results indicate that the time of complete records increases from 16 years for the intensity class II <I_0 ≤III to about 250 years for VIII <I_0 ≤IX. The slope of the graph for XI< I_0 ≤X is only defined by four single events giving rise to significant uncertainties for estimating the average recurrence interval of such events. Data of II <I_0 ≤III are not regarded complete even after TCEF correction, as the source catalogues have different threshold intensities and the ACORN catalogue is the only catalogue covering the II< I_0 ≤III intensity class.

4.2 Stepp (1972) completeness analysis (Stepp Test)

The Stepp Test (Stepp, 1972) has been used in numerous studies to obtain time intervals for which the recorded data is considered to be complete (Bollinger, 1973; Cuthbertson, 2006; Bus et al., 2009). The test relies on the statistical property of the Poisson distribution highlighting time intervals during which the recorded earthquake occurrence rate is uniform. Supposing that earthquake occurrences follow a Poisson distribution, the Stepp Test evaluates the stability of the mean rate of occurrences (λ) of events which fall in a predefined intensity range in a series of time windows (T). If λ is constant, then the standard deviation (σ) varies as 1/√T. On the contrary, if λ is not stable, σ deviates from the straight line of the 1/√T slope. The length of the time interval at which no deviation from that straight line occurs defines the completeness time interval for the given intensity range (Stepp, 1972; Fig. 6). This interval is visually determined from the plots. The test further evaluates the minimum observations length needed for establishing reliable average recurrence intervals for events of a certain intensity class (Fig. 6).

The completeness periods for various intensity classes of the declustered composite catalogue are analyzed for the time between 1048 (first data entry in the catalogue) and 2009 (962 years) using 21 time windows of different length (Fig. 6). Time windows were selected according to the number of earthquakes listed in the catalogue with 10 year time windows covering the period between 1900 and 2009. The time before 1900 is covered by windows of 25 years (1899–1750), 50 years (1749–1700), 100 years (1699–1500) and 452 years (1499–1048). The corresponding completeness time interval is estimated manually from the parts of the curves following the 1/√T slope as shown in Fig. 6. Table 4 summarizes the number of earthquakes of different intensity classes and corresponding completeness time intervals T of the declustered catalogue for I_0 = IV to IX. Completeness of records for the intensity class II < I_0 ≤III is not reached at any time. The results of the Stepp

Intensity	Clustered Catalogue			Declustered Catalogue		
I_0	T (years)	N	No	T (years)	N	No
III < I_0 = IV	1875-2009	1787	24790	1875-2009	1329	18666
IV < I_0 = V	1850-2009	1551	12056	1850-2009	1145	9196
V < I_0 = VI	1750-2009	523	2730	1775-2009	383	2312
VI < I_0 = VII	1700-2009	198	795	1775-2009	138	744
VII < I_0 = VIII	1500-2009	72	181	1750-2009	39	179
VIII< I_0 = IX	1600-2009	17	45	1600-2009	13	35
IX < I_0 = X	N/A	5	N/A	N/A	4	N/A

Table 4: Rate of earthquake occurrences for different intensity classes derived from the Stepp Tests of the clustered and declustered composite catalogue (Stepp, 1972). Note that declustering re-sults in significantly less events for smaller intensity classes. Intensity class IX < I_0 ≤ X is excluded since no completeness time period can be determined for this class. See text for more information. T: time period (completeness period) for which the catalogue is considered to be complete for an intensity class. N: number of recorded earthquakes of an intensity class within the completeness period T. No: cumulative number of earthquakes with intensities ≥ I_0 extrapolating the recurrence intervals derived for the completeness time period T to the total length of the catalogue (962 years between the first data entry and 2010).

Test further prove that the occurrence rate of the intensity class XI< I_0 ≤X is not stable for any time interval (Fig. 6) as the 962 years observation period is too short for constraining a stable average recurrence interval for the highest intensity class in the sample with reasonable accuracy.

