



Review Article

Integrated transnational macroseismic data set for the strongest earthquakes of Vrancea (Romania)

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ARTICLE INFO

Article history:

Received 29 January 2012

Received in revised form 22 January 2013

Accepted 24 January 2013

Available online 31 January 2013

Keywords:

Vrancea

Intermediate-depth earthquake

Macroseismic data and fields

Isoseismals

Diffused boundary method

ABSTRACT

A unique macroseismic data set for the strongest earthquakes occurring since 1940 in the Vrancea region is constructed by a thorough review of all available sources. Inconsistencies and errors in the reported data and in their use are also analysed. The final data set, which is free from inconsistencies, including those at the political borders, contains 9822 observations for the strong intermediate-depth earthquakes: 1940, $M_w=7.7$; 1977, $M_w=7.4$; 1986, $M_w=7.1$; 1990, May 30, $M_w=6.9$; 1990, May 31, $M_w=6.4$; and 2004, $M_w=6.0$. This data set is available electronically as Supplementary data to the present paper.

From the discrete macroseismic data, the continuous macroseismic field is generated using the methodology developed by Molchan et al. (2002). The procedure, along with the unconventional (smoothing method) modified polynomial filtering (MPF), uses the diffuse boundary (DB) method, which visualises the uncertainty in the isoseismal boundaries. The comparison of DBs with previous isoseismal maps supplies a good evaluation criterion of the reliability of earlier published maps. The produced isoseismals can be used not only for the formal comparison of the observed and theoretical isoseismals, but also for the retrieval of source properties and the assessment of local responses (Molchan et al., 2011).

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Contents

1.	Introduction	2
2.	Data processing and analysis	3
2.1.	Problems raised by the main features of the available data	3
2.2.	Data collection procedure	3
2.2.1.	Romania	3
2.2.2.	Former USSR	4
2.2.3.	Bulgaria	4
2.2.4.	Hungary	4

Abbreviations: DB, Diffused Boundary (method); DBs, map of Diffused Boundaries; FPS, Fault Plane Solution; IDP, Intensity Data Point; II, Instrumental intensity; MCS, Mercalli–Cancani–Sieberg magnitude scale; MMI, magnitude scale “Modified Mercalli Intensity”; MPF, Modified polynomial filtering (method); MSK, Medvedev–Sponheuer–Karnik magnitude scale; PGA, Peak ground acceleration.

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2.2.5.	Macedonia	4
2.2.6.	Serbia	4
2.2.7.	Cross-border reports	5
2.3.	Typical errors in data sources and hand-made files	5
3.	Processing of macroseismic data	5
3.1.	Processing of macroseismic map	5
3.2.	Processing of IDPs digital files	5
3.3.	Cross-checking of IDP-maps for inconsistencies	6
3.3.1.	Different sites with identical name	6
3.3.2.	Sites with equivalent coordinates but different names	6
3.3.3.	The English spelling of a name varies in different data files	8
4.	Data summary	8
5.	Application	8
5.1.	Method	9
5.2.	Isoseismals	9
5.2.1.	The 10 November 1940 earthquake	9
5.2.2.	The 4 March 1977 earthquake	10
5.2.3.	The 30 August 1986 earthquake	10
5.2.4.	The 30 May 1990 earthquake	11
5.2.5.	The 31 May 1990 earthquake	12
5.2.6.	The 27 October 2004 earthquake	14
5.3.	Site effects due to the strong aftershock of 31 May 1990	15
5.4.	Tectonic interpretation	15
6.	Discussion and conclusion	17
	Acknowledgements	18
Appendix A.	Revision of national macroseismic data	18
A.1.	Romanian data (edited by M. Popa, T. Kronrod)	18
A.2.	Bulgarian data (edited by I. Paskaleva and personal communication from R. Glavcheva)	19
A.3.	Former USSR data (edited by I. Sandu, T. Kronrod)	19
A.4.	Hungarian data (edited by K. Gribovszki)	20
A.5.	Serbian data (edited by S. Radovanovich)	20
A.6.	Macedonian data (edited by L. Pekevski)	20
Appendix B.	Web sites used for data checking	21
Appendix C.	Methods of generalisation of macroseismic map	21
C.1.	The modified polynomial filtering (MPF) method	21
C.2.	The Diffuse Boundary (DB) method	21
Appendix D.	Supplementary data	22
	References	22

1. Introduction

Seismic waves generated from the Vrancea seismoactive zone are of great interest not only for Romania, but also for the neighbouring countries due to their social and economical impact on these territories. Since 1900, the maximal seismic intensity registered so far is degree X on the MSK scale in 1940, while the area that experienced the degree VI (severe ground motion and building damage) includes Romania, the Republic of Moldova, a large part of Bulgaria and south-western Ukraine.

The aim of this paper is the cross-frontier integration of the macroseismic data for the main ($M_w \geq 6.0$) Vrancea earthquakes that have occurred since 1940 (Table 1) and the subsequent compilation to obtain a data set that is as homogeneous as possible to be used for reliable studies of source properties and local effects (Molchan et al., 2004, 2011). All data sources used herein are listed in the References.

The macroseismic information for an earthquake consists of a discrete set of data with two features that impede their effective immediate use: (1) measurement sites form an irregular set of points that depends on the distribution of the population in the area and (2) observed intensity values involve a “noise” component, which is due to measurement errors and local heterogeneities in the structure of the earth's crust.

The reliable determination of discrete macroseismic data points for cross-frontier macroseismic fields is even more difficult, as currently discussed (e.g., Stromeier and Grünthal, 2009; Tertulliani et al., 1999). In one of the first papers related to this issue, Ambrasey

and Moinfar (1988) demonstrates the highly baffling complexity connected with the use and interpretation of cross-frontier macroseismic data. Tertulliani et al. (1999) mention that “attempts at the unification of macroseismic practice among the countries have been rare and not very successful, due to the different and often incompatible local traditions for the derivation of intensity data”. A remarkable exception is the Catalogue of Earthquakes of the Balkan Region (Shebalin et al., 1972, 1974), which collects, after revision, data from many Balkan earthquakes. This catalogue contains a detailed table of historical and modern events and a set of 590

Table 1
Parameters of the study earthquakes.

Date	Time	Hypocenter ¹			M_w^3	I_0	Fault plane solution ⁴		
		Lat°N	Long°E	Depth (km)			Strike	Dip	Slip
1940, Nov 10	01:39	45.753	26.932	124	7.7	X	224	62	73
1977, Mar 04	19:21	45.851	26.969	98	7.4	IX	235	62	92
1986, Aug 30	21:28	45.554	26.587	135	7.1	VIII	240	72	97
1990, May 30	10:40	45.890	26.977	84	6.9	VIII	236	63	102
1990, May 31	00:17	45.883	26.997	82	6.4	VII	309	69	206
2004, Oct 27 ²	20:34	45.73	26.67	112	6.0	VII	219	81	107

¹ Hypocenters by Hurukawa et al. (2008).

² Hypocenter by Tugui and Craiu (2008).

³ M_w by Oncescu et al. (1999).

⁴ FPS for 1940 event by Oncescu and Bonjer (1997) and by Dziekonski et al. (1981) for other events.

isoseismal maps; however, a list of macroseismic observations is not given.

The reliable determination of macroseismic data points – which, for an earthquake, consist of a set of “site–intensity” pairs, from now on called Intensity Data Points (IDPs) – is essential for the strong intermediate-depth Vrancea earthquakes, which control the seismic hazard and cause severe damage to a large area (more than 407,000 km²) with a linear size exceeding 1500 km. This area includes at least 10 present-day independent states and a population of more than 37 million inhabitants. The strongest instrumentally recorded earthquake occurred in 1940 was responsible for felt intensities over an area of ~2 million km² (Riznichenko et al., 1980).

The macroseismic data are processed in two steps. In the first step, the initial data files are prepared to be suitable for further digital processing. For each IDP, the original geographical coordinates (*Lat*, *Long*) and intensity (*I*) are given, and these initial data files are used to build up the isoseismal maps of each considered earthquake (Panza et al., 2010). In the second step, described below in some detail, data files quality is improved by the (a) critical removal of inconsistencies in the *I*-values, (b) correction of site coordinates, and (c) addition and unification of site names. The data sets produced in this way are suitable for any further analysis aimed, for instance, at the retrieval of some earthquake source properties or local effects that are essential for a reliable assessment of seismic hazard in a large portion of Europe.

In this paper, the discrete macroseismic IDP-maps are generalised to continuous macroseismic *I*-fields using two formalised methods (Molchan et al., 2002), the resulting generalisation is compared with previous isoseismal maps available in the literature and its implications on the regional tectonics are shortly discussed.

2. Data processing and analysis

2.1. Problems raised by the main features of the available data

The macroseismic IDP-maps of the considered earthquakes include many countries and are characterised by a dense distribution of observation points. There are several factors that make a direct and non-critical use of these IDP data impossible:

- The relatively large time interval between the strongest events, from 1940 to 2004, during which political changes, renaming or liquidation of settlements, and changes of the base map took place, making difficult the correct identification of some observation points common to several IDP-maps;
- Observations have been performed in several countries independently; this fact should, in principle, not be very important for our purposes because all observations (excluding the Macedonian data given in the MCS scale and the Bulgarian data for the 1940 event) are given in units of the MSK-64 (from now on, simply MSK) scale. Nevertheless, the MSK scale is defined by 1-unit steps, while several half-integer *I*-values are given, as shown in Table 2;
- The multiplicity of data sources (publications, bulletins, internal reports, archival documents) in many languages requires close

cooperation between seismologists from different countries, which is the only way to reliably manage such data;

- The variety in the data formats: (1) the list of IDPs with *Lat*, *Long*, *I*, and site name (full description); (2) the list of IDPs with only *I* and site name; (3) macroseismic map only, without site names; and (4) original description of damage. Each type of data requires an ad hoc processing methodology. The original observations are not available to us in most cases.

2.2. Data collection procedure

The collection of macroseismic data is performed in three main ways: (a) direct field investigation (inspection of constructions and interviews with people), (b) telephone interviews and (c) circulation of questionnaires (e.g., see <http://terremoto.rm.ingv.it/index.php>). The quality of the primary data depends on the detail of the direct inspection, the time interval between the event and the survey, and the format of the questionnaires, which can differ from country to country. The overall procedure followed at the intensity assignment stage can change over time and from country to country also. Data are collected on the basis of national and cross-border reports. The main features of the analysed data sources are discussed in the following.

2.2.1. Romania

2.2.1.1. 1940 event. Most of the *I*-data are taken from the map drawn by Demetrescu (1941). One problem, which is not clarified in the literature, is the intensity scale he used. Demetrescu himself states that he used “the 12-degree international scale”, but he does not specify which of the two scales existed at that time: the 1904 MCS scale (Cancani, 1904) or the 1931 MMI scale (Wood and Newman, 1931). Considering the agreement between the intensity values given by Demetrescu (1941) and those in adjacent Moldova (which are in the MSK scale) and the fact that MMI and MSK scales may be treated as equivalent in our task (Decanini et al., 1995; Reiter, 1990) despite several publications with alternative *I*-values (see Bune et al., 1986), we conclude that Demetrescu's intensities can be considered together with the data in the MSK scale while maintaining a satisfactory level of uniformity in the entire data set.

2.2.1.2. 1977 event. The data are published by Radu et al. (1979a, 1979b) as macroseismic map (IDP-map). Immediately after the event, questionnaires were distributed to all municipalities and smaller villages in Romania. The intensity *I* in a site is calculated for each questionnaire with the equation $I = (I_b + I_p)/2$, where *I_b* and *I_p* are the intensity assessed on the basis of the damage to buildings and of the behaviour of people, respectively. The resulting intensities are $I_{a,p} = \frac{1}{k} \sum I_{a,p}^{(k)}$, where *k* is the number of questionnaires for a point. The error estimate for such values is as low as ±0.25, but according to the discrete nature of the macroseismic scale, all intensities are rounded to integer values.

2.2.1.3. 1986 event. The intensity map by Radu et al. (1987) was digitised and geo-referenced by the IPRS³ of University Karlsruhe, and the data set for this event was compiled by adding the data from EQ1986 (1990) and Kondorskaia et al. (1989) (K.-P. Bonjer, personal communication).

2.2.1.4. 1990 events. The initial intensity maps by Radu and Utale (1990, 1991) were digitised and geo-referenced by the IPRS of University Karlsruhe.

Table 2

Intensity data available for each event in different countries as integer values (as required by MSK scale) and as half-integer.

Country	Integer <i>I</i>	Half-integer <i>I</i>
Romania	1977, 1986, 1990, 2004	1940
Bulgaria	2004	1940, 1977, 1986
Former USSR	–	All data
Hungary	1977	1986, 1990
Serbia	1940, 1990, 2004	1977, 1986
Macedonia	1986, 1990	1977

³ International Postgraduate Research Scholarship.

2.2.1.5. 2004 event. The intensity data were collected by [Drumea et al. \(2006\)](#). The data were gathered by telephone interview and questioning in absentia basically. Thus for the majority settlements the number of the data changes from one up to several. Exception is made with a southwest part of the Odessa area where mass gathering the macroseismic data has been carried out by direct contacts with inhabitants, survey of the damaged buildings, and also with the help of questioning of educational institutions. Data for ground floor are used only.

2.2.2. Former USSR

2.2.2.1. 1940 event. Damage was investigated by special expedition in 29 Nov.–25 Dec. ([Tsshoher et al., 1941](#); [Sagalova, 1958, 1962](#); see [Archival materials of the Central State archive of Moldavian SSR](#) for the original data description). [Medvedev \(1948\)](#) estimated intensity for 117 large cities from Romania to Russia, including detailed data for Moscow, and published isoseismal map, the scale Mercalli–Cancani is used. These I -values were reconsidered to MSK scale by [Bune et al. \(1986\)](#). Special attention was given to this event in the Republic of Moldova ([Sukhov, 1960](#)).

2.2.2.2. 1977 event. The data were gathered by (a) the direct inspection of construction, accounting for the floor level and their total number, (b) the dispatch of uniform questionnaires and (c) interviews on the state of people's health (EQ1977, 1981; [Ananin, 1980, 1981](#)). Using the isoseismal map ([Ananin, 1980, p. 194](#)), we added several observations with $I = NF$ (not felt).

In the *Republic of Moldova*, the data gathering began one hour after the event ([Moscalenko and Roman, 1980](#)), and I values were defined by the quantitative technique developed by [Onofrash and Roman \(1980\)](#). In *Ukraine (without Crimea)*, the Odessa, Nikolaev and Kherson provinces were directly surveyed with questionnaires dispatched to the entire region, with preference given to questionnaires of inhabitants of a ground floor; for the other questionnaires, an amendment for the floor effect was introduced ([Kostiuk et al., 1980](#)). In *Crimea*, direct interviews and the distribution of questionnaires were realised ([Ananin et al., 1980](#); EQ1986), and each I value was defined by the technique developed by [Ananin \(1980\)](#) and then reduced to the ground floor by means of the following corrections: -1 (for floors from 2 to 4), -1.5 and -2.0 (for higher floors). These data were finally published in the form of an IDP-map. Along the *northern shore of the Black Sea* ([Karamzin et al., 1980](#)), the field survey began one month after the event and the filled-in questionnaires were returned within the two months following the event, doubtful questionnaires were revised by personal interview. For each IDP, a matrix of the distribution of effects was constructed and then used to define the I -value.

2.2.2.3. 1986 event. The analysis of the consequences of the earthquake was performed according to the “[Recommendations on the organisation of macroseismic observations in the epicentral zone of strong earthquakes](#)” (1983).

In the *Republic of Moldova* (EQ1986; [Eshanu et al., 1988](#)), a standard questionnaire was published in newspapers, while a more detailed questionnaire was disseminated among permanent correspondents. The field survey started within three days after the event. The questionnaires about sites with an abnormal landform or with very soft ground were excluded, and the data on buildings of type C, as defined by the MSK scale, were not considered. I -values were assigned using formalised statistical procedures ([Onofrash and Roman, 1980](#)), with larger weight given to the data supplied by qualified correspondents. The published list of IDPs contains, for each IDP, an abbreviation of the name (4 letters), indication of the data type, geomorphology code, *Lat*, *Long*, and I -value with its dispersion. In the *Crimea* (EQ1986, pp. 111–115), the data were collected at 170

sites, with 154 surveyed directly. The observed I was reduced to the ground floor as follows: $I-0.5$ (for the second floor), $I-1$ (for higher floors). The final data were published only in the form of an IDP-map.

2.2.2.4. 1990, May 30 and 31 events. In *Ukraine, the Republic of Moldova and Romania* ([Drumea et al., 1992](#)), the data were collected by (a) direct interview of inhabitants, (b) survey of damages to constructions of type B, as defined in MSK scale, (c) dissemination of questionnaires to executive committees and schools and (d) publication of questionnaire in newspapers. Pertinent documents stored by the National Insurance and the “Commissions to fight against earthquake consequences” were included in the investigation. The published list of IDPs contains for each IDP an abbreviation of the name (4 letters), I -value and epicentral distance; only IDPs in which I is estimated with a limited scatter (i.e. accuracy ≤ 0.5 according to [Drumea et al., 1992](#)) were included in the publication.

