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The revision of the October 30, 1901 earthquake, west of Lake Garda (northern Italy)

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ABSTRACT On November 24, 2004 an earthquake (M_w= 5.0) struck the west side of Lake Garda (northern Italy), producing moderate but widespread damage. It provided the opportunity of reviewing the seismicity of all the area over the past two centuries, whose former most significant event is the October 30, 1901 earthquake (M_w= 5.5), while other minor but damaging events are the January 5, 1892 (M_w=5.0) and November 16, 1898 (M_w=4.6) earthquakes. On the reviewing we found common similarities in ground shaking distribution as recurrent damaged spots, amplification zones due to local site condition or energy radiation. We believe that these findings are suitable to provide information for provisional purposes in low hazard level area hampered by the lack of knowledge about the seismic sources. New data are provided both in MCS scale and EMS. The sensitivity of a source parameters estimation technique was evaluated for the major event.

Key words: MCS intensity, EMS intensity, northern Italy, damage scenario.

1. Introduction

The repetition of events in the same area with similarities in the damage distribution is a rather common case. Some examples from Italy include the Santa Sofia 1768 (M_w=5.8) and 1918 (M_w=5.8) or the Mugello 1542 (M_w=5.9) and 1919 (M_w=6.2) earthquakes in the northern Apennines, as well as the Irpinia and the Benevento areas in the southern Apennines, affected by events with the same damage patterns in the central Apennines. The last important case in Italy is the L'Aquila 2009 earthquake (M_w=6.3) that hit the same area of the 1461 (M_w=6.4) event (Stucchi *et al*., 2009).

In this context, the Lake Garda territory (northern Italy, Fig. 1) lends itself to an interesting case study that experienced earthquakes in the last centuries with comparable level of damage. We focused our attention on the study of macroseismic information of the historical events because they play an important role in the definition of the seismicity of this area, where geological and geophysical evidence is still poor.

The seismic hazard level of the western Lake Garda is classified modest to rather strong, characterized by predictable horizontal acceleration peaks ranging from 0.150 g to 0.175 g according to the 475 year return period seismic hazard map [Fig. 1, inset: Gruppo di lavoro MPS (2004)], but the risk level should be considered high because of the productive, economic, and touristic features of this territory, thus requesting a reliable predictive risk estimation. Indeed, the Lake Garda is famous for its natural beauty, witnessed by the construction of patrician villas in Roman times and, nowadays, by a large influx of foreign tourists. Millions of visitors are recorded each year, 70% of which came from the central-northern Europe. The request of hotel and tourist facilities led to a complete saturation of the building stock located mainly on the shoreline, close to the only communication line running along the coast, and creating a critical vulnerable urban situation with high exposure level.

Westward of Lake Garda, tourist facilities pass to a large variety of economic activities, including a remarkable steel industry concentration in the Val Sabbia, a valley west of Salò drained by the Chiese River (Fig. 1). The local industrial production represents an important part of the national framework, testified by the presence in the area of 2.8% of the national active companies (ISTAT, 2001).

The most recent strong earthquake occurred on November 24, 2004 (M_w=5.0) and, although without casualties, has caused damages up to 215 million € in 66 municipalities: 500 residential buildings were damaged (and about 40 demolished), 200 public structures and 300 churches were cracked. Nearly 1200 buildings, 10 of which had strategic public interest and more than 50 with historic or artistic value, became unfit for use and over 2300 people were displaced. The pipeline of water supply, the electricity network, and some segments of the secondary road network suffered heavy damage. In addition, the widespread occurrence of steep slopes in the area favoured the co-seismic collapse of boulders.

In the present study we review the macroseismic information of the October 30, 1901 event and other minor damaging events (January 5, 1892 and November 16, 1898) occurred during the XIX century in the western Lake Garda area, by analyzing the common features in the damage distribution in the light of the knowledge acquired from most recent and best-studied 2004 event.

As a result, the careful revision of the macroseismic field enhances the assessment of the magnitude of the updated major historic event and of the geometric parameters of its seismic source. A rough estimation of expected damage for the repetition of the revised major event is then performed, especially in light of the recent Po Valley earthquake that, despite its magnitude (events less than 6), has crippled the local economy and caused extensive damage.