5. Applying completeness analyses to a sub-region: the Vienna Basin

We applied the methodology described above to a sub-region in order to check whether the completeness time intervals derived for the whole catalogue are appropriate for sub-samples of the area or not. The evaluation is done for an area along the Vienna Basin Fault System (Decker et al., 2005; Beidinger and Decker, 2011), which could be defined as a source zone for seismic hazard assessment. The analyzed source zone is defined as that area where the active fault system separates into several fault splays, i.e. approximately between the cities of Gloggnitz (Austria) and Nove Mesto nad Váhom (Slovakia). The extent of the source zone as well as the local earthquake data for this source zone is shown in Fig 7. After declustering, the dataset comprises 707 earthquakes with epicentral intensities between II and IX occurring between 1468

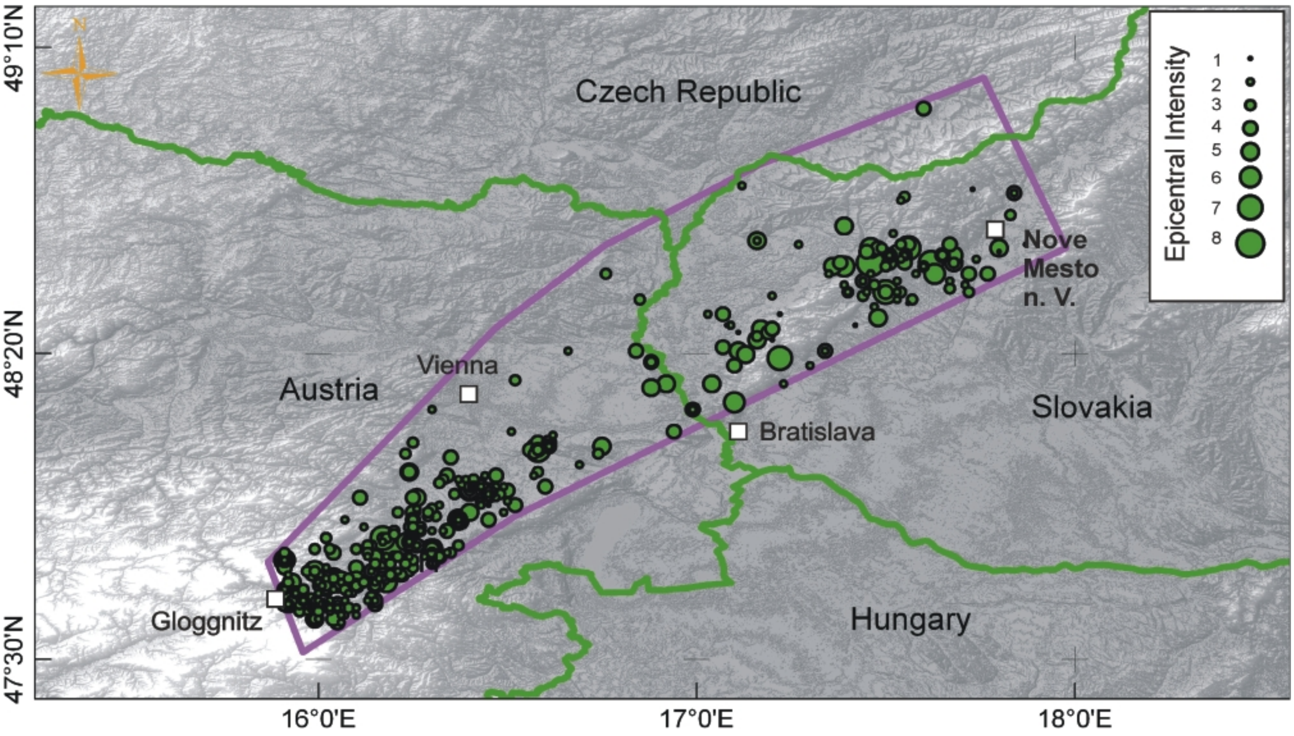

Figure 7: Seismicity recorded in the Vienna Basin source zone (Austria and Slovakia). The composite catalogue comprises 707 earthquakes with epicentral intensities II to IX in the time between 1468 and 2009 AD.

Intensity	Whole Region (Declustered Catalogue)			Vienna Basin Source Zone		
I_0	T (years)	N	No	T (years)	N	No
III < I_0 = IV	1896-2009	1357	21999	1923-2009	185	2061
IV < I_0 = V	1858-2009	1178	10548	1963-2009	65	922
V < I_0 = VI	1855-2009	360	3093	1952-2009	12	172
VI < I_0 = VII	1819-2009	130	858	1929-2009	6	61
VII < I_0 = VIII	1768-2009	38	204	1905-2009	4	21
VIII< I_0 = IX	1763-2009	12	53	1468-2009	1	1
IX < I_0 = X	1348-2009	4	6	N/A	N/A	N/A

Table 5: Earthquake occurrence rates for different intensity classes derived from TCEF completeness corrections. The table compares the completeness periods derived for the declustered composite catalogue of the whole region and the Vienna Basin source zone. Note that completeness periods for the Vienna Basin Source Zone are significantly shorter than those derived for the whole region. T: time period (completeness period) for which the catalogue is considered to be complete for an intensity class. N: number of recorded earthquakes of an intensity class within the completeness period T. No: cumulative number of earthquakes with intensities ≥ I_0 extrapolating the recurrence intervals derived for the completeness time period T to the total length of the catalogue between the first data entry and 2010 (962 years for the declustered composite catalogue and 542 years for the Vienna Basin source zone). There are no records of earthquakes with I ≥ IX for the Vienna Basin source zone.

and 2009. We consider this number of seismic events large enough for statistical analysis.