2.2.2.5. 2004 event. In *Ukraine and the Republic of Moldova*, data were collected by telephone interview and questionnaires. In the southwest of Odessa province, 34 localities were directly surveyed starting two weeks after the event. The intensity values for the 2004 event ([Seismological Bulletin of Ukraine for 2004, 2006](#)) are revised using additional original data and published by [Skliar et al. \(2010\)](#).

2.2.3. Bulgaria

2.2.3.1. 1940 event. The I -data were taken from a macroseismic map in the Forel–Mercalli scale ([Davison, 1921](#); [Kiroff, 1941](#); [Mercalli, 1902](#)) and converted to the MSK scale following [Shebalin et al. \(1972\)](#).

2.2.3.2. 1977 event. The I -data were obtained by the direct survey of damage to construction in more than 106 villages and towns, using a specific questionnaire ([Brankov, 1983](#)).

2.2.3.3. 1986 and 1990 events. The I -data were obtained mainly via questionnaires with the help of civil protection offices in the country and personal communications with [Glavcheva](#).

2.2.4. Hungary

2.2.4.1. 1977 event. A preliminary intensity value, I_k , is determined from each questionnaire k ; the intensity I , finally assigned at a site, is the most probable value in the set $\{I_k\}$ ([Zsíros, 1989](#)).

2.2.4.2. 1986 and 1990 events. The determination of I in each locality is made as follows ([Zsíros, 1994](#)): (1) for each observation j of each questionnaire, k , the intensity I_{jk} is determined; (2) for each individual intensity I , the weight $A_k(I)$ is the number of $I_{jk} = I$; (3) the relative weight (relative reliability) is $B_k(I) = A_k(I) / \sum A_k(I)$; and (4) the estimated intensity for a site is $I(\max B_k(I))$.

2.2.5. Macedonia

At the occurrence of the strong earthquake in Vrancea, no macroseismic questionnaire was circulated, and the estimation of the macroseismic effects was based on the newspaper reports from various towns/settlements in Macedonia.

2.2.6. Serbia

The data were obtained from the catalogue of macroseismic data ([Fig. 1](#)). The “Macro-catalogue of Serbia” for the period 306–2006 (6818 pages with 30,480 earthquakes) was compiled by different scientists in different time intervals; in 1940, the author was [Jelenko Mihajlović](#). As demonstrated by the analysis performed during the compilation of the Balkan catalogue ([Shebalin et al., 1972](#)), [Mihajlović](#) modified the used macroseismic scale over time, i.e., he inconsistently applied the Rossi–Forel and then the Mercalli scales. Therefore,

-583-

Редни број	Датум	ВРЕМЕ (средње-европско) с. м. сек.	С Е И З М И Ч К А П О Ј А В А										Место	Координате		Срез	Народна република
			Тутњава пре потреса		ПОТРЕС		Тутњава после потреса		Трајане сек.	Правци ос: поглав погресу	Ширина	Дужина					
			јач.	тип.	јач.	тип.	јач.	тип.									
			јач.	тип.	јач.	тип.	јач.	тип.	јач.	тип.	јач.	тип.					
26924	10-XI-1940	Reg 01°40'44" E	Dr. Beograd, Crkvice, Vrancea, Bucarest, Romania.														
				IV	III					10-15	E	Јабучевац	44° 22' 20"	23'	Брза Царака	Србија	
				IV	III							Карбуново	44° 14' 20"	26'	Невошњин Крпина	*	
				IV	III												

Fig. 1. Sample page from the Macro-catalogue of Serbia for the 1940 Vrancea earthquake.

damage field reports for Serbian territory given in the Macro-catalogue until 1950, including the 1940 Vrancea event, have been reinterpreted using the MSK and European Macroseismic scales (Radovanovich, personal communication). After 1964, the MSK scale is used in Serbia.

2.2.7. Cross-border reports

2.2.7.1. 1940 event. Additional and updated data were published by Moscalenko (1980), who revised several data using additional publications, original damage descriptions and news pertinent to Romania, Bulgaria and the Republic of Moldova. Additional data were published by Nikonov (2010), who used several tens of sources (e.g., news, journals, historical records) pertinent to Russia, Ukraine, Byelorussia, Poland and Estonia.

2.2.7.2. 2004 event. Several additional data (12 IDPs) pertinent to Romania, Ukraine, Turkey, Germany and the Republic of Moldova were produced by the “Community Internet Intensity Map” (Wald and Dewey, 2005) using questionnaires and taken from the website <http://earthquake.usgs.us>.

2.3. Typical errors in data sources and hand-made files

The macroseismic data for each earthquake (IDP-map) are formed by a set of IDPs, and each IDP is defined by its *I*-value and site identification: name, latitude (*Lat*) and longitude (*Long*). For the benefit of any potential end user, the procedure adopted for data processing and some still open, related problems are described in Section 3. The details of revision of national macroseismic data are given in Appendix A. As a consequence of the checks described there, the number of sites with observations from several different events increases (compare lines “Initial data” and “Final data” in Table 4, Section 4), and simultaneously, the anonymous IDPs almost disappear. Therefore, the total number of sites is smaller than in the original raw data.

3. Processing of macroseismic data

3.1. Processing of macroseismic map

In the case of published macroseismic maps, the initial data file is the result of digitisation, therefore the accuracy of the digitised coordinates depends on the accuracy of the symbol positioning on the original map and of the digitisation itself (boning of cursor and sensitivity of digitiser). (Supplementary Fig. D1) The names of the

locations are, in general, absent, therefore the IDPs inserted in the digital data sets should pass the following tests:

- Comparison of the *I*-values in nearby IDPs. It permits to detect an IDP with the *I* value strongly different with respect to its neighbours. This IDP is directly checked on the original map;
- Positioning a given IDP on Google Earth. It reveals doubtful coordinates if the IDP falls in an unpopulated area. When the distance from the IDP to the nearest locality is small and noticeably less than the distances to other cities/villages, the coordinates may be simply corrected. When the distance from the IDP to the nearest locality is large, or the IDP is positioned on the sea or in another country, such gross errors may be corrected only by the author of the digital data set. When an IDP is located between several small villages near to each of them, an accurate identification of the site is impossible and such data are lost.

Common errors detected in the initial data files are duplications of the same site with slightly different coordinates (distance < 2.5 km) and/or different *I*-values assigned to a given event. In such cases, the correct IDP is identified only by looking on the original map. The location of an IDP in a non-populated area is often caused by the low accuracy in digitisation or by random human errors, while data omissions during digitisation can be sorted out only resorting to the original maps.

3.2. Processing of IDPs digital files

In this case the initial data file to be checked is based on the hand-made table (called the base table) and/or publication(s) containing IDPs: (name, *Lat*, *Long*, *I*). Some of the IDPs in the base table have no coordinates or no names. In some publications IDPs may have no coordinates. Errors in the initial data file may be caused by errors in the base table and additionally during the conversion of the data to the electronic format.

Technical mistakes are inevitable when compiling manually large data sets. To correct the largest part of such mistakes, prominent features of the data (e.g., IDPs cannot be located in the sea, within rivers, in not populated areas), publications and Internet resources (see Appendix B) are used. The check and the necessary correction of a data file are done as follows.

Due to misprints and to the uncertainty in the source code (publications and/or base tables), more than one value of intensity are assigned to a given site (*Lat*, *Long*). The correct value of *I* is selected by looking at surrounding IDPs and by direct consultation with the author of the base table. If the difference between two *I*-values in

Table 3
Collected IDPs.

Country	Earthquake						Summary	Sites number
	1940	1977	1986	1990main	1990aft	2004		
Byelorussia	1	46	60	–	–	–	107	76
Bulgaria	200	1196	276	90	–	11	1773	1346
Hungary	1	63	42	95	–	–	201	149
Macedonia	1	23	12	6	–	–	42	24
Moldova	25	264	214	76	62	33	674	394
Romania	217	1314	1046	946	392	22	3937	2124
Russia	17	30	31	–	–	–	78	61
Serbia	326	302	39	20	–	2	689	612
Ukraine ¹	43	843	472	431	348	162	2299	1316
Other ²	4	7	7	–	–	4	22	19
Summary	835	4088	2199	1664	802	234	9822	6121

¹ Ukrainian data contain results of detailed observations in Crimea peninsula (170 IDPs for the 1977 event and 122 IDPs for the 1986 event).

² Armenia (1 in 1977), France (1 in 1940), FRG (1 in 2004), Georgia (3 in 1977), Lithuania (2 in 1977, 7 in 1986), Latvia (1 in 1977), Estonia (1 in 1940), Poland (1 in 1940), Turkey (1 in 1940, 3 in 2004).

the same site is 0.5, on account of the integer nature of all macroseismic intensity scales, we prefer the integer *I*-value.

The comparison of a data file with the source code(s) permits to add site names to the data file and to correct misprints; the following mistakes are the most common ones:

- Wrong typing of Arabic numerals, especially due to the poor printing quality (poor readability) of the source code: 5 ↔ 6, 0 ↔ 6, 3 ↔ 8 (misreading), 4 ↔ 5, 8 ↔ 9 (miswriting), 483 ↔ 843 (dysgraphic errors);
- Exchange of *Lat*, *Long* order and/or of *Lat*'s and *Long*'s fractional part;
- Omission or repetition of IDPs;
- Mixing between adjacent source lines.

The completion of an IDP description is necessary if the base table contains sites identified by intensity and name only. For these sites, the coordinates are searched in the internet geographical sites and checked by Google Earth. Russian names of foreign settlements may be spelled differently by different scientists and/or for different events or they may be misprinted and this causes obvious difficulties in the search of coordinates. Other problems may come from (a) the existence of the same name for different villages, (b) the renaming of the settlement after the macroseismic observation was made, (c) the absence of very small villages in all used Internet resources, (d) the disappearance of a village with time, (e) the use of a non-standard name of the observation point (camp, forestry, refuelling, state farm, etc.) and (f) serious (not obviously amendable) errors in name spelling. Sometime the present-day name of a renamed city/village may be found in Google.

The comparison of an initial data file with original publication(s) allows for the recovery of IDPs eventually lost while the initial data file was compiled. Some of them are mistakes made by the author of the base table. Sometimes sites with intensity 'no felt' (*I*=NF) are omitted deliberately, since the author considered them as not useful. To minimize this erroneous omission, all *I*=NF sites for which it has been possible to retrieve geographical coordinates are added to the data file.

When necessary, to complete the IDP description, the anonymous sites are named with the help of Google Earth. If the given coordinates fall in a not populated area or the given settlement is no-named there, the author is asked to improve the site definition. Very often anonymous IDPs fall between several nearby small villages, in such cases

the correction of coordinates and name may be done with the help of the original damage description only.

3.3. Cross-checking of IDP-maps for inconsistencies

The comparison among sites with identical or near coordinates in different IDP-maps evidenced three major problems: (a) different sites with identical name, (b) sites with equivalent coordinates but different names and (c) the English spelling of a name varies in different initial data files.

The formal variation of the site position reduces the amount of earthquakes, N_{eq} , observed in the same site (see line "Initial data" in Table 4, Section 4). On the other side, this quality improvement makes it impossible to analyse site effects and their variation for the majority of sites, contrary to what has been done by Molchan et al. (2011). The accessible accuracy of coordinates is 1 min = ~1.8 km as a rule, while the typical size of a village is 2–4 km or more (in Romania). Therefore, for the same-named sites, distant ≤ 1.5 km in several IDP-maps (with the exception of the dense Romanian and Bulgarian observations) identical coordinates in all IDP-maps are assigned automatically. Naturally, coordinates of close sites in the same IDP-map are not replaced.

3.3.1. Different sites with identical name

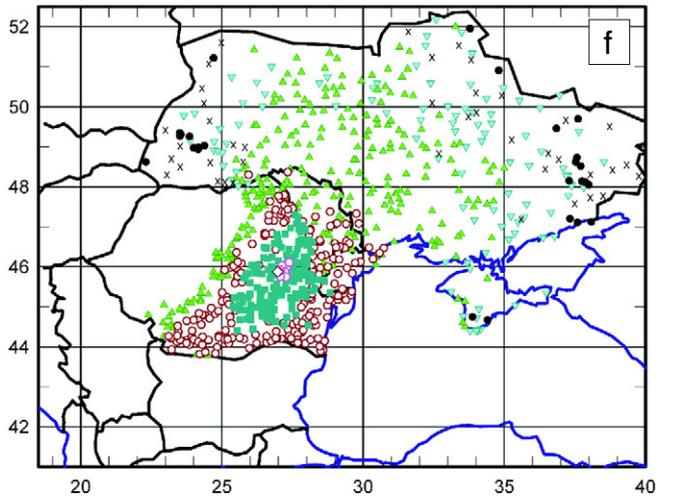
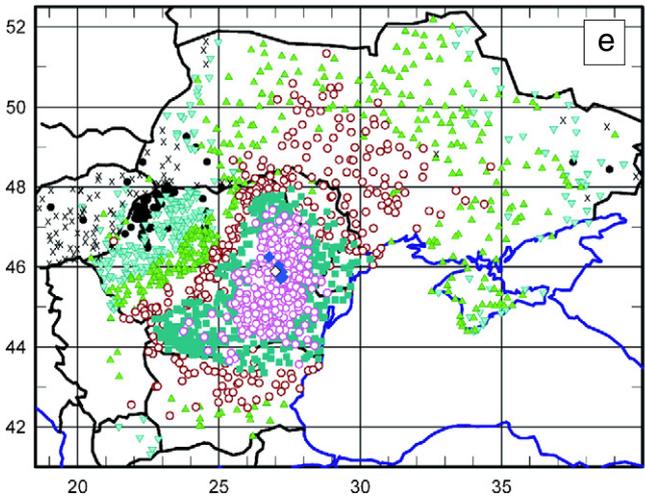
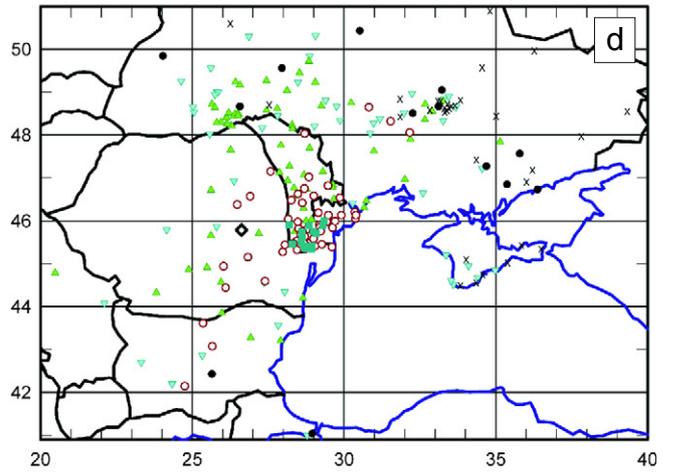
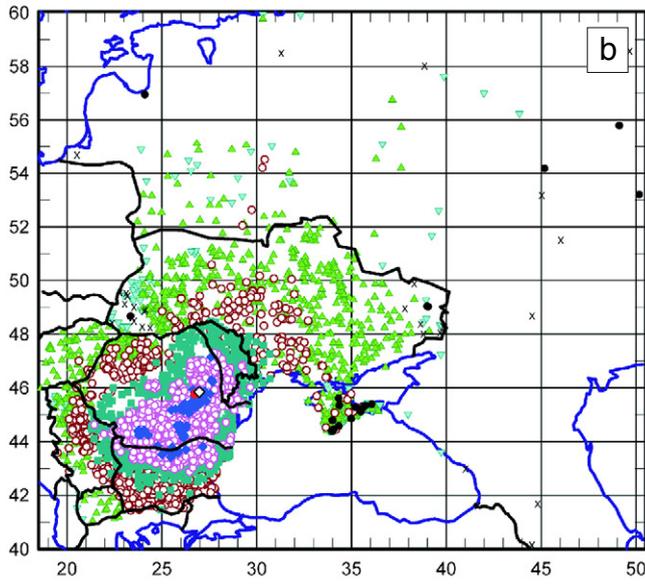
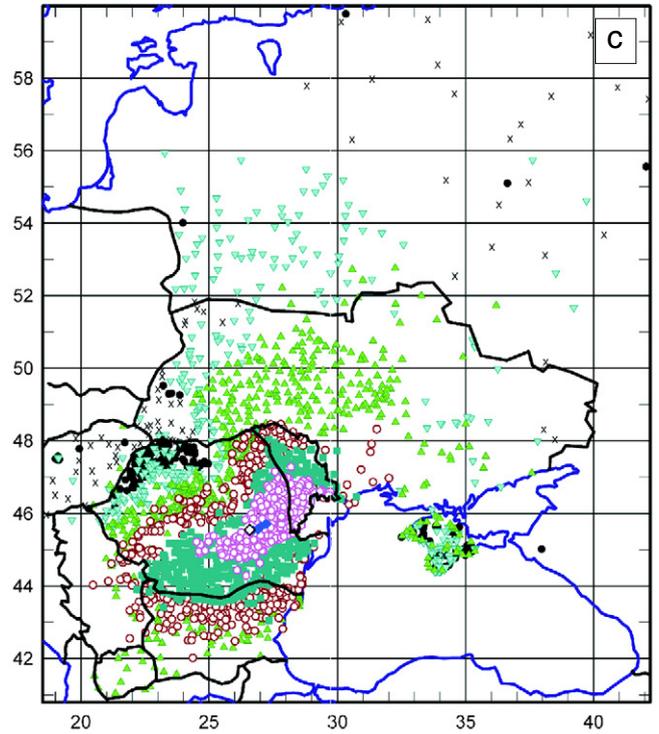
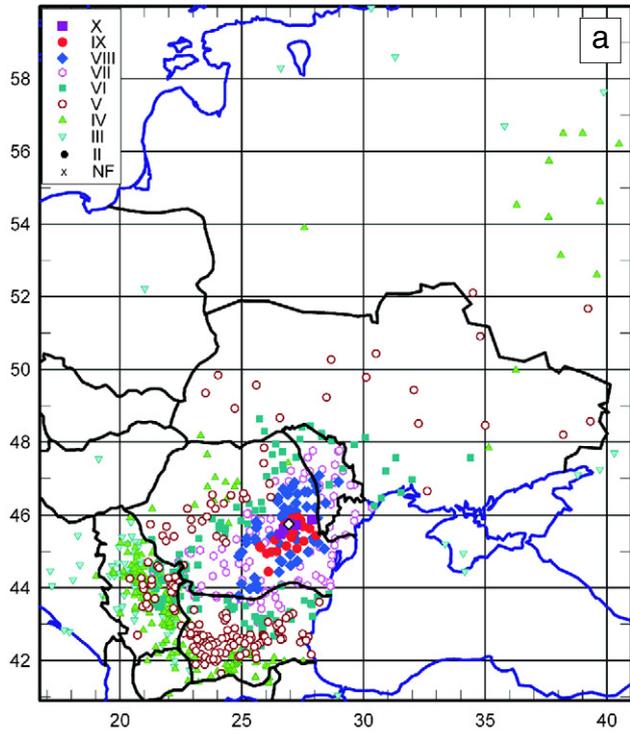
There are, at least, six possibilities to explain the difference in the coordinates of the same-named sites: (1) evident errors in the base table or in the initial data file that can be easily corrected using Google Earth and Global Gazetteer (there are several tens of these cases); (2) for the big cities frequently different coordinates are given, but these differences are less than the size of the city, therefore, for the cities that are represented by only one IDP, the coordinates of the city centre are entered in the data files; (3) when dense observations are available, several nearly identically named IDPs in one city or in a linearly extended village are available; if in different maps the same settlement contains more than one IDP with different localization, these data represent really independent observations and they are used as such (these cases are typical for Romanian data); (4) slight discrepancy between the coordinates of the same-named sites is possible as a consequence of not sufficient accuracy in the available maps or in their digitisation (Bulgarian and Romanian data); (5) in some initial data file (and corresponding base table) coordinates are given with accuracy 0.01°; (6) quite often identically-named IDPs are located at great distance because of: (a) real existence of villages with the same name, or (b) typing error in the coordinates or in the names, or (c) extension of the district name to all villages of that district. The cases (a) and (b) are checked using Internet resources and some mistakes are removed.