2. The Lake Garda seismicity

The northern Italy seismicity is characterized by the north-eastern sector, historically affected by earthquakes which may reach M=6.5, and the western Alps, that have experienced in the past earthquakes with $5.0<M<6.0$. The two areas are separated by a central sector where seismic activity, albeit very irregular and generally moderate, produced the 1117 earthquake, considered as the most destructive event of northern Italy. Unfortunately, our knowledge of this central sector, especially for the older centuries, is still limited, as the catalogue completeness for earthquakes of M>5.5 seems to have been achieved since the XVI-XVII century (Albarello *et al.*, 2001; Albini and Rovida, 2010).

Basing on historical seismic catalogues the seismicity of the Lake Garda region is low, displaying few M_w>5.0 earthquakes during the last millennium (Rovida *et al.*, 2011). Clusters of seismicity are recorded on the eastern side of Lake Garda, while other events are located around

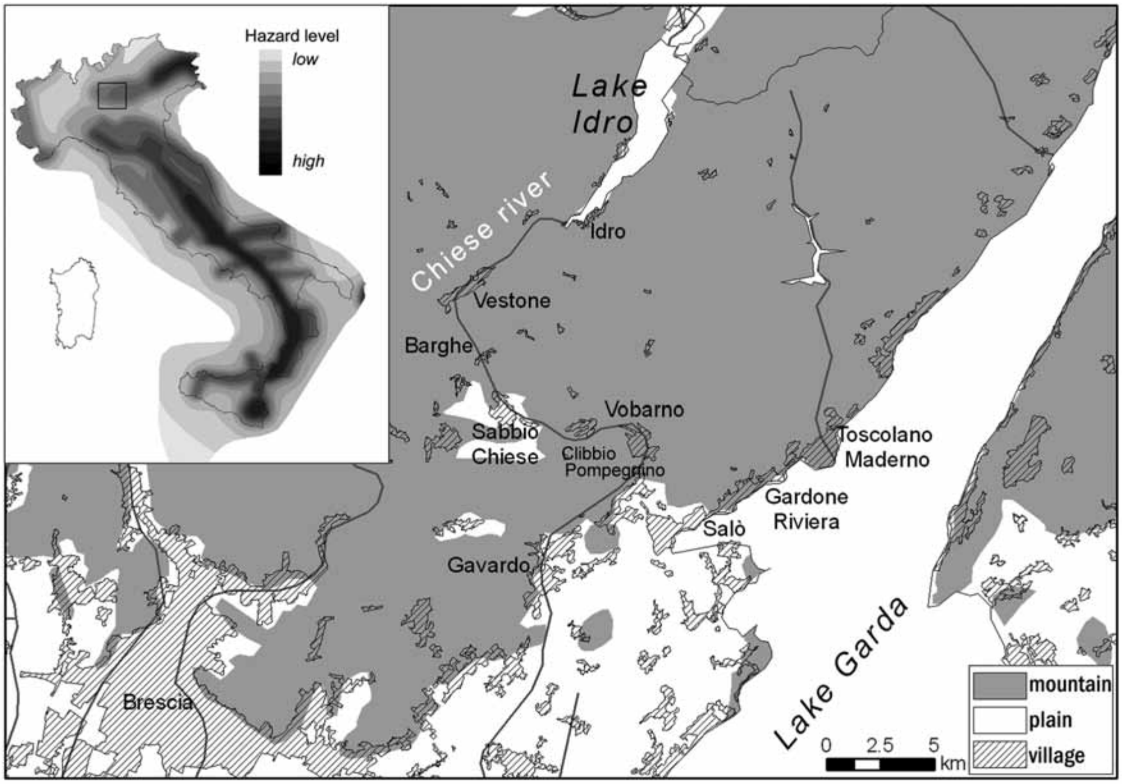

Fig. 1 - Map displaying the regional geographical context of the study area. The main localities in Val Sabbia and along the Lake Garda discussed in the text are displayed. Inset: national seismic hazard map (modified from http://zonesismiche.mi.ingv.it/, Gruppo di lavoro MPS, 2004).

its southern part, as those of 1826, 1892, and 1898 (Fig. 2). Several historical moderate events, occurred in 1065, 1197, 1521, 1540, and 1894, are all centred on the city of Brescia, raising doubts about their correct localization. At this regard, earthquakes known to parametric catalogues between the XI and XVIII century are poorly documented and tend to be biased by the major urban centres, for historical and cultural reasons. A partial exception is represented by two major earthquakes that occurred respectively in 1117 (I_0=IX, M_w=6.5) ~20 km SW of Verona (outside Fig. 2) and in 1222 (I_0=VIII-IX, M_w=6.0) in the Brescia Plain (Fig. 2), for which many documentary traces are available, but not sufficient to provide a good localization for both the events.