The analysis of the completeness time intervals for different intensity classes using the Stepp Test uses fourteen time windows of different lengths covering the period of 542 years between 1468 and 2009 (Fig. 8). The results indicate that different intensity classes are considered to be complete from the following years up to 2009: intensity classes III< I_0 ≤IV and IV< I_0 ≤V starting with 1900, V< I_0 ≤VI and VI <I_0 ≤VII from 1800 onwards, and finally, VII< I_0 ≤VIII for the complete time interval covered by the catalogue since 1468. Tables 5 and 6 compare the completeness time intervals obtained for the entire area with those obtained for the Vienna Basin source zone using TCEF and the Stepp Test. Data show that the completeness time intervals obtained for the subregion are significantly shorter than the estimates derived for the whole region. This result strongly suggests that completeness time intervals obtained for the sub-region are significantly shorter than those of the whole dataset.

TCEF analysis of the data from the Vienna Basin supports this interpretation. Time frequency curves show significant increases of slopes around 1900 for all intensity classes, but also several inconsistencies in the slopes after 1900 (Fig. 9). The graphs show that records of events up to intensity VI (eventually even up to VII) are not complete for the 20th century. This is well illustrated by the number of independently recorded earthquakes from the declustered catalogue for V< I_0 ≤VI showing 9 events in the period 1890-1914, only one record be-

Intensity	Whole Region (Declustered Catalogue)			Vienna Basin Source Zone		
I_0	Time(Years)	N	No	Time(Years)	N	No
III < I_0 = IV	1875-2009	1329	18666	1900-2009	246	1957
IV < I_0 = V	1850-2009	1145	9196	1900-2009	129	745
V < I_0 = VI	1775-2009	383	2312	1800-2009	29	110
VI < I_0 = VII	1775-2009	138	744	1800-2009	11	35
VII < I_0 = VIII	1750-2009	39	179	1468-2009	7	7
VIII< I_0 = IX	1600-2009	13	35	N/A	N/A	N/A
IX < I_0 = X	N/A	4	N/A	N/A	N/A	N/A

Table 6: Comparison of earthquake occurrence rates for each intensity class (e.g. IV < I ≤ V) between the declustered composite catalogue of the whole region and the Vienna Basin source zone following the completeness method of Stepp (1972). T: time period (completeness period) for which the catalogue is considered to be complete for an intensity class. N: number of recorded earthquakes of an intensity class within the completeness period T. No: cumulative number of earthquakes with intensities ≥ I0 extrapolating the recurrence intervals derived for the completeness time period T to the total length of the catalogue between the first data entry and 2010 (962 years for the declustered composite catalogue and 542 years for the Vienna Basin source zone). There are no records of earthquakes with I_0 ≥ IX for the Vienna Basin source zone. Intensity class IX < I0 ≤ X is excluded for the declustered composite catalogue since no completeness time period can be determined for this class. For more information see text.

tween 1915 and 1952, and 12 recorded events in the period 1953-2009. These changes of the apparent earthquake frequency are not imaged by the Stepp Test. We interpret the fluctuations as a result of an incomplete earthquake record rather than as a consequence of changing seismicity.

The conspicuously low number of earthquake records in the time between about 1920 and 1950 is apparently related to the contemporary social, economic and political situation, which is characterized by the decline of the Austrian-Hungarian Empire in 1918, the subsequent economical crisis and Austrian civil war, and World War II. Such circumstances distracted attention from earthquakes and led to malfunction of the previously established macroseismic reporting system that was based on the imperial administration. Also, the seismographs at ZAMG in Vienna, located in the centre of the analyzed source zone, were destroyed by war action in 1944 and not operational until 1951 (Hammerl et al., 2001). We therefore conclude that earthquake records from this time period are not complete since the "lower seismicity" period coincides with the time of dysfunctional recording system.