Often several of these small villages are not present in the mentioned information resources; these cases are checked by the regional authors, using large-scale national maps. Case (c) is dealt with in detail in Appendix A.

3.3.2. Sites with equivalent coordinates but different names

A site may have several names for four reasons: (1) mixing between adjacent source lines occurred during the compilation of the initial data file: *Lat*, *Long*, *I* are taken from one line, but the name from an adjacent one; (2) near-frontier settlements may have, indeed, two names (e.g., Camenca and Kamianka); (3) renaming of city/village in the time interval between the considered events (Romania) or after 1990 (Bulgaria, Ukraine, Crimea); (4) low accuracy of digitisation may lead to the assignment of similar coordinates to distinct but near sites (2–4 km apart) in several IDP-maps when the

Fig. 2. Collected macroseismic data: (a) 1940 event, two IDPs are out of the panel (Marseille, *I* = 3.0; Samara, *I* = 2.5); (b) 1977 event, (c) 1986 event, (d) 2004 event, (e) 1990 (main event), (f) 1990 (aftershock). The legend given in panel (a) is common to all panels, the rhombus represents the epicentre.



digitiser step is 1'. All these cases are resolved with the help of the original source, Google Earth and other pertinent Internet resources.

3.3.3. The English spelling of a name varies in different data files

The English spelling of national village names is not unique: (a) Global Gazetteer lists up to 5 name variants and gives the official one; (b) national names may contain characters not present in the standard ASCII table and therefore are not acceptable for some programmes and text editors and their Latin transcription may lead to different spelling in different data files; (c) many names are given with misprints in the source codes.

All these inconsistencies make it difficult the site identification in several *I*-maps. Correct spelling is important for the sites identification and for searching additional information about the site. The use of the Latin name spelling given in Google Earth or in Global Gazetteer led to the unification and correction of more than 300 site names.

4. Data summary

The summary of all collected data is given in Table 3, while the maps of the macroseismic data for all considered events are shown in Fig. 2.

The density of observations is very important for the analysis of the shape of the isoseismals. This density helps to understand whether the shape of the published isoseismals is objective or the result of author preconception. The strong decrease of observation density with increasing epicentre distance is shown in Fig. 3. In addition, the density of observations is well correlated with the density of population. The best observations exist for the 1977 event; the peak of density at an epicentral distance ~500 km is due to the detailed observations made in the Crimean peninsula. From Fig. 3 it can be concluded that isoseismals at a distance >400 km are not be supported by data, and for the 2004 event there is not method that allows to draw reliable isoseismals.

The unification of name spellings and the improved precision in the definition of coordinates permit an increase in the number of observed events at a site, N_{eq} and, thus, the expansion of the database so that it is suitable for the analysis of the effects at a site. The statistics of sites with a different number of observed earthquakes, N_{eq} , is given in Table 4.

The compilation of all available macroseismic data for each earthquake is contained in separate MS Excel files (with extensions of XLS), and it is available as Supplementary data (see Appendix D).

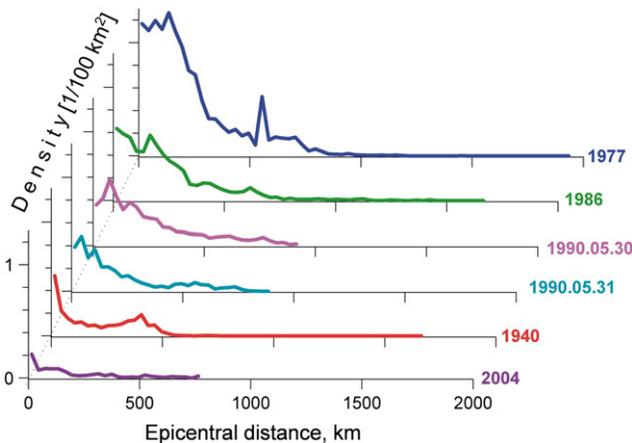


Fig. 3. Density of macroseismic observations [1/100 km²] for the considered earthquakes. The density is measured as the number of macroseismic observations per 100 km² relative to the annular overlaid region of 30-km thickness at epicentral distance *r*.

Table 4
Number of earthquakes observed in sites.

Number of sites	Number of observed events, N_{eq}					
	6	5	4	3	2	1
Countries with many data						
Byelorussia	–	–	–	–	19	57
Bulgaria	–	4	13	61	245	1034
Hungary	–	–	–	10	32	106
Macedonia	–	–	–	2	13	9
Moldova	4	10	25	37	68	250
Romania	1	10	145	340	648	980
Serbia	–	–	1	4	63	544
Ukraine	15	27	95	131	250	798
Summary						
Initial data	–	14	53	124	620	7911
Final data	21	55	276	599	1352	3819

5. Application

The macroseismic data have two properties that hamper their direct, effective use:

- (1) The distribution in space of IDPs is irregular because it depends on the population distribution in the affected area and on the activity of seismologists away from the epicentre;
- (2) Observed *I* values involve a “noise” component, which is due to measurement errors and local site effects. For example, in Italy the observed spatial variations of *I* over distances in the range from 20 to 40 km may be as large as 2 to 3 intensity units (Molchan et al., 2002).

This difficulty can be overcome, to a certain extent, by generalising the IDP-map to the *I*-field using isoseismals that act as a smoothing filter. Isoseismal of intensity *I* (in macroseismic scale) represent the boundary between the areas of intensity *I* and *I*-1, e.g. intensity inside isoseismal *I* is $\geq I$ (an “isoseismal” is specific case of an “isoline”). Based on the experience of smoothing small data sets, Shebalin (2003) summarised the main rules to be followed in the hand-drawing of isoseismals: (a) isoseismal zones must be simply connected and embedded, (b) adjacent isoseismals are approximately similar, (c) the curvature of an isoseismal must be as small as possible and nonnegative and (d) along azimuth, consecutive isoseismals must be neither too close nor too far from each other. Accordingly, Bune et al. (1986), Drumea and Shebalin (1985) and Drumea et al. (1992, 2006) reduce the isoseismal shape to the simplest possible one. Many investigators published hand-drawn isoseismal maps for the considered Vrancea earthquakes (e.g., Evseev et al., 1968; Radu et al., 1987; Radu and Utale, 1989, 1990, 1991; Shebalin et al., 1972). Most of the maps are truncated at the Romanian border or are strongly smoothed; thus, the latest macroseismic maps by Bonjer et al. (2010) cover only the central part of the macroseismic fields. In the last few years, Enescu and Enescu (1999, 2005, 2007) and Lungu and Craifaleanu (2007, and references therein) produced isoline maps based on instrumental data.

Since (a) all epicentres are located on a line ~70-km long, oriented NE-SW, (b) the maximum intensity I_0 is reached at a distance of ~23 km to the SE of the corresponding epicentre (Enescu et al., 2004) and (c) the fault plane solutions (FPS) are similar in most cases (Radulian et al., 2002), it is reasonable to attempt the definition of a common model for the shape of the isoseismal for the strongest intermediate-depth Vrancea earthquakes. Enescu et al. (2001) proposed a procedure to build isoseismal maps for Vrancea intermediate-depth events with Gutenberg–Richter magnitudes of $M_{GR} > 6.7$, starting from instrumental data and based on the concept of reference (“etalon”) event.

Thus, they selected the earthquake of August 30, 1986 as the reference earthquake and, based on the 35 instrumental PGA recordings available for this event, shaped standard isoseismals, which are conceived as a sort of reference matrix for any other Vrancea strong event. The generalised isoseismals for 1986 event (Fig. 4) reproduce the instrumental data and roughly reproduce the observed intensity distribution, with two main exceptions: (1) the area of the largest intensity is significantly overestimated and (2) the band of computed isoseismals near the Carpathian arc is strongly smoothed (compare Fig. 4 with Fig. 8a in Section 5.2). The generalised macroseismic field (intensity as a function of epicentral distance and azimuth) is defined by three independent parameters: (1) maximal intensity, I_0 , (2) focal depth, h and (3) directivity factor, δ , of the rupture propagation (Enescu et al., 2004; Enescu and Enescu, 2007; Marmureanu et al., 2008, 2011). In the authors' opinion, this standardisation is justified because the FPS for the Vrancea strong events are very close to each other and the procedure practically removes undesirable site effects. In these circumstances, having at-hand attenuation relationships properly evaluated, the construction of isoseismal maps for other real or potential earthquakes, with given I_0 , h and δ) is possible (see relation (4) in Enescu and Enescu, 2007). For Vrancea subcrustal earthquakes, Enescu and Enescu (2007) give the qualitative assessment: “the domain of maximum intensity $I_0 = 8.5\text{--}10.0$ corresponds to the domain of $M_{GR} = 6.9 (7.0)\text{--}7.7$ or of moment magnitudes $M_W = 7.1\text{--}7.9$ ”.

The main features of the maps generated accordingly are, however, based on a small number of observations, which is concentrated near the epicentre and approximately 10–15 times smaller than the amount of macroseismic data, and thus the generalisation of the isoline shape and area based on a few cases is not fully convincing. One striking example is the isoseismal elongation r (ratio between maximal and orthogonal linear sizes), which is much larger for the “etalon” map than for the map based on macroseismic observations. For the reference earthquake (see Fig. 4), r is large: $r = 5.3$ for $I = VIII$ and $r = 3.7$ for $I = VII$. For the real events, however, it is significantly lower, from 1.2 up to 3.3 (see Table 5 and figures in Section 5.2). Thus, the “etalon” earthquake approach may be applicable to the Romanian area only with great care.

For intermediate-depth Vrancea earthquakes with M_W in the range from 5 to 8 and depth from 70 to 160 km, a more convincing model for the prediction, in Romania, of various ground motion parameters, based on instrumental observations and geological data is proposed in a series of publications by Sokolov (see Böse et al., 2009 and references therein). The model includes the regional Fourier

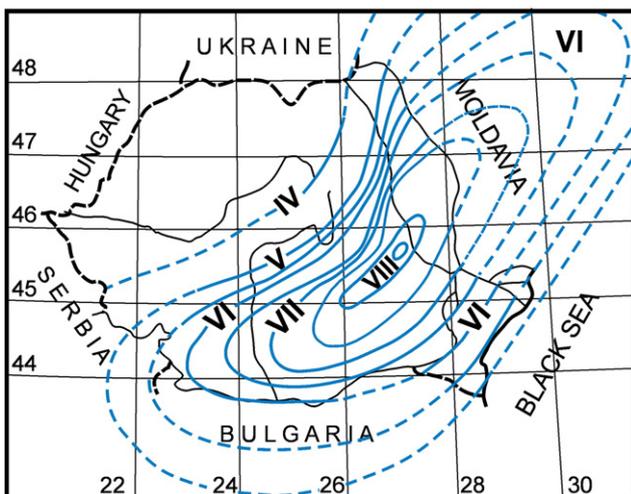


Fig. 4. Isoseismal map of the etalon earthquake (Enescu and Enescu, 2007) as modified by Marmureanu et al. (2011).

Table 5
Reliable elongation of MPF isoseismals (Intensity in MSK scale).

Date	M_W	Depth (km)	Elongation r (ratio between maximal and orthogonal linear sizes)
1986, Aug 30	7.1	135	$r = 2.5 (I = VII), r = 3.1 (I = VI)$
1940, Nov 10	7.7	124	$r = 2.1 (I = IX), r = 2.1\text{--}3.3 (I = VIII)$
2004, Oct 27	6.0	112	$r = 2.5 (I = V)$
1977, Mar 04	7.4	98	$r = 1.2\text{--}3.1 (I = VII)$
1990, May 30	6.9	84	$r = 1.7\text{--}2.0 (I = VII)$
1990, May 31	6.4	82	$r = 1.8 (I = VI \text{ and } VII)$

amplitude spectrum source scaling and attenuation model and generalised frequency-dependent amplification functions for specific local site conditions. The modelled space distribution of ground motion parameters (e.g., PGA) is in good agreement with the observed one.

5.1. Method

In comparison with instrumental observations, the macroseismic data are by far the richest set of observations available for the Vrancea intermediate-depth earthquakes, and in many studies, macroseismic observations have been used to generate attenuation curves for their subsequent application to seismic hazard assessment. Hand-drawn isoseismals do not conform to the Galileian rule of repeatability. Because macroseismic data have to reliably assess seismic hazard, for the smoothing of IDP data and their generalisation to the macroseismic field (I -field), the following two formalised methods (Molchan et al., 2002) are applied: modified polynomial filtering (MPF) and diffuse boundary (DB) methods. To make this paper self-contained, we summarise the two techniques in Appendix C.

5.2. Isoseismals

5.2.1. The 10 November 1940 earthquake

This strong event ($M_W = 7.7, I_0 = X$) affected a large area of Europe, from Turkey to St. Petersburg. (Supplementary Fig. D2) The first isoseismal map was compiled by Demetrescu (1941),⁴ and it is limited to Romania and north Bulgaria. The isoseismal maps for the central part of the I -field were drawn by Sagalova (Evseev et al., 1968), and by Radu (1971). The sketchy map, which is based on updated data, was compiled by Drumea and Shebalin (1985). The maps by Bune et al. (1986) and by Drumea et al. (2006, Fig. 8) are based on all available IDPs, but a severe smoothing approach has been used. The newest IDP-map was created by Pantea and Constantin (2011), who used over 4500 re-evaluated macroseismic questionnaires.

The isoseismals produced with the two formalised methods (Molchan et al., 2002) are shown in Fig. 5.⁵

All maps show an NE-SW trend of isoseismals (elongation), in agreement with the the rupture plane strike ($N 35^\circ E$) (De Rubeis et al., 1994). The intensity distribution around the axis of elongation is relatively symmetric. However, in the isoseismals beyond $I = VIII$ a slight tendency to deviate to the West is visible to the SW (in the northern part of Bulgaria) and a slightly more rapid attenuation to the NW (in the Carpathians back-arc region), compared with the attenuation to the SE (Dobrogea and Black Sea region), is seen. An unexpected significant attenuation of intensity $< VII$ in the southwestern direction is found as a consequence of the use of the updated Serbian and Macedonian data. In the central part of the I -field, the presence of the Carpathian arc introduces several distortions in the shape of isoseismals, which are not closed lines but lose the convex

⁴ Here and in the following, the published maps are manually redrawn because the quality of the original maps available to us does not satisfy journal quality requirements.