These earthquakes have not been considered in the present study because the 1117 is probably located far away in the eastern bank of the Lake Garda, whereas the 1222, alternatively located SE [Rovida *et al.* (2011), based on the study of Boschi *et al.* (2000)] or SW of Lake Garda (Boschi *et al.*, 1995), seems to display an area of major effects different from the damage distribution of the 1901 earthquake, object of the present paper.

None of the events of the area is definitely associated to surface faulting. Even though some authors claimed to have identified active faults in the Lake Garda region from geological evidence (Castaldini and Panizza, 1991), the definition of the seismogenic source responsible for

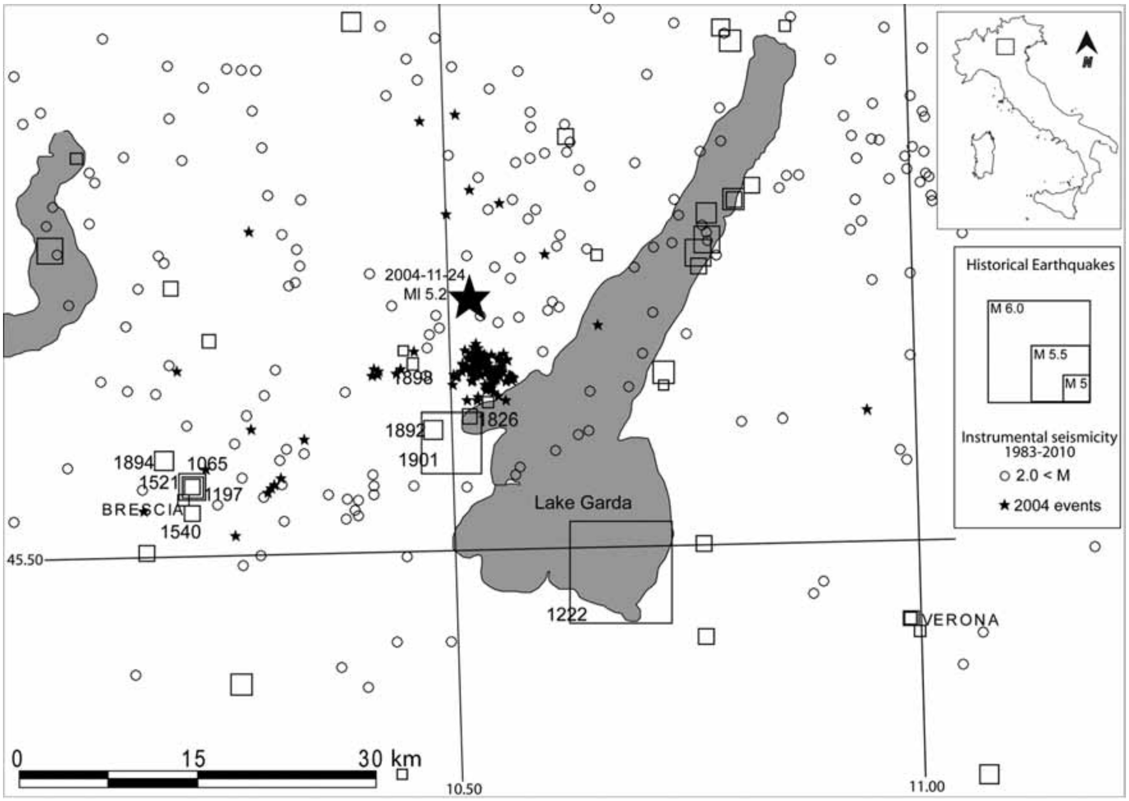

Fig. 2 - Distribution of historical seismicity (squares) in the 1000-1980 time interval (Rovida *et al*., 2011) and recent seismicity (circle) from 1983 to 2010 (ISIDe Working Group, 2010). Black stars represent the 2004 seismic sequence (Augliera *et al*., 2006).

the 1901 event is still mainly based on the macroseismic information (DISS Working Group, 2010). The identification of the seismogenic sources in this sector of the Alps remains indeed a hard task. The limited source dimensions, mainly belonging to blind thrusts, as well as the strong exogenic modelling of the area occurred during glacial stages make interpretation of recent deformations difficult (Galadini and Stucchi, 2007) and the few recognized surface ruptures in the southern Alps do not match any known historical earthquakes (e.g., Galadini *et al.*, 2001).