6. Discussion and Comparison of results

The results of catalogue declustering and the application of different completeness analyses to the entire study area show significant differences in the estimated seismicity parameters such as the mean annual rate of seismic activity, the resulting intensity-frequency relation coefficients (a- and b-values in Gutenberg-Richter relation) and the completeness level of the seismic data, above which the earthquake catalogue is considered to be complete at a certain time. The GR a- and b-values obtained from the datasets after declustering and different completeness analyses are summarized in Table 7 and Fig 10. Even if we know that GR- relations based on clustered and uncorrected data is meaningless in a strict sense, we computed it here to demonstrate the effect of declustering and the different completeness methods._

Declustering of the data has only a minor impact on the estimated seismicity parameters leaving the b-values unchanged but reducing the a-value for about 0.1 to 0.2 (Fig. 10, Table 7). The clustered catalogue therefore tends to overestimate the number of earthquakes of higher intensities. The observed effect is due to the fact that declustering removes a large number of small intensity aftershocks from the time period after about 1900. However, for the centuries before about 1900, declustering also removes a significant number of high-intensity aftershocks (aftershocks with small intensity are hardly docu-

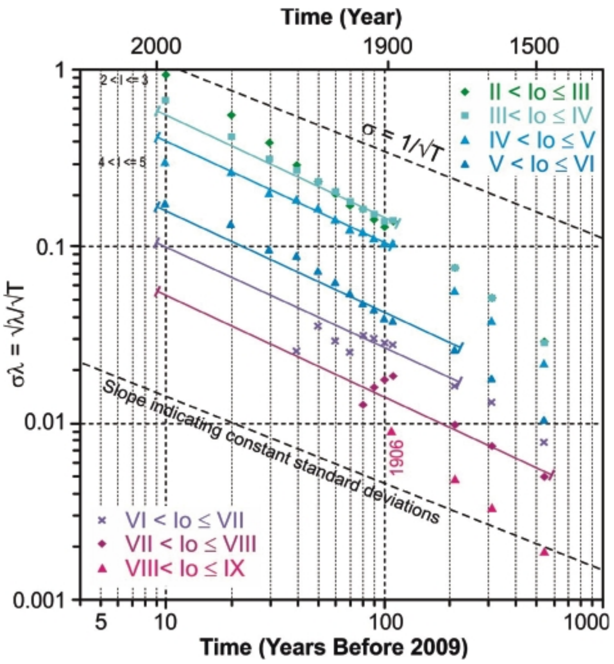

Figure 8: Stepp plots for earthquakes of different intensity classes recorded in the Vienna Basin source zone. The length of the time interval at which no deviation of σ from the straight line 1/√T occurs defines the completeness period for the given intensity class. For the intensity class I_0 > VIII, only one event is reported (Dobra Voda 1906, I_0 = IX).