⁵ These maps (and all following produces maps) are drawn using Lambert's projection.

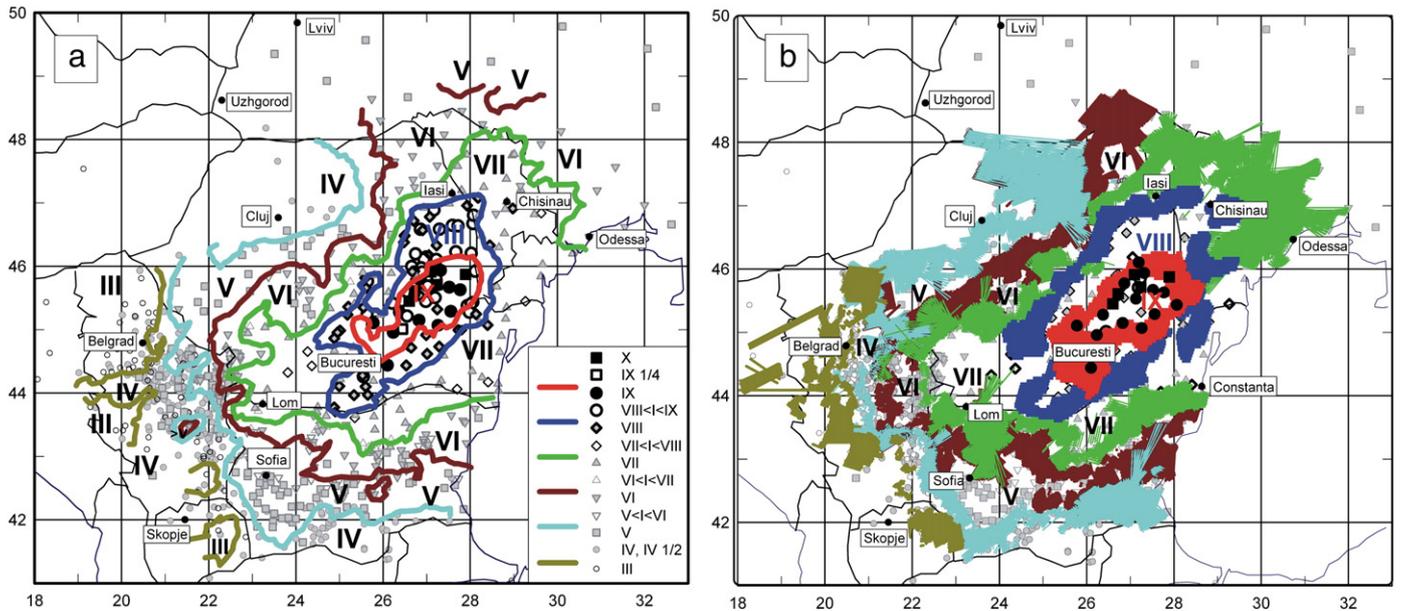


Fig. 5. Maps of the macrosismic field for the 1940 Vrancea earthquake: (a) MPF isolines, (b) diffused boundaries (DBs). DBs are boundaries between areas of different intensities, with the thicknesses of DBs indicating uncertainty in the placement of the boundaries.

shape or show complicated concavities (Fig. 5a). According to the DB approach (Fig. 5b), these features are indeed not relevant because of the high uncertainty of the isoseismal position due to the availability of too few data in the highest part of the Carpathian arc.

The isoseismals by De Rubeis et al. (1994) are calculated using a filter technique with a smoothing radius of $R = 70$ km. The use of constant R results in very smoothed isolines with respect to the MPF isoseismals, which are produced using variable R (see Section C.1 in Appendix C). The strange NW-SE elongation of the strongest isoseismal $I = IX$ in this map contradicts the IDPs with $I = X$ gaunt in a SW-NE line (Supplementary Fig. D3).

The complicated shape of the south-western extremity of the $I = VIII$ isoseismal and the DB (Fig. 5) is due to the lack of observations: there are only three IDPs just north of Craiova (around the point 44.5° , 24.0°). This scarcity of data also explains the low-intensity zone reported by De Rubeis et al. (1994).

The I -map can be considerably improved when the data by Pantea and Constantin (2011) for Romania will be available in electronic form.

5.2.2. The 4 March 1977 earthquake

The event ($M_w = 7.5$, $I_0 = IX$) affected a large area of Eastern Europe, from Greece to St. Petersburg. The first map, with a complicated shape of the isoseismal $I = VII$ and limited to Romania, was published by Radu et al. (1979b). (Supplementary Fig. D4). The maps by Shebalin (as reported by Radu et al., 1979b), Radu et al. (1979a) and Bune et al. (1986) are strongly smoothed and, in their central part, are similar to the map by Radu et al. (1979b). The macroseismic data set is very rich and sufficiently dense up to an epicentral distance of ~ 600 km. The maps generated by the MPF and DB methods (Molchan et al., 2002) are shown in Fig. 6.

Islands with $I \geq VIII$ are present in all maps. The significant extension of the isoseismals towards the S, due to the low attenuation to the south of the Carpathian arc (Panza et al., 2006; Radulian et al., 2004, 2006) and the strong directivity effect of the source towards the SW, as shown by the rupture process investigation (Müller et al., 1978), is evident in Fig. 6. The decrease of data density in the Eastern Carpathians does not permit to identify the change in attenuation between the foredeep area and the intra-Carpathian basin (Popa et al., 2005). On the other hand, the availability of a large

data set that we have compiled confirms the particular shape of the isoseismal IV between Budapest and Lvov and permits a more accurate definition than in previous studies of the shape of the isoseismal segments of intensities IV and III in the northern and eastern parts (Fig. 6a). The zone of low intensities (III and II) in SW of Ukraine correlates with a basin of thick (>3000 m) sediments (Chop–Mucachevo depression in the Transcarpathian inner trough). The isoseismal III at $54^\circ N$ latitude is lying on plain and is not connected to any tectonic features. The great linear extent of isoseismals $I = IV$ and III to the north of $\varphi = 50^\circ N$ and to the west of $\lambda = 20^\circ E$, and between the Adriatic and Black Seas in the map by Radu et al. (1979a) are not supported by the data and their shape is therefore doubtful.

The isoseismal map for the central part of the I -field (Fig. 7) was compiled by Enescu and Enescu (2007), starting from the so-called “etalon earthquake” and using the generalised attenuation curves. Enescu and Enescu (2007, p. 22) claim that the map in Fig. 7 is “more comprehensive than the observed macroseismic map” for future potential earthquakes. In our opinion, this is too strong statement. The shape of isoseismals in their map differs noticeably from that shown in Fig. 6. In particular, (a) the isoseismals in Fig. 7 are too regular when compared with the space distribution of the observations and their elongation and bending are too emphasised; (b) the broadening of isolines VI and VII towards the west in the southern part, visible in Fig. 6, is absent in Fig. 7, (c) the isoline $I = VIII$ is too long, (d) in the NE part (outside of Romania), the isoseismals in Fig. 7 are in contradiction with the reality. All this can lead to significant mistakes at calculation of seismic hazard. The model by Sokolov et al. (2008, Fig. 9) is more suitable. Therefore, we think that some caution in the estimation of seismic hazard is necessary owing to the real uncertainty of isoseismals, as well evidenced by the DB representation (Fig. 6b).

5.2.3. The 30 August 1986 earthquake

The event ($M_w = 7.1$, $I_0 = VIII$) affected a large area from Macedonia to Latvia, but reliable isoseismals may be drawn only in the area from central Bulgaria to Ukraine (Fig. 8). On both maps, the intensity boundaries in the centre are shifted to the south-east and go around the bend of the Eastern Carpathians. In the northern part of our isoseismals for $I = VI$ and V, the attenuation is only gently less than

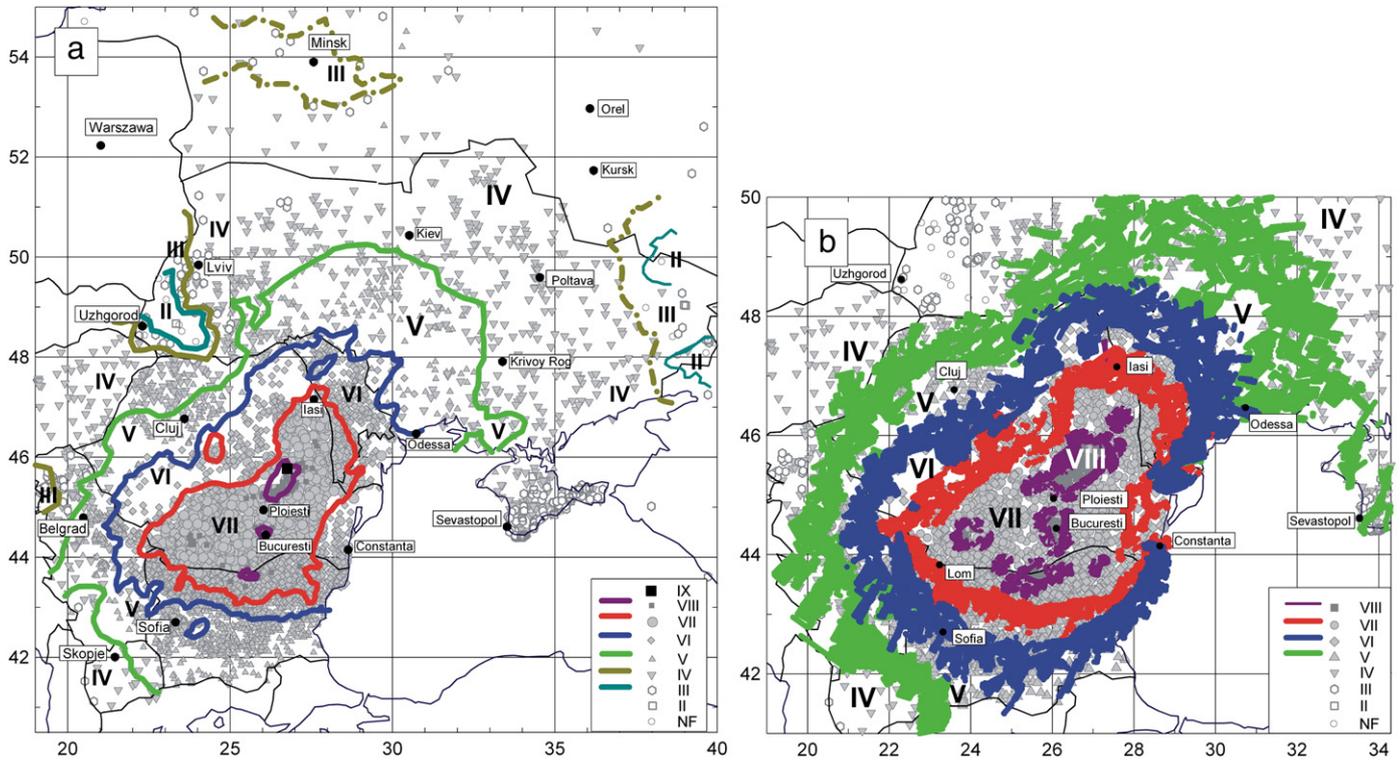


Fig. 6. Maps of the macroseismic field for the 1977 Vrancea earthquake: (a) MPF isolines (solid lines), dashed lines represent MPF isolines obtained with averaging radius, R , $80 < R \leq 180$ km; (b) DBs.

in the southern part. In contrast with the 1977 event (see Fig. 6), the attenuation in the area north of isoseismal $I = V$ is slowly decreasing over the large and flat surface that characterises the Russian Plain (with an average height of less than 200 m).

For $I \leq III$, the IDPs are very rare in the northern part of the IDP-map. Therefore, we calculated the MPF isoline $I = III$ with special parameters (data was fitted with a polynomial of degree one). This isoseismal (see Fig. 8a) is practically linear and has a NW-SE direction that marks the abrupt transition from the flat country (Russian Plain) to the Central Russian heights.

A similar shape of isoseismals in the central part of the I -field is observed in previous maps. (Supplementary Fig. D5) The isoline $I = IV$ in the map by Drumea et al. (2006) should not be drawn as a

solid line because the DB for $I = IV$ (Fig. 8b) shows a great uncertainty for this boundary (a band more than 100-km wide). The isoline $I = III$ outside of Ukraine is based on a very small number of observations with $I < III$, so its shape is, in fact, indefinable.

5.2.4. The 30 May 1990 earthquake

This earthquake is the main shock ($M_w = 6.9$, $I_0 = VIII$) in the sequence of two strong events generated close to each other in space and time. The MPF isoseismals and DBs for $I = VII$ and VI are elongated in an N-S direction (Fig. 9), which differs significantly from that common to the other major Vrancea earthquakes. Surprisingly, this difference is not caused by the fault plane solution, which is practically the same as the typical fault plane solution of the other Vrancea strong earthquakes (Radulian et al., 2002). Moreover, the group of IDPs with the largest intensity (VIII) extends towards NNW (see $I = VIII$ in Fig. 9a and b), whereas the isoseismal $I = V$ has the typical SW-NE elongation. Earlier published isoseismals give a clear example of the influence of author preconception when matching the data space distribution by hand-drawn isolines (Supplementary Fig. D6).

From a comparison of the isoseismal map by Radu and Utale (1990) with the isolines of instrumental intensity, II , defined as $\log PGA = 0.2712 \cdot II + 0.1814$, Enescu and Enescu (2005, p. 149) concluded that: “The distribution of the maximum values of ground motion acceleration is in disagreement with the macroseismic intensity distribution. This proves that macroseismic intensity estimates are of a highly subjective nature.” We show, that in the zone with sufficient number of stations the DB for $I = VII$ agrees with the isoline by Enescu and Enescu (Fig. 10) that contradicts their statement. In the map for PGA by Enescu and Enescu (2005), the shape of the isoseismals of intensity less than VII (Supplementary Fig. D6) is similar to that of isoseismals of $I = VII$ but disagrees with the DB and MPF isoseismal shapes shown in Fig. 9, because used stations are concentrated in epicentral zone. This fact is not surprising because the Romanian macroseismic data contain 946 IDPs, while the isolines for PGA are drawn using records from only 41 stations. Therefore,

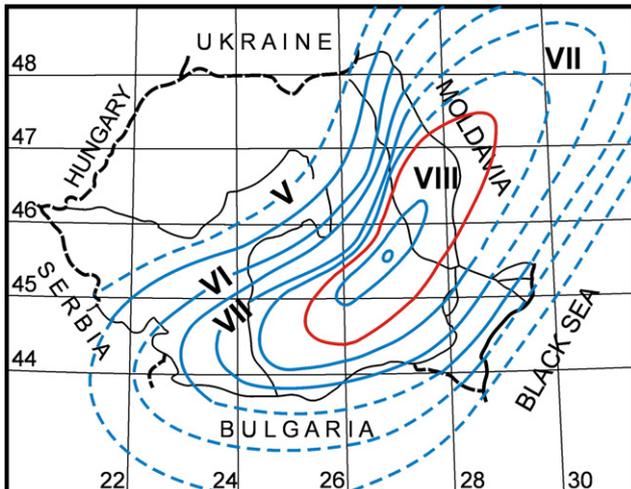


Fig. 7. Isoseismal map for the 1977 Vrancea earthquake, compiled by Enescu and Enescu (2007, Fig. 8) using the generalised attenuation curves (so-called “etalon earthquake”).