3. The historical investigations

3.1. Material and methods

Our study focused on the research of unpublished information and the revision of the already known sources. The research of unpublished information started from the recovery of the original data provided by seismological compilations and was carried out by means of a systematical sifting of national and local coeval newspapers and a careful digging into local archives. Another important source is represented by the “seismic postcards”, a documentation provided by the widespread network of local correspondents to the former Central Bureau of Meteorology and

Geodynamics (UCMG) in the morrow of an event and currently stored in the archive of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). These postcards have been an important source of macroseismic information in Italy for about 70 years, starting from 1887 till the late 1950's. In the present study they were critically revised, independently by the former interpretations.

We also assessed the macroseismic intensity of the revised earthquakes both in MCS and in EMS98 scales, according to the recommendation of using EMS98 intensity also for historical events (Grünthal, 1998). The intensities assessment into the EMS98 scale was performed by means of a real evaluation of the descriptions from the sources (Grünthal, 1998; Musson *et al.*, 2009). The EMS98 scale organizes the buildings in vulnerability classes and in our study we assumed that all the damaged buildings were stone rural houses not perfectly held, thus classifiable in the most vulnerable category "A" (Grünthal, 1998), due to the age and the bad state of maintenance a detail also attested by contemporary sources.

3.2. The January 5, 1892 and the November 16, 1898 earthquakes

New information concerning the 1892 and 1898 events emerged during the study of the 1901 earthquake, the maximum historic event of this area.

The Lake Garda area was hit by an earthquake on January 5, 1892, with epicentral intensity I_0=VI-VII MCS (M_w=5.0) according to CPTI11 catalogue (Rovida *et al.*, 2011). A revision of all available sources allowed a more accurate assessment of intensities, even the seismic postcards (UCMG, 1892-1901) were reassessed, independently by the former interpretation given by Cancani (1902).

The maximum intensity VII-VIII MCS, formerly assigned to the village of Campazzi, on the east side of the Lake Garda (Fig. 3a), resulted by the observation of a single damaged rural building (Goiran, 1892). As we do not consider this observation significant enough to assess the intensity degree to the whole locality, we moved this intensity attribution to a more pertinent V-VI MCS. Following this adjustment, the maximum intensity site becomes Salò (VII MCS), where some chimneys fell down and some buildings suffered large cracks. Intensity VI-VII MCS has been confirmed for two localities (Soprazocco and Vobarno) and newly assigned to Gavardo. The data revision accomplished the generation of a new macroseismic field (Fig. 3a). Maps herein presented show the MCS data for sake of the comparison with the previous published intensity fields [DBMI11: Locati *et al*. (2011)].

After the revision, the number of intensity-assigned localities increased from 91 to 96 (Table 1) and the comparison between the previous and the new assigned intensities shows that more than 40 localities changed their former intensity assessment, of which almost 30 increase their value.

Another minor event (I_0=VI, M_w=4.6) struck on November 16, 1898 the same area, but it is scarcely known because of its low damage impact. A coeval compilation (Baratta, 1901) informed that major effects occurred in Val Sabbia. The revision of the seismic postcards (UCMG, 1892-1901) also provided also useful information about the "*not felt*" data allowing to better define the whole perception area of the earthquake. The Fig. 3b shows the distribution of macroseismic observations, which after the revision passed from 23 [DBMI11: Locati *et al*. (2011)] to 43 (this study: see Table 2). Moderate damage was recorded in Salò and in Val Sabbia (Fig. 3b), together with few rock collapse episodes.