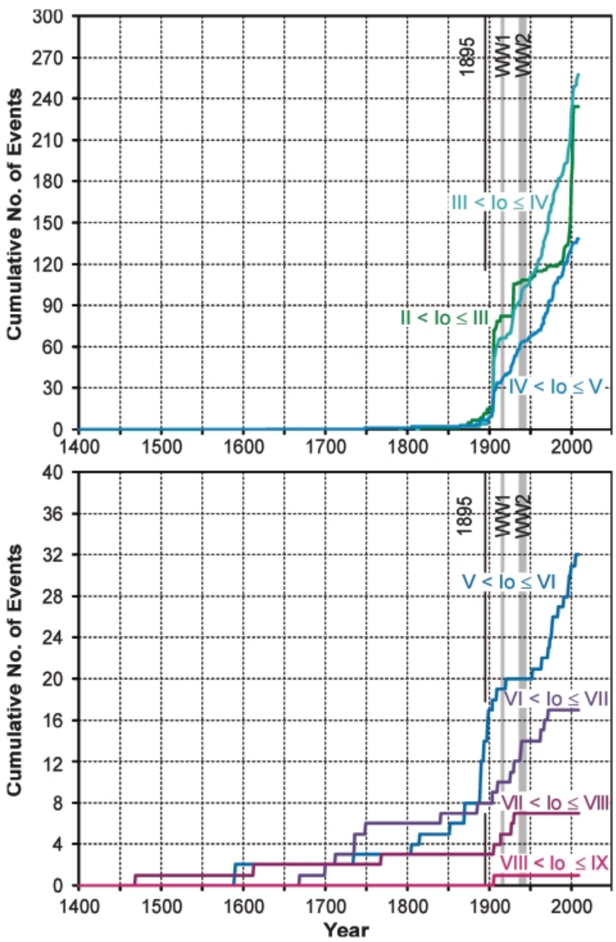

Figure 9: Temporal course of earthquake frequency (TCEF) for single intensity classes for the Vienna Basin source zone. Time intervals with the steepest slope of the curves regarded as periods with complete earthquake records of a certain intensity class. Note the prominent plateaus of the curves between about 1914 and 1950 for the intensity classes III < I_0 ≤ VI indicative for incomplete earthquake records in the time between and shortly after World War I and II. The strong increase of records of earthquakes with I_0 ≥ II is due to the implementation of a network of digital seismic stations in Austria in 1991. Note the different scales of cumulative event numbers on the upper and lower panel.

mented for that time).

When comparing correction procedures, slightly lower a- and b-values of the GR-relation corrected with the Stepp Test is caused by the fact that the highest intensity class (IX< I_0 ≤X)

Catalogue / Correction Method	GR-parameters	
	a-value	b-value
Clustered CC uncorrected	2.84	0.49
Declustered CC uncorrected	2.70	0.48
Declustered CC TCEF Correction	3.94	0.59
Declustered CC Stepp Test Correction	3.64	0.55

Table 7: Gutenberg-Richter parameters (GR-parameters) to the clustered and declustered composite catalogues (CC = composite catalogue) and after applying different completeness corrections (TCEF and Stepp Test) on declustered composite catalogue, While the a-values vary significantly between the different applications, b-values seem to be influenced rather by the choosen completeness correction method than by declustering. Intensity I_0 = X is not included in corrections based on the Stepp Test as no completeness time period was determined for this class.

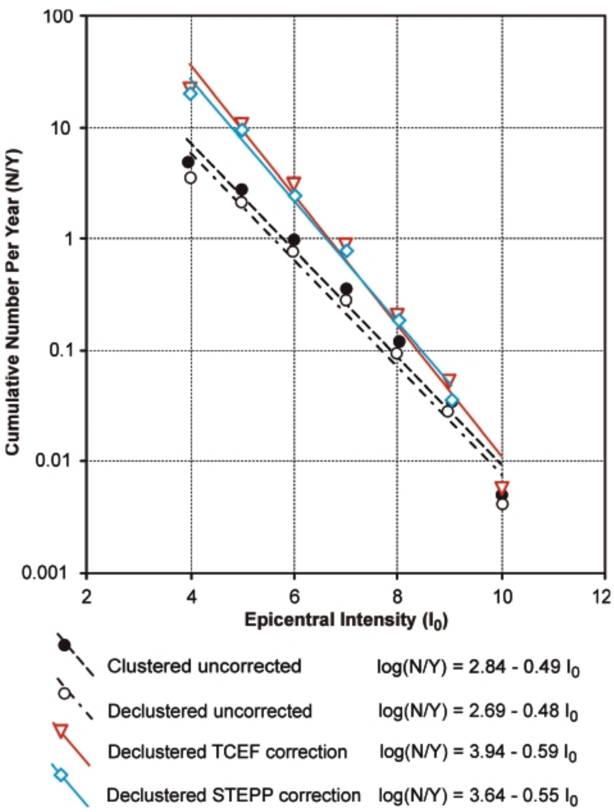

Figure 10: Comparison of Gutenberg-Richter plots derived from the raw composite catalogue (black solid dots) and the different corrections applied to the catalogue (declustering, TCEF completeness correction of the declusterd catalogue, Stepp Tests completeness correction of the declustered catalogue). Declustering of the data has only a minor effect on the a-value. Completeness corrections generally result in higher a- and b-values (compare Tab. 7). G-R regressions for the Stepp Tests do not include intensity class I_0 = X as the test shows that historical observation periods are too short for establishing reliable recurrence intervals. See text for further discussion.

has been excluded from the computation of the GR-relation. Correcting completeness time periods following Stepp (1972) shows that the observation time of about 1000 years is too short to obtain reliable average recurrence intervals for this intensity class. The Stepp Test not only provides completeness time intervals, but also gives insights how many earthquakes have to be observed in order to derive reliable average recurrence intervals for a certain intensity/magnitude class. According to Stepp (1972) minimum time intervals that cover at least 5 to 15 mean return periods are required for reaching stable estimates of mean recurrence intervals. Having observed fewer earthquakes (as in the composite catalogue), the occurrence rates tend to be underestimated. Including, however, IX< I_0 ≤X data in the estimation of seismicity parameters after performing the TCEF-correction results in a slight overestimation of the number of events for lower intensities and an underestimation of larger events. The b-values of the GR-relations after using TCEF and Stepp Test differ by 0.04.