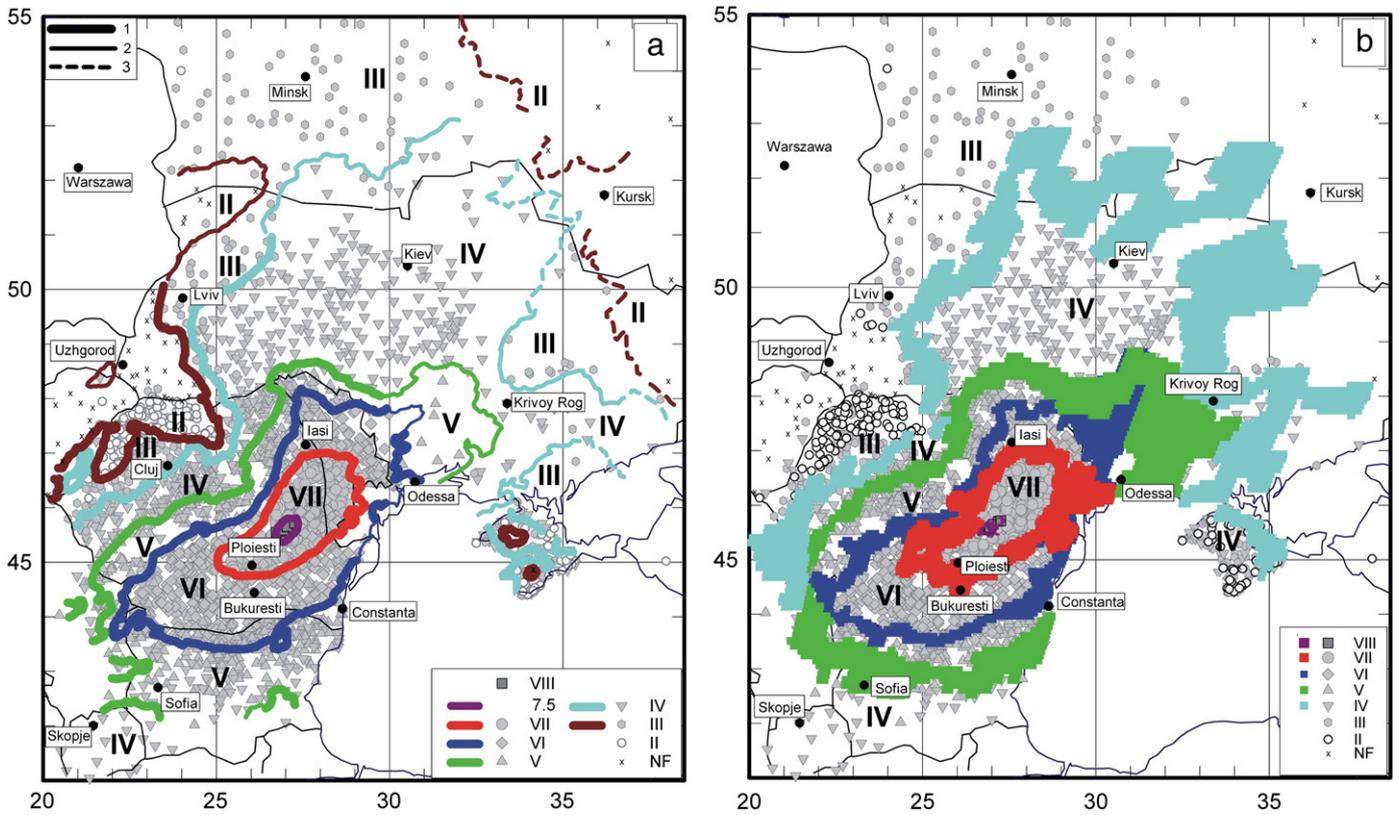


Fig. 8. Maps of the macroseismic field for the 1986 Vrancea earthquake: (a) MPF isolines, (b) DBs. Legend for (a): 1 – averaging with $R \leq 70$ km (thick lines); 2 – averaging with $70 < R \leq 120$ km (thin lines); 3 – smoothing by polynomial of rank 1 with $100 < R \leq 200$ km (dotted lines).

the macroseismic data allow consider a reliable ground motion field over a much greater area, than the present day instrumental observations can provide.

5.2.5. The 31 May 1990 earthquake

The strong aftershock on 31 May ($M_w = 6.4$, $I_0 = VII$), which occurred approximately 13.5 h after the main shock, has a fault plane solution with the nodal planes rotated by approximately 90° with respect to those observed for the main shock (Fig. 11). The fault plane

solutions fit the two classes of typical fault plane solutions for the Vrancea intermediate-depth events, as discussed in several papers (e.g., Enescu and Zdravcevsu, 1990; Mandrescu et al., 1988; Moldoveanu and Panza, 2001; Onescu, 1987; Onescu and Trifu, 1987). The FPS for the main shock belongs to the class of solutions typical for the largest earthquakes ($M_w > 6.5$), while the FPS for the aftershock belongs to the second class of solutions, typical for the events with $M_w \leq 6.5$. There is no indication for a correlation of the two solution classes with a preferred depth interval (Onescu and

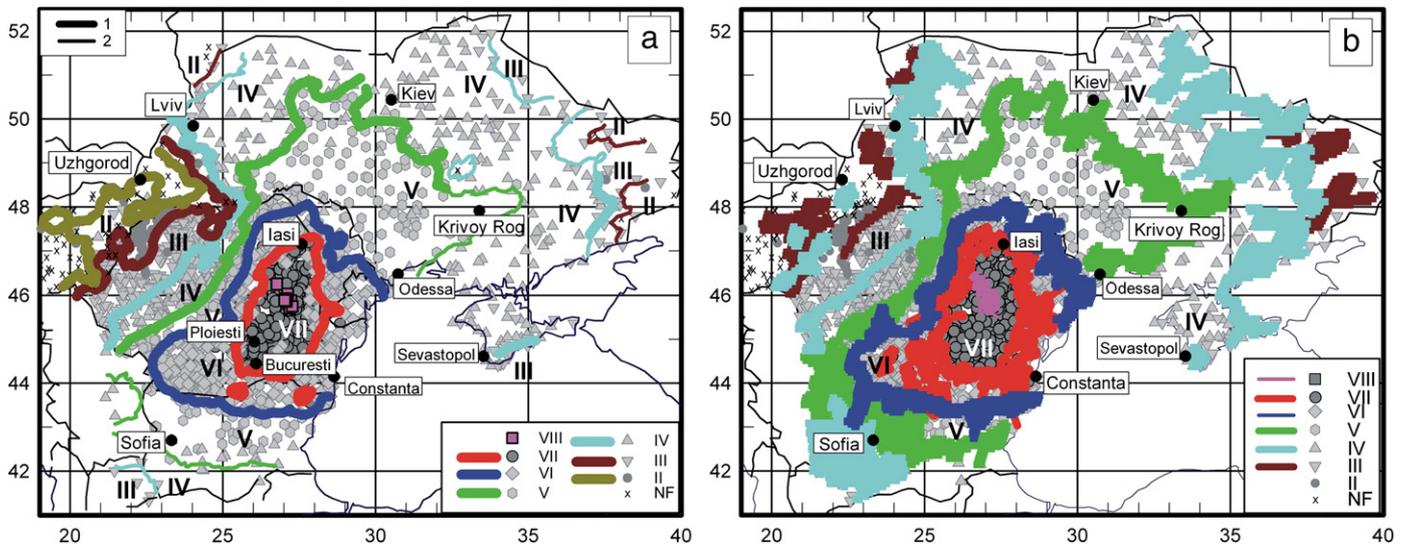


Fig. 9. Maps of the macroseismic field for the 30 May 1990 Vrancea earthquake: (a) MPF isolines, (b) DBs. Legend for (a): 1 – averaging with $R \leq 70$ km (thick lines); 2 – averaging with $70 < R \leq 120$ km (thin lines).

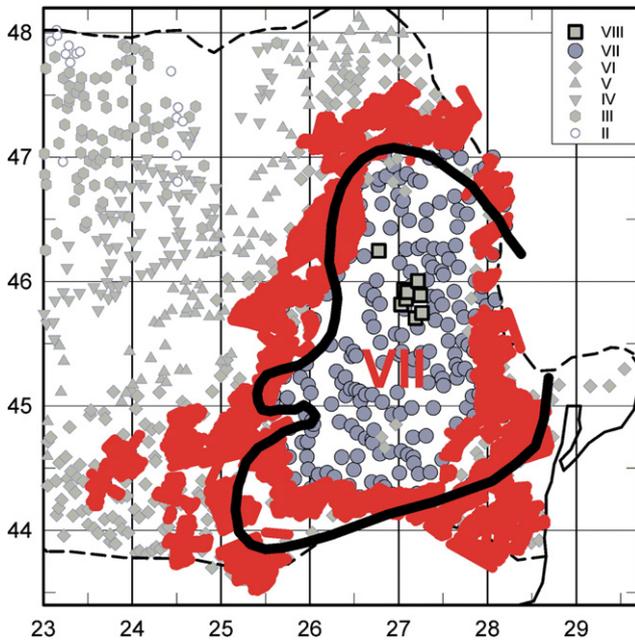


Fig. 10. Comparison of the DB for $I=VII$ (red areas) with the instrumental intensity II ($PGA=0.12\text{ g}$) isoline (black) of the 1990 (main) event as drawn by [Enescu and Enescu \(2005\)](#).

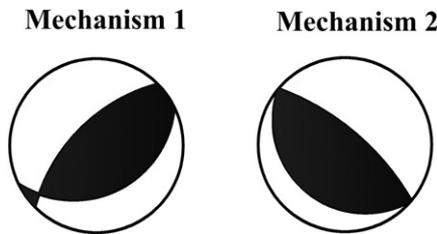


Fig. 11. Fault plane solutions for the Vrancea events of 30 and 31 May 1990 (after [Moldoveanu and Panza, 2001](#)).

[Trifu, 1987](#)). Solution 2 is less frequently observed, while Solution 1 is observed not only in the case of all major events but also commonly for events of any size.

The event on 31 May is well observed in the eastern half of Romania, Republic of Moldova and Ukraine. Despite the difference in the fault plane solution, the elongation of the isoseismals of the strong aftershock ([Fig. 12](#)) does not differ significantly from that of the main shock (see [Fig. 9](#)). The presence of the Carpathian arc causes only some asymmetry in the MPF isoseismals and DBs.

The isoseismal maps for the 1990 aftershock ([Fig. 13](#)) by [Radu and Utale \(1990\)](#) for the macroseismic data and by [Enescu and Enescu \(1999\)](#) for the instrumental data (29 stations) differ strongly. The map of [Radu and Utale \(1990\)](#) shows the standard NW-SE elongation, while in the map of [Enescu and Enescu \(1999\)](#) the inner isolines show an unusual N-S direction, similar to that of isoline $I=VII$ of the 1990 main event and the external isolines trend NNW. Both maps shown in [Fig. 13](#) are in conflict with the results of the DB method ([Fig. 12b](#)) with respect to shape and the orientation of isoseismals $I=VI$ and $I=V$.

The difference between the distribution of intensities and accelerations can be a problem of balance between frequency content and strong ground motion duration. A high-frequency radiation (acceleration) may not necessarily lead to longer strong motion duration and vice-versa. The basic hypothesis in [Enescu and Enescu \(1999\)](#) is the direct correlation between the focal mechanism and the ground motion distribution. According to this hypothesis, the two classes of fault plane solutions should lead to different intensity/acceleration distributions in space. Other studies, however, show that other factors related to structural properties apparently predominate, while the focal mechanism plays a secondary role ([Popa et al., 2005](#)).

According to our analysis of the intensity distribution for the two events of 1990, we conclude that: (1) the fault plane solution does not play an essential role in controlling the particular distribution of intensities, i.e., the difference in the focal mechanisms of the two shocks is not visible in the intensity distribution, which contradicts the main hypothesis of [Enescu and Enescu \(2005\)](#) and (2) for the smaller Vrancea shocks ($M_w < 6.5$), the change in frequency content can modify the shape of the highest intensities relative to the shape typical for the major shocks, i.e., rotation from a NE-SW direction to a N-S direction ([Radulian et al., 2004, 2006](#)). As a general remark, we draw attention to an important factor that is frequently ignored when interpreting earthquake effects: the complex, non-linear interaction of the source radiation (frequency content and directivity) with a given local site structure can vary with varying source mechanism (and source depth), thus significantly changing the pattern of the observed intensities. For example, the synthetic ground motion computed by a hybrid approach in Bucharest for different sources in

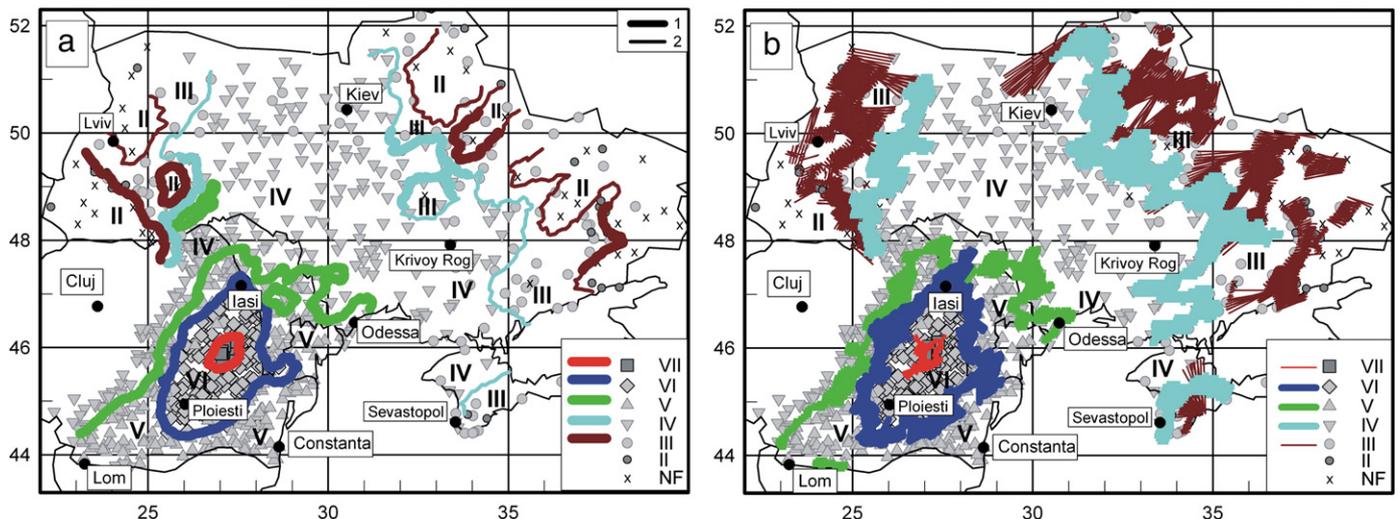


Fig. 12. Maps of the macroseismic field for the 1990 (aftershock) Vrancea event: (a) MPF isolines, (b) DBs. Legend for (a): 1 – averaging with $R \leq 70\text{ km}$ (thick lines); 2 – averaging with $70 < R \leq 120\text{ km}$ (thin lines).

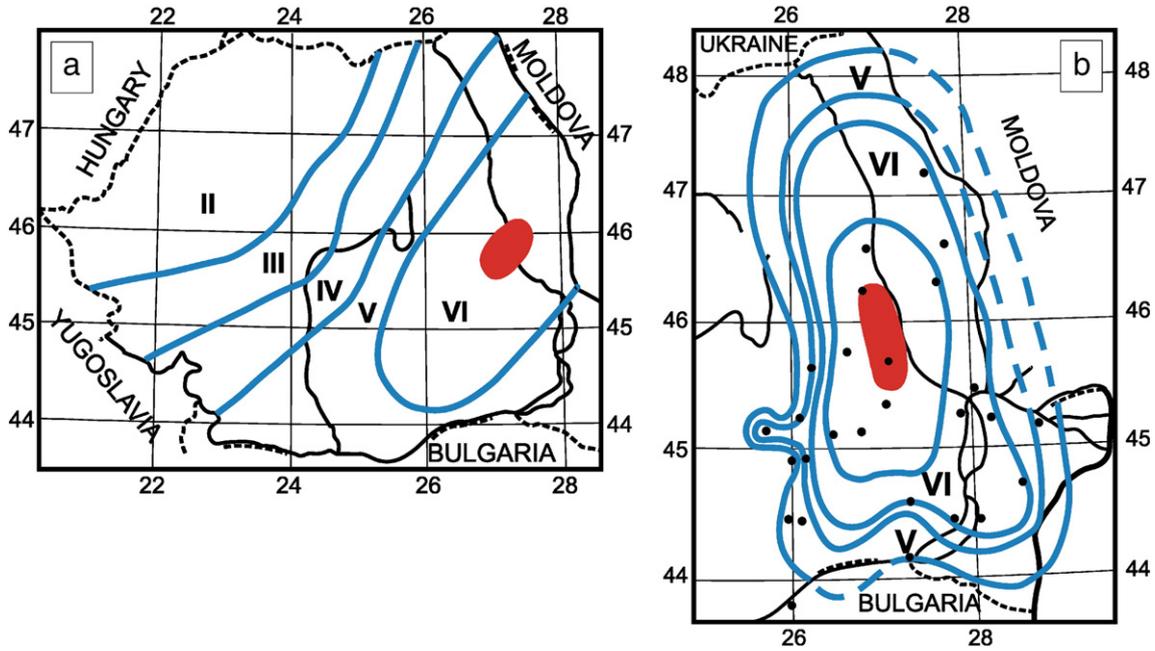


Fig. 13. Isoline maps for the aftershock 31 May 1990 by: (a) Radu and Utale (1990); (b) Enescu and Enescu (1999, Fig. 5), where PGA is transformed to the instrumental intensity, I by the relation $\log \text{PGA} = 0.2712 \cdot I + 0.1814$. Black points are the observation points (seismologic stations); red zones are the areas of $I = \text{VII}$.

the Vrancea region shows significant variability from one event to the other (Cioflan et al., 2007, 2009).

5.2.6. The 27 October 2004 earthquake

For the event ($M_w = 6.0$) with $I_0 = \text{VII}$, data are scanty, and the density of observations is very low, even near the epicentre (see Fig. 3). Therefore, the MPF isoseismals (Fig. 14a) are poorly constrained (for $I \leq \text{VI}$, the averaging is done with a large radius: $40 < R < 180$ km), and the typical NE-SW elongation is seen only for

the isoseismal VI. DBs outline the standard SW-NE elongation and confirm the large uncertainty of the MPF isolines (Fig. 14b).