Comparing the results of the composite catalogue with the composite catalogue for the Vienna Basin (Tables 5 and 6), there are two points that attract attention: Firstly, the time periods where the sub-catalogue is considered complete for most of the intensity classes are much shorter for the Vienna Basin than for the whole region. Considering that the Vienna Basin source zone is not the most active region in Austria, the shorter completeness time intervals for the Vienna Basin can also be explained by larger recurrence intervals of earthquakes with larger intensities. For example, the interevent times for intensity class VI< I_0 ≤VII are about 10 times larger for the Vienna Basin than for the whole region, therefore missing 1 event out of 7 per century (as for the Vienna Basin) affects the completeness tests more than missing 1 event out of 68 per century (as for the whole region). On the other hand, the obvious plateau during the 20th century within the cumulative number of events for the Vienna Basin (Fig. 9), shows that the earthquake record for this region is far from being complete. Even though this may only have a low impact on the average occurrence rates for the whole region, this result strongly suggests that completeness assessment of the whole dataset overestimates data completeness significantly. It therefore seems not advisable to use the completeness time intervals obtained from the whole region for single sub-regions without any additional completeness analysis. This is not obvious in many currently valid hazard assessments checking completeness from the whole area and extrapolating to seismic source zones.

7. Conclusions

Analyzing the completeness of earthquake catalogues is a necessary prerequisite for a seismic hazard assessment. We determined the completeness of a composite catalogue for Austria and the surrounding region following the TCEF as well as the method described by Stepp (1972). Comparison of both methods leads us to prefer the latter, because it also provides information on the minimum observation time required to derive reliable recurrence intervals for events of a certain intensity class. As most of the catalogue's record is pre-instrumental, those completeness analyses were performed on intensity data avoiding ambiguities arising from intensity-magnitude conversion. The main difference between the TCEF and the Stepp Test is that TCEF includes also the highest intensity class because of the assumption of the TCEF that all earthquakes of the highest intensity class have been observed during the length of the catalogue. Accordingly, this intensity class is considered as complete and used in the GR calculation. GR calculation based on the Stepp Test does not consider this intensity class due to the lack of sufficiently long observation periods.

The resultant GR-relations show that:

1) Declustering has only minor effects on the a- and b-value of the GR relation.
2) Completeness analyses have large effects on lower intensity classes, which result in more realistic b-values for the whole region and lead to longer recurrence periods for most of the large events,
3) Including the highest intensity class (($IX< I_0 \leq X$ for the whole dataset,$VIII< I_0 \leq IX$ for the Vienna Basin subregion), as done using the TCEF completeness analysis, underestimates the frequency of earthquakes of higher intensities.
4) The Stepp Test seems to be more reliable regarding for assessing recurrence periods and the frequencies of strong earthquakes with high intensities.

We have shown that earthquake records in Austria and the surrounding region cover the critical minimum observation period for all intensity classes except for $IX< I_0$. Stable estimates of mean recurrence periods are derived from the following completeness time intervals: $III< I_0 \leq IV$: 1875–2009; $IV< I_0 \leq V$: 1850-2009; $V< I_0 \leq VI$: 1775-2009; $VI< I_0 \leq VII$: 1775-2009; $VII< I_0 \leq VIII$: 1750-2009; $VIII< I_0 \leq IX$: 1600-2009. Both methods, the Stepp Test and TCEF, reveal completeness time intervals. The Stepp Test, however, indicates that the catalogue length of 962 years is not sufficiently long to reach a stable estimate of the mean occurrence rate of earthquakes with epicentral intensites $IX< I_0$.

Analysis of the sub-catalogue for the Vienna Basin source zone leads to recurrence intervals that are about 10 times higher than those obtained for the whole region. The completeness time intervals for the sub-catalogue revealed from both, TCEF and Stepp Test, are much shorter than those obtained for the whole catalogue. Careful examination of the data by the TCEF method shows that data up to intensity $VI< I_0 \leq VII$ are not complete even for the 20th century. This incomplete record, which we associate on the historical evolution between WWI and WWII, is not recovered by the Stepp Test.

Comparison of the completeness time intervals derived for the whole dataset and the Vienna Basin source zone leads us to conclude that completeness time intervals estimated from a larger region generally overestimate the completeness time intervals of sub-regions.

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