Several maps for the 2004 event, based on different types of data, are given by Bonjer et al. (2008). The joint use of instrumental records from different types of instruments and international macroseismic data (Wald and Dewey, 2005) allowed reliable isoseismals to be drawn. The composite isoseismal map (Fig. 15b) shows the typical NE-SE elongation and a practically symmetric shape of isoseismals IV and V. In Romania, isoseismal V (Fig. 15b) is more reliable than

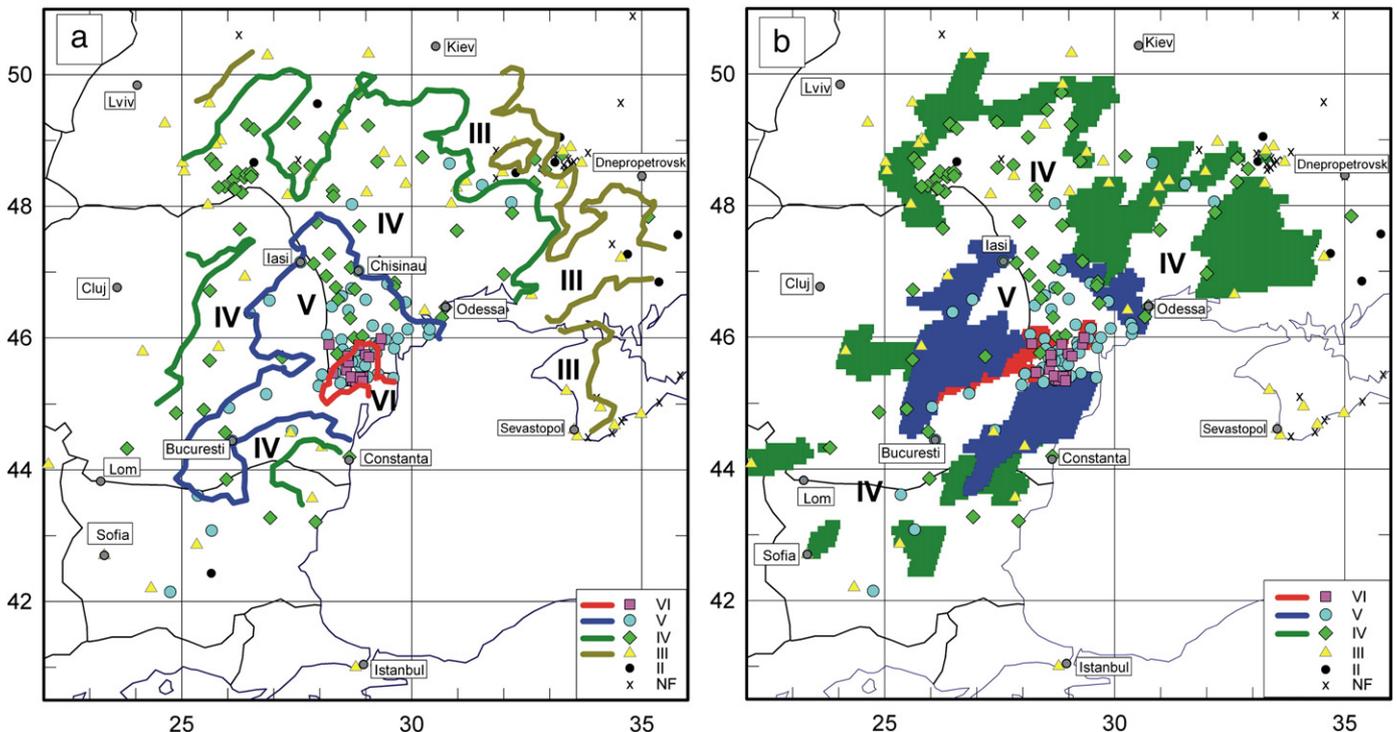


Fig. 14. Maps of the macroseismic field for the 2004 Vrancea earthquake: (a) MPF isolines, the averaging of $I = \text{VI}$ is made with $R < 40$ km, while the averaging of the other intensities is made with $40 < R \leq 180$ km, (b) DBs.

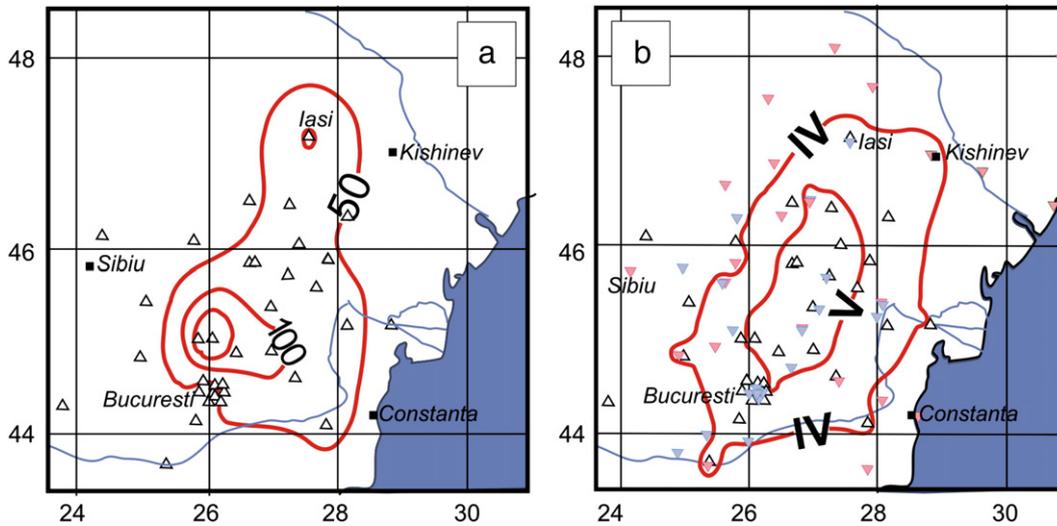


Fig. 15. Isolines by [Bonjer et al. \(2008\)](#) for the 2004 Vrancea earthquake: (a) isoaccelerations map [cm/s^2] constructed using 40 Kinematics (K2) stations, (b) composite isoseismal map based on the instrumental data from three networks (CRC461-NIEP K2, INCERC and NCSRR) and the macroseismic data from “Community Internet Intensity map” (see [Wald and Dewey, 2005](#)).

MPF isoseismal V (Fig. 14a) due to the use of instrumental data. In contrast, the isoseismal IV in Fig. 15b has a smaller extension to the north than that given by the MPF because [Bonjer et al. \(2008\)](#) use only international macroseismic data (~20 IDPs not far from the epicentre), while the national macroseismic data contain 230 IDPs.

The map of acceleration isolines, based on the records of 40 Kinematics (K2) stations (Fig. 15a), differs from the composite isoseismals, because as a rule, the shape of an isoline is also controlled by the space distribution of the observation points. Thus, the non-typical N-S elongation of the II isolines (Fig. 15a) can be assumed to be due to the small number (29) of registration points that were used.

5.3. Site effects due to the strong aftershock of 31 May 1990

Let us compare the two *I*-maps for the main event on 30 May 1990 ($M_w = 6.9$, $h = 84$, $I_0 = \text{VIII}$) and its strong aftershock on 31 May ($M_w = 6.4$, $h = 82$, $I_0 = \text{VII}$), which occurred 13.5 h later. These unique observations offer the rare opportunity to analyse aftershock effects. Both events were well observed in Romania. For the aftershock, the observations for the moderate intensity, $I < \text{VI}$, are not complete in the Republic of Moldova and Ukraine because many people did not return home after the main shock ([Drumea et al., 1992](#)); therefore, we only consider the Romanian data. The IDPs for the aftershock cover the Vrancea zone and the eastern part of Romania, but not the inner Eastern Carpathians, Transylvania or the Banat regions. Surprisingly, in the area covered by IDPs from both events, there are many sites with IDPs reported for the aftershock but not for the mainshock. It is probable that, because the questionnaires were completed after the occurrence of both earthquakes, the impression from the second shock was stronger at some points. As a rule, the intensity of shaking during the aftershock is one unit less than during the main shock, but there are significant exceptions (Fig. 16). Sites with relatively extensive damage are candidates for special analysis (Supplementary Table D2).

Even if the fault plane solution for the main event differs from that of the aftershock ([Radulian et al., 2002](#)), the intensity distribution shown in Fig. 16 appears to indicate that the site effects and propagation effects may explain the observations. Two features are particularly relevant: (1) the tendency to record lower damage at a great distance from the epicentre, which can be explained by the stronger attenuation of the seismic waves generated by the aftershock due to their different frequency content relative to the mainshock ([Radulian et al., 2004, 2006](#)) and (2) a rather complex spatial distribution of the effects in the

epicentral area, which makes any modelling of the aftershock effect difficult (a mixture of positive and negative ΔI).

5.4. Tectonic interpretation

The present publication makes available two critical elements for the reliable investigation of the distribution of macroseismic effects for the Vrancea intermediate-depth earthquakes: (1) an integrated, homogenized cross-border database and (2) an objective, formalised approach to trace isoseismals, i.e. to transform the discrete intensity information (*I*-data) into a macroseismic field. The modified polynomial filtering (MPF) and diffuse boundary (DB) methods ([Molchan et al., 2002](#)) visualise the uncertainty in the isoseismal boundaries and remove subjective biases that may affect the geologic interpretation of isoseismals.

In the following, we shall briefly discuss the possible dependence of isoseismals shape on the location, depth, magnitude and orientation of the principal axes of the studied events.

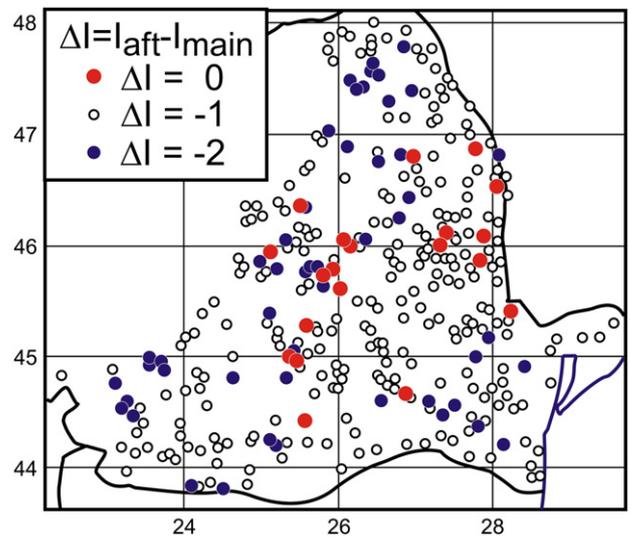


Fig. 16. Site-effects due to the 1990 (aftershock) Vrancea event: comparison between the aftershock effect (I_{aft}) against the effect of main shock (I_{main}): black symbols ($n = 254$) correspond to $I_{\text{aft}} - I_{\text{main}} = \Delta I = -1$ (the most frequent situation, well in agreement with the difference in magnitude between 1990 main- and after-shock); red symbols ($n = 20$) represent sites with $\Delta I = 0$; blue symbols ($n = 51$) represent $\Delta I = -2$.

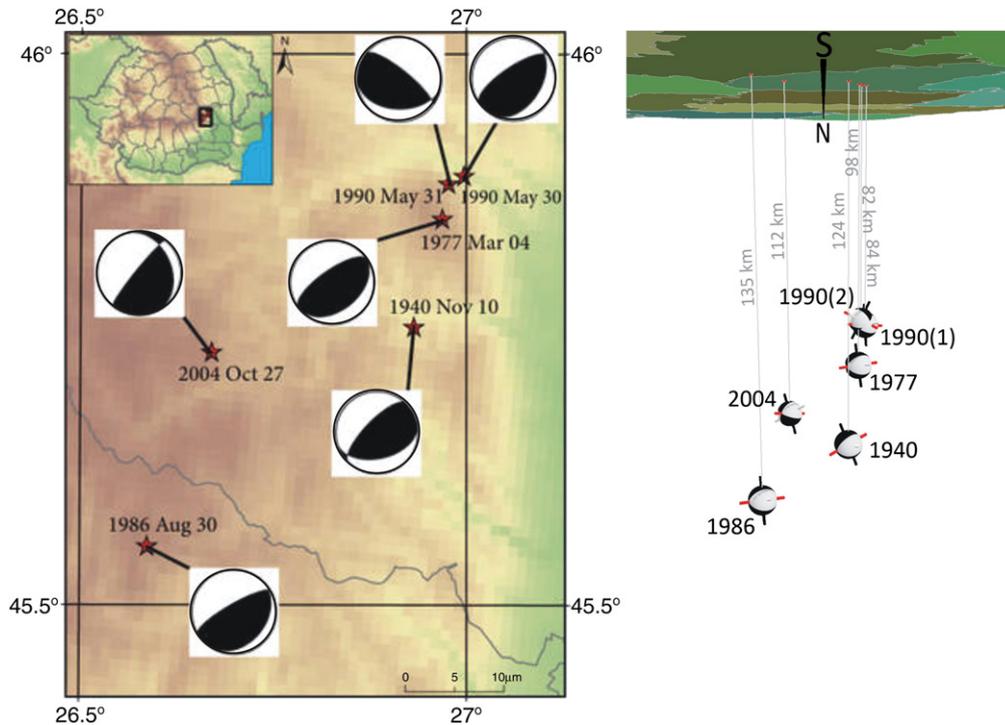


Fig. 17. Fault plane solutions of Vrancea strong events considered in this study: epicentral location and map view (left), hypocentral location and side view (right). The quadrants on the lower hemisphere and the principal axes (white for P-axis, black for T-axis and red for null axis) are seen from South to North in the right graph. Different coloured areas on the Earth's surface represent the administrative provinces in the study region.

One well-defined feature of the isoseismals of Vrancea intermediate-depth earthquakes is their NE-SW elongation. The main debate is if the focal mechanism or structural features (of Vrancea region and its surroundings) are responsible for this elongation (e.g., Enescu and Smalbergher, 1980; Enescu and Zugarvescu, 1990; Popa et al., 2003; Radulian et al., 2006). One strong argument in favour of the predominant role of source effect is the similarity of the focal mechanisms, as shown in the Fig. 17 (e.g., Enescu and Smalbergher, 1980; Enescu and Zugarvescu, 1990). However, in spite of the significant variation in the fault plane solution for the shock of 31 May 1990, with respect to the other studied events (including that of the day before, 30 May 1990), the isoseismals of this event have the general NE-SW trend common to all other events. More than that, the investigation of instrumental data for moderate events shows that for all the studied events, independently of their fault-plane solutions, the same NE-SW elongation is observed (e.g., Popa et al., 2003; Radulian et al., 2006). Therefore, we conclude that the NE-SW elongation effect is mainly due to the lateral variations in the lithosphere structure (Martin et al., 2006; Raykova and Panza, 2006).

A secondary asymmetric feature, shown by many previous isoseismal maps near to the Eastern Carpathians Arc bend, is less pronounced or even disappears when isoseismals are traced by MPF and DB methods. This can be explained by the reduced density of the macroseismic data in this area (see Fig. 18). Nevertheless, the strong attenuation toward NW, as suggested at least for the recent earthquakes instrumentally recorded and located in the Vrancea subcrustal seismic active body (Oth et al., 2008; Popa et al., 2005; Russo et al., 2005), is probably a real effect, but difficult to detect with macroseismic data. It is worth mentioning that the instrumentally recorded data are from moderate-size events ($M \sim 4$), with relatively high characteristic frequencies, while the macroseismic data are representative of relatively longer period waves in the range 0.5–1.0 s. Therefore, the comparison is not so obvious and possible frequency dependence cannot be disregarded.

An interesting effect, which can be seen in our maps, is the dependence of the isoseismal's elongation on the focal depth. If we measure

the elongation by r (ratio between maximal and orthogonal linear sizes for a given isoseismal curve), then we obtain the values shown in Table 5. Clearly, the shallower the focus the wider is the characteristic ellipse (compare 1986 and 1977 events, for example).

For a laterally homogenous lithosphere structure the isoseismal shape should be not very sensitive to focal depth variations in the range from 80 to 160 km. In our opinion, the narrower shape for the deeper focus is mainly the effect of a lateral variation in the upper mantle structure, as revealed by tomography inversion (Martin et al., 2006; Raykova and Panza, 2006) and discussed in different geodynamic models (e.g., Ismail-Zadeh et al., 2012; Tondi et

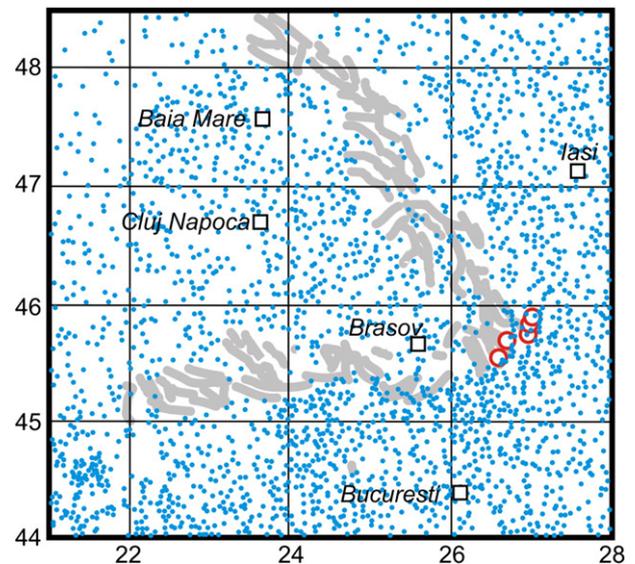


Fig. 18. The relatively very low observation density inside the highest part of the Eastern Carpathians (outlined by the grey lines) and in the Apuseni Mountains is clearly visible. Red circles are the hypocenters of the considered events. Size of IDP symbol is ~ 2 km.

al., 2009). The lithosphere–asthenosphere structure beneath the SE-Carpathians is laterally heterogeneous, particularly across the arc bend in Vrancea. Down to about 90 km of depth the lateral variation is less marked than at greater depth: the low velocity anomalies come into play first toward NW (Transylvania) around 90 km of depth, than toward SE, below the Moesian Platform at about 130 km of depth and finally toward NE below the Eurasia Platform.

The variation of the thickness of the lithosphere in the region from about 90 km to 170 km is evidenced by tomography investigations using body wave (Koulakov et al., 2010; Martin et al., 2006) and surface wave (group velocity) data (Raykova and Panza, 2006). The tendency of isoseismal ellipses to have decreasing minor axis (perpendicularly to the Carpathians Arc) with increasing focal depth, can be thus explained by the uprise of the asthenosphere flow (Doglioni, 1994; Ismail-Zadeh et al., 2012) below the Transylvanian Basin on one side and below the Moesian Platform on the other side. Such lateral effects are supported also by the recent analysis of Ren et al. (2012) based on P-wave finite-frequency teleseismic tomography (see Fig. 10 in their paper) and they may well induce relatively higher attenuation along NW–SE direction.

Other elements, like epicentral location, magnitude and orientation of the principal axes seem to play a secondary role in shaping the macroseismic field, while local structure effects can explain some features, such as: the expansion of the isoseismals toward SSW (see 1940, 1977 and 1990 both shocks), the area of relatively lower intensity at the south-west border of Ukraine (see 1977, 1986 and 1990 main shock) or the local maxima significantly shifted with respect to the epicentre towards the Carpathians foredeep area.

6. Discussion and conclusion

The most possible complete dataset possible of macroseismic information for $M_w \geq 6$ earthquakes occurring in the Vrancea region since 1940 is constructed. The effects of the seismic radiation of the Vrancea intermediate-depth earthquakes are strongly felt over a large part of Europe, it is therefore crucial to collect and integrate information from all the affected countries: Byelorussia, Bulgaria, Hungary, the Republic of Macedonia, the Republic of Moldova, Romania, Russia, Serbia and Ukraine. The procedures followed in each country for the collection and map representation of the macroseismic information are briefly described and discussed.

The database is built in two steps: (i) collection of original information available for the study area and (ii) critical revision of the data to obtain a unified and coherent dataset suitable for further geological and geophysical applications. The integration of cross-border macroseismic data is a complex and difficult task, and the main problems encountered can be summarised as follows (see Section 3 and Appendix A for details):

- Correct identification of the observation points due to political changes, renaming of sites, changes in mapping basis, etc. during the relatively extended time interval covered by the data (1940–2004);
- Inherent differences in assessing intensity independently in each country;
- Data are taken from sources written in different languages and from a variety of documents (e.g., publications, bulletins, internal reports and archival documents);
- Many identically named IDPs cannot be located with certainty, so part of the observation is irremediably lost;
- Original observations are not available in most cases.

One particularly significant problem is posed by the accuracy of the geographical coordinates. Localities often occupy an area comparable with the coordinate precision (~500 m in the best cases). In some cases, a single intensity value is assigned to the entire

settlement; in other cases, several I values are provided for the same inhabited locality. As a general rule, one IDP is associated with each locality, and the corresponding latitude and longitude are computed using Google Earth, Global Gazetteer or other high-quality software useful for locating the central point of the city/village. A short description of the Internet resources that have been used is given in Appendix B.

The available data sources, inadequacies, errors and their implications are analysed and critically revised. After solving the inconsistencies and performing the cross-border integration, the final dataset contains 9822 IDPs (835 for the 1940 event, 4088 for the 1977 event, 2199 for the 1986 event, 1664 for 1990 (mainshock), 802 for 1990 (aftershock), and 234 for the 2004 event) in 6121 observation sites of 18 countries. The data are provided as MS Excel files for any potential end user as Supplementary data to the present paper.

The data compiled in this work are generalised to I -fields by means of two formalised methods: MPF and DB (Molchan et al., 2002). Short description of these methods is given in Appendix C. The MPF isoseismals and DBs are reproducible and permit the definition of the area of each I -field, consistent with the available observations. The main properties of the macroseismic fields evidenced by our processing can be summarised as follows.

Despite the high density of observations, the uncertainty in the position of the isoseismal lines is considerable (~60 km in the best case) due to noise in the data caused by site effects and observation errors. When the seismic hazard is computed, this uncertainty is too often neglected with obvious consequences on the reliability of the related hazard estimations. For the 1940, 1977, 1986, 1990 (main) and 2004 events, the isoseismal for the highest intensity is not traced because only a few IDPs are available. The comparison of the DB results with previous published isoseismals permits us to evaluate the reliability of the isoseismals published so far.

In their central part, the isoseismals are elongated in the SW–NE direction. This direction correlates with the strike of the rupture plane, which is typical for the Vrancea major earthquakes, and with the relatively more rigid and thick lithosphere characterising Moesian and East European platform areas (Ismail-Zadeh et al., 2012; Martin et al., 2006; Raykova and Panza, 2006). The influence of the bend of the Carpathian arc gives rise to complexity in the shapes of the isoseismals, but the natural decrease of the density of observations inside the largest part of the Eastern Carpathians (Fig. 18) does not allow tracing this effect in detail, and the earlier published isoseismals are quite subjective in this area. “The strong reduction of the wave amplitudes in the Transylvanian Basin and in the inner Eastern Carpathians causes the asymmetry of isoseismals” (Popa et al., 2005). This statement is well consistent with the lower intensities isolines for the 1977, 1986 and 1990 (main shock) events. To the south, the isoseismals are extended westward because of the low attenuation in the Moesian platform. To the north, in the central Ukraine, the attenuation also decreases in correspondence of the Russian Plain, and the isoseismals and DBs deviate to the east. The DBs show a very large uncertainty of isoseismals here (>100 km). In the NE part of the IDP-map for the 1986 event, the isoline $I = III$ marks the linear NNW–SSE-trending boundary of the Central Russian heights.

A visible change in the intensity distribution (rotation from a NE–SW direction to a direction close to N–S) is observed for events below $M_w = 7$ (the two shocks of 1990). It looks like that this change in direction is not a focal mechanism effect, but rather it is caused by frequency-dependent propagation: the frequencies, relatively higher with respect to those radiated by the 1940, 1977, 1986 earthquakes, of the 1990 sources seem to excite differently, during their propagation, the crossed medium. Consequently, a possible frequency dependence of the isoseismal shape should be considered when dealing with events of different sizes (Radulian et al., 2004, 2006).

Macroseismic data are essential for the reliable assessment of seismic hazard (Caputo et al., 1973, 1974; Leydecker et al., 2008). For

Vrancea intermediate-depth earthquakes, some caution in the calculation of seismic hazard is necessary due to the real uncertainty of isoseismals (see Figs. 5b, 6b, 8b, 9b and 12b). The presented set of isoseismals can be used not only for the reliable assessment of seismic hazard but also for a comparison between observed and theoretical isoseismals—which involves the synchronous testing of crustal and source models—for geodynamic studies.

Acknowledgements

Editor in Chief Prof. H. Thybo, Dr. R. Tatevossian and the anonymous reviewer have made many critical remarks, which have been gratefully accepted and taken into consideration. The main results of the present paper were obtained within the framework of the CEI project 1202.038-09 “Unified Seismic Hazard Mapping for the Territory of Romania, Bulgaria, Serbia and Macedonia” and represent an example of efficient cross-border cooperation under the coordination of the Department of Mathematics and Geosciences – University of Trieste and of the Abdus Salam International Centre for Theoretical Physics in Trieste, SAND group. Significant contributions are acknowledged from different research teams: F. Romanelli, F. Vaccari, A. Peresan and C. La Mura (Trieste); C.O. Cioflan (Bucharest); M. Kouteva-Guentcheva and R. Glavcheva (Sofia); B. Pustovitenco (Simferopol); D. Dojcinovski (Skopje); [A.V. Drumea](#), N.Y. Stepanenko, V. Alcaz, I.V. Alexeev, N.A. Simonova and V.Y. Cardanets (Kishinev); and P. Varga and T. Zsiros (Budapest).

Appendix A. Revision of national macroseismic data

The Internet geographical sites used for data checking and correction are Global Gazetteer, Geographical Names, Ukrainian Cities and Garmin Map Source (JPS maps) (see Appendix B). The Google is used to find missing information. The accuracy of IDPs coordinates varies from the country to the country. (Supplementary Fig. D1).

A.1. Romanian data (edited by M. Popa, T. Kronrod)

A large number of data has been collected for all six events: 1940, 1977, 1986, 1990 (main), 1990 (aftershock) and 2004. The final number of IDPs is 3937, associated with 2124 sites.

The data sources are macroseismic maps at different scales and with a minimal number of geographical names (Radulian, 1999). Therefore, the IDP coordinates are obtained from the digitisation of maps with variable accuracy.

In the data we assembled, a site is named after the surrounding administrative unit (typically with a linear size of several tens of km) instead of the specific local name. As a result, the data set contains a large amount of IDPs named alike: 342 names assigned to different sites have been identified, and their repetitions vary from 2 to 20. The distance between IDPs with the same name varies widely as well. Remote settlements with identical names are infrequent. In the case of dense observations, several IDPs with identical names may fall within linearly extended villages or an interconnected group of villages. The problem of assigning the correct names has been partly solved by the addition of local names identified using JPS-maps (see Appendix B).

A.1.1. Data for the 1940 event

The macroseismic map by Demetrescu (1941) was published without a coordinate grid but with the precise shape of the coastline and the course of Danube, Prut and Olt rivers. The site names are given for IDPs with $I > 7$ and along the Danube; in the other parts of the map, there are a few isolated names. The reconstruction of the coordinate grid has been done by the IPRS of University Karlsruhe, which produced good quality data with a moderate observation density: The step in I -values is taken as half-integers («4-5» → 4.5), and

the additional author remarks are used to assess values to a ¼ of a degree (“5+” → 5.25, “9-” → 8.75).

A.1.2. Data for the 1977, 1986 and 1990 (main and aftershock) events

The original macroseismic maps, at a scale of 1:1000000 (Radu et al., 1987; Radu and Utale, 1989, 1990, 1991), were digitised and geo-referenced by the IPRS of Karlsruhe University. The IDPs are given by symbols with a diameter of ~4 km, and when symbols of nearby IDPs partly overlap, the accuracy of coordinates is degraded. The data contain many sites are named by the names of the larger nearby administrative units.

Given the poor precision of the digitisation of the data for the 1977 and 1986 events, the coordinates are known with accuracy not better than 4.5–5 km. In the data for the 1990 event, *Lat/Long* values are distributed quite uniformly and given the size of the symbols in the map, the accuracy of coordinates is not better than 3 km. Such an estimate is confirmed by the distances between the nearest IDPs with identical names in the IDP-maps.

A.1.3. Unification of the coordinates for a given site

As a result of the digitisation, the localisation of the cities represented in the IDP-maps by only one IDP is unstable, e.g., the coordinates of Constanta (Romania) vary from one event to another as follows:

- (1) 44.156° N 28.634° E for the 1940 event
- (2) 44.140° N 28.566° E for the 1990.05.30 event, distance from (1) = 5.1 km
- (3) 44.150° N 28.588° E for the 1990.05.31 event, distance from (2) = 1.8 km
- (4) 44.180° N 28.640° E for the 2004 event, distance from (3) = 4.5 km

Thus, the real coordinates cannot be defined by comparing the same site in several I -maps, and consequently, the geographical names mentioned in the maps do not permit an association of the observed intensity with a well-defined settlement. Irrespective of the reasons, this situation makes these data unsuitable for defining possible variations of site effect with varying earthquake sources (Molchan et al., 2011). Naturally, if a site appears only once in all the IDP-maps, erroneous spelling and coordinates remain undiscovered.

To uniquely identify an observation point (site) in several IDP-maps and assign a fixed localisation and name to a site, we proceed as follows:

- (1) We average with weight (Table A.1) the coordinates of IDPs of nearby identically named sites. These IDPs must belong to different IDP-maps, should not contain nearby IDPs with a different name and should be located not farther than the coordinate accuracy (Table A.1). The formal number of sites decreases after the averaging of coordinates.
- (2) If averaged IDPs have different names (renaming, spelling error), each of these nearby IDPs is characterised by averaged coordinates and a unique common name. In the case of several unique names, we take the most recent one.
- (3) Despite the unification of coordinates, many sites with the same name are retained because of the large density of observations and large extent in space of cities/villages. The greatest number of sites is identified in the following populated areas:

Table A.1
Averaging parameters for Romanian data.

Event	1940, 2004	1990main, 1990aft	1977, 1986
Distance for averaging coordinates	2 km	3 km	4 km
Weight	2	1.5	1

Ramnicu Valcea (11), Ploiesti (11), Geamana (10) and Sirineasa (10) (the number in parentheses indicates the amount of sites where IDPs are available).

All averaged coordinates are checked and corrected by independent internet sources. The initial and extended numbers of observed events, N_{eq} , in a given site are summarised in Table A.2.

A.2. Bulgarian data (edited by I. Paskaleva and personal communication from R. Glavcheva)

The final number of IDPs for the four events of 1940, 1977, 1986 and 1990 (main) is 1773 in 1346 sites. The misprints in the data are rare and the repetitions of sites with similar coordinates were frequent in the data for the 1940 event only.

The values of the coordinates are the result of map digitisation with step $\approx 1' \approx 1.85$ km for *Lat*. Even if such a step is less than the size of a typical village, it leads to discrepant site positions in the set of different IDP-maps. The distances between these localisations are no more than two digitiser steps and much less than the distance from the nearest sites. Therefore, the coordinates of these identical IDPs derived from different maps are averaged. Most of the sites have local names. In the data files, there are IDPs from several groups of remote settlements with the same name (e.g., four villages with the name Novo Selo). The English spelling of the Bulgarian names was unified for sites for which 2–3 versions of their names are available. For anonymous sites (with distances from the nearest site ranging from 5 to 34 km), names are taken from Google Earth, and the coordinates used correspond to the centre of the considered city/village.

For the 1977 event, the observations in Bulgaria are very dense: the cities Pleven, Razgrad and Metchka are represented by three IDPs at a distance from each other of 0.25–0.6 km, and 22 cities/villages contain two IDPs, at a distance from each other of 0.25–2 km.

A.3. Former USSR data (edited by I. Sandu, T. Kronrod)

For all six considered events, data are available for the Republic of Moldova, Ukraine, Russia and Byelorussia, while there are few, isolated data for Armenia, Georgia, Lithuania, Estonia and Latvia.

The base tables, i.e., the handmade tables from publications, archival documents and subsequent investigations (see Section 3.2), are prepared by the Institute of Geology and Seismology of the Republic of Moldova (Kishinev). The base tables contain site names, *I* and coordinates (not everywhere) given with two decimal digits (accuracy ~ 2 km in the best case), and in publications as a rule, a site is defined only by its name and *I*.

The names in the publications and base tables, given in Russian, are transformed as follows: national name \rightarrow Russian name (USSR standard) \rightarrow English transcription of Russian name in the initial data files. As a result, the name spellings are frequently different in several initial files and differ from the standard national names. In these cases, the Latin name spelling is taken from Google Earth; if the name does not exist there, the official name from Global Gazetteer is used.

Table A.2

Number of earthquakes observed in Romanian sites.

Number of observed events	6	5	4	3	2	1
Initial number of sites	–	–	–	2	161	3605
Final number of sites	1 ¹	10	145	340	648	980

¹ Bucharest.

A.3.1. Moldavian data

The coordinates of IDPs are taken from a 1:500,000 scale map with an accuracy worse than 1 minute. For sites with different positions in the different available files, the coordinates are taken mainly from Global Gazetteer. We have found moderate amount of various mistakes (Supplementary Table D1). The number of observation is 674 in 394 sites.

A.3.2. Data for Ukraine, Russia, Byelorussia, etc.

Coordinates of the IDPs are defined using 1:750000 scale maps (Evseev, 1969). The best accuracy is 750 m and is ~ 2 km in most cases. For the 1940 event, three IDPs are added from the publication by Moscalenko and Roman (1980) and 26 IDPs from the publication by Nikonov (2010). The data for the 1977 event are contained in the initial file without site names, and the low accuracy of coordinates permitted the assignment of names by means of Google Earth only to part of the IDPs.

A.3.2.1. Ukraine (without Crimea). The publication used (Kostiuk et al., 1983) for the 1977 event contains a list of observations {name, *I*} subdivided by provinces. A province name is very helpful during the search for coordinates by settlement name. We have not been able to identify coordinates of two villages: Orzhivka, *I* = 4 and Nadove, *I* = 4.5 and these IDPs are lost.

The base table for Ukraine (639 IDPs) contains 180 IDPs without coordinates. To link the given names with anonymous coordinates in the initial file, we had to find the coordinates for those names by means of the Internet. The comparison of the two versions of coordinates (obtained from Google Earth and given in the initial file) reveals the very low accuracy of coordinates in the initial file and many mistakes in the base table, inherited by the initial file. For example, we find 14 cases of site positioning in an incorrect province (effect: localisation error up to 4°).

113 IDPs from the base table and 9 IDPs from publications have been added to the initial data file. We had to discard 18 published IDPs, whose names can be associated with several (up to 11) villages in the same province. Some gross errors (5 cases), in which the anonymous IDP falls outside Ukraine or in the sea, led to the exclusion of some IDPs because we did not find a plausible cause for the errors. A similar situation appeared in the data for other parts of the former USSR: we found 15 errors in 73 IDPs.

A.3.2.2. Crimea. The initial data file for Ukraine contains only 22 IDPs, while dense observations in Crimea for the 1977 event are published as a macroseismic map (Ananin et al., 1980). The separate base table, which was manually compiled by Stepanenko (Kishinev) using the published macroseismic map, contains 177 observations: {*I*, name}. One site with coordinates 45.117°N, 35.483°E is present twice as Dalniye_Kamyshi (old name), *I* = 4.5, and Primorskiy (modern name), *I* = 2.5; intensity 4.5 is selected. Four IDPs are discarded because they cannot be found by name (two pioneer's camps, "forestry" and "refuelling"). Another four IDPs are lost because their names are not uniquely connected with a specific settlement due to several identically named villages (Aleksandrivka, *I* = 5; Lugovoe, *I* = 4; Privol'ne, *I* = 4 and Novonikolaivka, *I* = 3.5). As a result, we have a final 141 observations in the Crimean peninsula for the 1977 event.

Data for the 1986 event are published (EQ1986, 1990) as a list {name, *I*, distance to epicentre}. This format discourages the search for site localisation by name. The comparison of the initial data file with the base table and the publications combined with the check of coordinates by Google Earth reveals the presence in the initial data file of several errors that can be summarised as follows: (a) 52 sites with *I* > 1 and all sites (42) with *I* = NF (not felt) given in the base table are lost; (b) 1 site with *I* > 1 and 9 sites with *I* = NF given only in the publication are lost; (c) the file contains 32 unnamed and unpublished sites, 3 of which define unpopulated places and

are discarded; (d) 56 misprints; (e) 14 sites existing in the initial file as two versions, correct and mistaken and (f) 4 sites with $I=4$, which are absent in the source codes, are located between several small villages and cannot be linked with a settlement, and thus they are discarded as presumably erroneous. In addition, 9 errors have been found in the base table. Three published observations are not localised and discarded: Vilkovintsi, $I=4$; Kriakovets, $I=3$; state farm “Lenino”, $I=2.5$.

A.3.2.3. Crimea. The full table of observations {name, I , province}, kindly supplied by B. Pustovitenko (Simferopol), contains 130 IDPs without coordinates. After appointment of coordinates, six sites are not identified and discarded (Abrikosovka in the Belogorsk district, $I=3.5$; Vishenki, $I=3.5$; Aleksandrovka in the Krasnoperekop district, $I=2.5$; Kirovskoe in the Chernomorsk district, $I=2.5$; Orlovka in the Bakhchisaray district, $I=2.5$ and Kirpichniy in the Simferopol district, $I=NF$). As a result, 124 observations in the Crimean peninsula are available for the 1986 event.

Data for the 1990 (main), 1990 (aftershock) and 2004 events contain infrequent misprints and isolated instances of omitted observations. Lists of IDPs for the 1990 events are published (Drumea et al., 1992) without province name and without epicentral distances. Although this information shortage complicates site searches, 30 sites for 1990 (main) event and 12 sites for the 1990 (aftershock) event are added to collected data.

The list of IDPs for the 2004 event (Seismological Bulletin of Ukraine for 2004, 2006; Skliar et al., 2010) contains the province names and partly the district names; 21 IDPs are added from these publications. Four published observations are not localised and lost: Doroshevka, $I=4$ and three IDPs associated with several identically named villages (Dachne in Crimea and Aleksandrivka in Kirovograd province, $I=3.5$; and Novonikolaivkain Kirovograd province, $I=3$).

The number of observed events at the Ukrainian and Byelorussian sites see in Table 4 (Section 4).

A.4. Hungarian data (edited by K. Gribovszki)

The data set for the 1977, 1986 and 1990 (main) events consists of 201 IDPs in 149 sites.

Published complete tables {name, Lat , $Long$, I } are available for the 1986 and 1990 (main) events (Zsiros, 1989, 1994). These publications contain comments about the reliability of intensities.

The data for the 1977 event are published as a list {name, I } (Csomor and Kiss, 1977). The coordinates for the 1977 event are assigned using the national map. The accuracy of intensities is low because only a few questionnaires were collected.

All Hungarian sites have unique names except Budapest for the 1977 and 1986 events, represented by 10 IDPs in different districts of the city.

A.5. Serbian data (edited by S. Radovanovich)

A total of 689 IDPs in 612 sites are available for the 1940, 1977, 1986, 1990 (main) and 2004 events. Different sites with the same name are found, typically in rural areas (in 14 cases 2–3 villages have the same name).

In this work, the intensities for 1940 event are re-evaluated in the MSK scale. In the “Macro-catalogue of Serbia”, 1073 localities have been recorded with originally defined intensities. For 325 localities, there is a description of the earthquake effects, which enabled the definition of macroseismic intensities according to the MSK scale. For 748 localities, there were no descriptive data about damage, and thus earthquake intensities could not be redefined although arguments exist that the earthquake was felt in those places. The number of originally defined intensities in these locations is given in the top line of Table 5. For 325 localities, where damage descriptions exist,

Table A.3
Number of initial and revised IDPs in Serbian data for 1940 event.

IDPs:	Intensity				
	VII	VI	V	IV	III
Initial	59	47	56	409	502
Revised	6	54	30	164	71

the revision of intensities was performed based on the characteristics of the buildings (vulnerability class), the degree of damage and the quantity of damaged constructions.

Buildings with wood-framed masonry were the most common structure type in the rural areas of East and Central Serbia until 1945. These buildings, where soil or unbaked bricks make up strongly connected walls, (a) behaved quite well under seismic load even when the walls were damaged, because the wooden frames remained secure due to their higher ductility, furthermore (b) the damages reported for this type of building were classified as effects of VII degree MSK according to the description “some houses collapsed and chimneys fell” (see village Jabukovac in Fig. 1). On account of (a) and (b), the appropriate description of damage according to the MSK scale is: VII degree “collapse of some buildings, with chimneys collapsed”; VI degree “chimneys falling down with cracks in the walls and falling plaster”; V degree “falling plaster and cracks in the walls” and IV degree “shaking of furniture, windows and doors”. As a consequence, the final seismic intensity for 19 localities turns out to be 2 degrees less than the intensity originally defined by Mihajlović in 1941, including some localities where intensity VII has been reduced to intensity V (see bottom line in Table A.3).

In sites where the earthquake intensity was significantly higher or lower than the intensity in the surrounding area, local soil conditions are analysed to understand the reason for the anomalous intensity. As a consequence of Vrancea intermediate-depth earthquakes, an anomalously large macroseismic effect is observed in the villages of Central Serbia. They sit on alluvium in the valley of the Great Morava River. The IDPs of these villages are included in the data set despite their peculiar local ground conditions. The data for the 1977, 1986, 1990 and 2004 events are taken from the “Macro-catalogue of Serbia” without revision.

The effect of intermediate-depth Vrancea earthquakes on all buildings and structures, which have a long oscillation period and are located on soft and unconsolidated soil, is evident in the spatial distribution of the macroseismic effects of the 1940 Vrancea earthquake. The question remains whether the probabilistic EMS-98⁶ approach, which is to be adopted, is able to account for the significant effect of distant earthquakes (such as the ones in Vrancea) in the area of East and Central Serbia.

A.6. Macedonian data (edited by L. Pekevski)

The data for the 1977, 1986 and 1990 events are represented by 42 IDPs in 24 sites (Cejkovska et al., 1995; Hadzievski et al., 1988; Jordanovski et al., 1991, 1998). The coordinates are given with low accuracy, two sites had wrong coordinates. Observations are not dense: distances between the nearest IDPs are 5–36 km.

The Vrancea strong earthquakes were felt throughout the whole territory of Macedonia. Because of the large epicentral distance (>700 km) and because of the long-period components of the seismic waves, the local soil influence (local macroseismic increment) was practically negligible, and the entire Macedonian territory was affected by intensity V on the MCS scale during the 1986 event and by intensity IV (MCS) during the 1990 event. In 1977, the MCS intensity that affected Macedonia varied from VI in the north-east to IV in the south-west (Hadzievski et al., 1983).

⁶ European Macroseismic Scale (Grünthal, 1998).

Because the intensity is given in the MCS scale, I -values are transformed to the MSK scale (used in all other I evaluations) by the equation: $I_{MSK} = I_{MCS} \cdot 5/6$ (Decanini et al., 1995). The original values, I_{MCS} , are kept in final data file as comments.

Appendix B. Web sites used for data checking

Geographical names is a worldwide list of geographical names. Access to a name is only by country → name. The formal accuracy of coordinates is 1 second; names are given in Latin transcription. In the worldwide list there are few erroneous coordinates and in the study area three errors have been identified and duly corrected. http://www.geographic.org/geographic_names.

Global Gazetteer is a worldwide list of cities/towns. Access to group of names is by country → starting letters of a name or by country → province → starting letters of a name. Coordinates are given with formal accuracy of 1 minute. It also incorporates elevation (in ft and m), rough topographic maps, Google maps, etc. Villages are frequently absent. Global Gazetteer, version 2.2, 1996–2010, Falling Rain Genomics, Inc. <http://www.fallingrain.com/world/>.

Google Earth, v. 5.1.3535.3218, is a worldwide rich geographic information and it includes topographic maps, satellite maps and additional information. Access is by coordinates or by city name (for large cities only). High coordinates accuracy is provided, national and Latin names are given, the size of populated area is visible. The details of the map content are varying in space. The symbols of city/village are often shifted with respect to the centre of the settlement. In Byelorussia and the Republic of Moldova villages are named rarely. <http://earth.google.com>.

Ukrainian cities is a rich list of Ukrainian cities/villages. Access to group of names is by province → 1st letter of a name. Names are given in Russian, as in macroseismic data sources for Former USSR. Formal accuracy of coordinates is of the order of seconds. Some errors in coordinates exist. <http://town-map.com.ua>.

Google is used to find the city/village names that are not found in other Internet sites. It is also useful to find alternative names or, sometime, new names of localities after their renaming <http://www.google.com>.

The *Garmin Map Source* version 6.15.11 contains highly detailed maps of major metropolitan areas in Europe. It can display the current location on a map. The maps are vector-based and stored in the built-in memory or loaded from additional flash media. The built-in map (or 'basemap') displays all country borders and major cities only. We used a local version with accuracy below 1 second (Garmin R.O.A.D 3.02) that has been developed by a Romanian company (<http://www.garmin.ro>).

Appendix C. Methods of generalisation of macroseismic map

Two formalised methods are offered by Molchan et al. (2000, 2002). We describe these methods following Molchan et al. (2002).

C.1. The modified polynomial filtering (MPF) method

To smooth IDP-maps, the local polynomial filtering (Tosi et al., 1995) is extended to make the adjustment of the smoothing radius to the local density of observations possible. "A circle $B_R(g)$ of radius R is centred at a point g of a regular grid. The radius is increased in the interval $(0, R_0)$ until at least $n_p(g_k, I_k)$ points with n_l different intensity values fall into the circle. The data in the circle are fitted with a polynomial of degree two, $P_2(\cdot)$, by the least squares method. The value of $P_2(g)$ is assumed to be the estimate $I^*(g)$ of I at g " (Molchan et al., 2002).

The typical parameters for the Vrancea events are $n_p = 12$, $n_l = 3$ and $R_0 = 70$ km. "The distribution of I at the periphery is estimated at a point g , when the points that fall into $B_R(g)$ are seen at an angle

$\varphi \geq 190^\circ$ looking from the centre, thus avoiding unjustified extrapolation of the I observations. For the resulting smoothed $I^*(g)$ field, the area where $I^*(g) > (I - \Delta/2)$ is adopted as the isoseismal area of level I . Here, $\Delta = 1$ is the step in I^* (ibid).

C.2. The Diffuse Boundary (DB) method

The DB method allows for the visualisation of the uncertainty of isoseismals. "Let us consider the one-dimensional case of (g_k, I_k) macroseismic observations. In 1D case, by definition, the isoseismal areas are a set of embedded intervals with intensity $\geq I$ whose length increases with decreasing I . For a given intensity level, J , we must separate $I_k \geq J$ points (labelled '+') from $I_k < J$ points (labelled '-') on the line. When the observations are error-free, a cluster of pluses lies between two clusters of minuses. The empty intervals Δ_1 and Δ_2 that separate the pluses from the minuses define the diffuse isoseismal boundary of level J .

Because real data involve some noise, a few '-' points may be present in the cluster of pluses. In Fig. C1, an 1-D variant is shown where the plot starts from the barycentre of the pluses taken at zero, and the interval boundary Δ_2 is defined. The noise level that is present in the data can be quantified considering a small parameter ε and the interval $\Delta_2 = (a, b)$, which separates the cluster of pluses $[a', a]$ from the cluster of minuses $[b, b']$. Pluses surrounded by minuses, when found at the periphery (on the right in Fig. C1), can be naturally assumed to be erroneous. Δ_2 has the following property: the number of pluses in the interval $[a, \infty)$ is less than $\varepsilon \cdot 100\%$ of the total number of pluses in $[0, \infty)$, while the number of pluses in $[a', \infty)$ is greater than $\varepsilon \cdot 100\%$. In this case, Δ_2 is taken as the right-hand diffuse boundary between the pluses and minuses. A similar definition is valid for Δ_1 . Thus, the parameter ε specifies the threshold of the possible error in the peripheral pluses" (ibid).

To go to the two-dimensional case "let us assume that the area G_I inside isoseismal, where the intensity is greater than or equal to I , is convex, and let us consider a strip, L , across an I -map. The strip is defined by the width H , the direction φ of its axis and the distance r of its axis from the epicentre. Projecting all IDPs that fall within this strip onto its axis, we get the 1-D case: two intervals Δ_1 and Δ_2 on the L line will characterise the uncertainty of an isoseismal of level I , when the I -map is viewed along the L line. The resulting boundary Δ for the strip L is the local diffused boundary (LDB).

Evidently, a single LDB can be unstable due to the noise in data, its strong dependence on the parameter ε . Sorting all possible LDBs (r, φ) (after discretization) on the IDP-map, we obtain a two-dimensional family of LDBs for given intensity I . To obtain a more stable object, the DB-function, the LDBs are additively accumulated in each point of the area covered by macroseismic observations. The area where DB-function exceeds the p level of maximum is considered as the diffused boundary, DB, of level p " (ibid).

The algorithm described above is valid for a convex G_I . Consequently, a DB isoseismal loses some of the Δ_i intervals for the boundary points of G_I , which are internal to the convex hull of G_I .

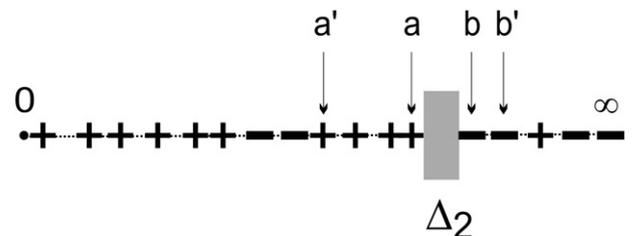


Fig. C1. The schematic definition of the interval boundary between pluses and minuses (DB method), for more details see Molchan et al. (2002).

Nevertheless, this fact does not hamper the identification of large-scale disconnected components of G_f or of peculiarities at the boundary of G_f (Kronrod et al., 2002; Molchan et al., 2002).

“The DB method involves two basic parameters: the strip width H and the noise parameter ε . The former is a smoothing parameter governed by the density of the observations: the higher the density, the smaller is H .” (ibid) The typical values used for the data of the Vrancea earthquakes are $\varepsilon = 5\%$ and H in the range 20–60 km.

The DB method is well suited to dealing with the comparison of peak values of ground motion, PGA, PGV (peak ground velocity) and PGD (peak ground displacement), when available, and I distributions in space.

Appendix D. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.tecto.2013.01.019>.

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