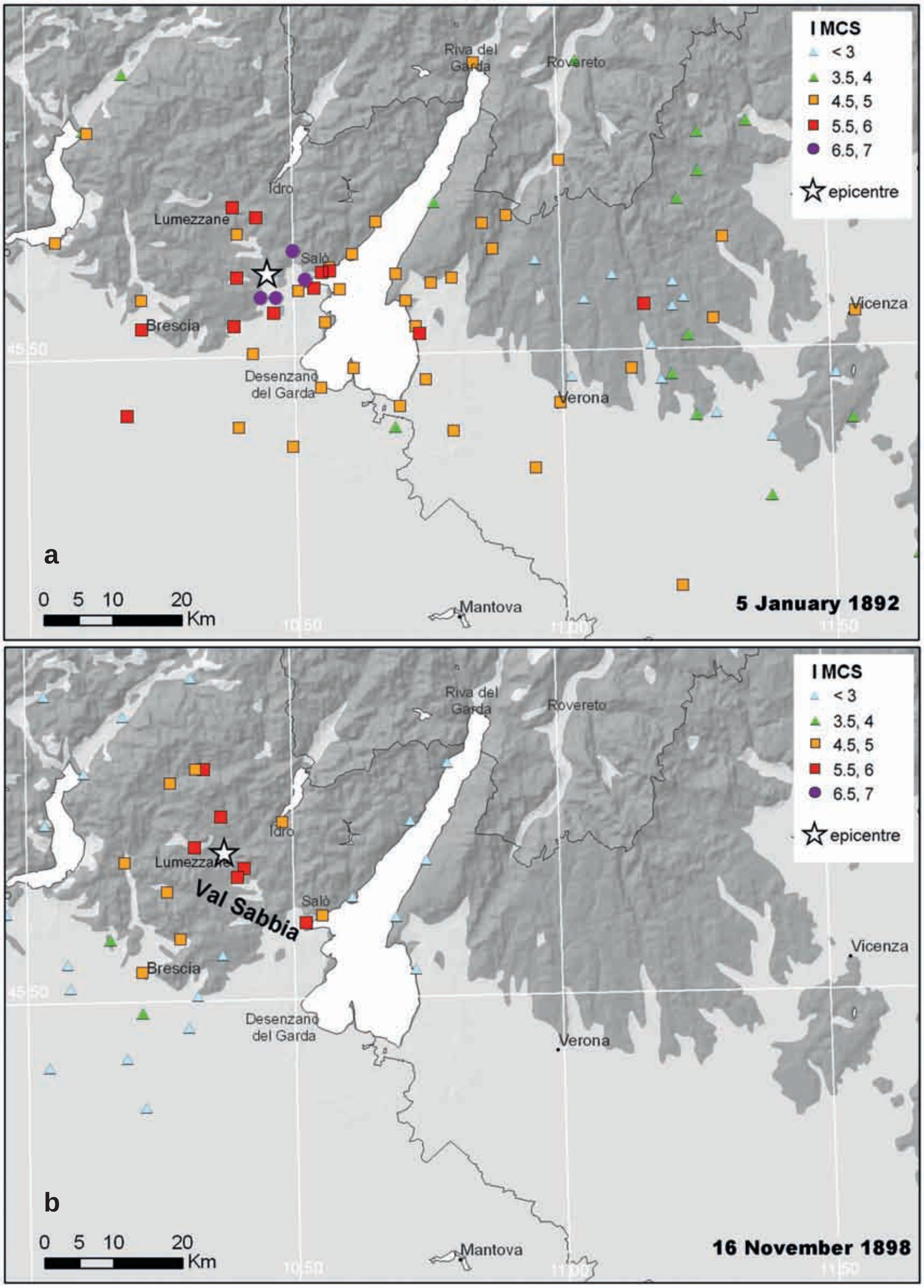

Fig. 3 - Revised macroseismic data of the 1892 earthquake (a). Revised macroseismic data of the 1898 earthquake (b). Star indicates the macroseismic epicentre location calculated with the new data by the Boxer 4.0 code (Gasperini *et al*., 2010).

Table 1 - Macroseismic intensities of the January 5, 1892 earthquake. Revised intensities are given in EMS and MCS; the latter are compared with the MCS intensity values included in DBMI11.
SC = Special Cases: MS = Multiple settlement: settlement whose traditional place name refers to a set of small settlements in a limited area, including small islands. The code represents a warning for the user.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI11	*I* MCS	*I* EMS
Salò	BS		45.606	10.522	6-7	7	6-7
Soprazocco (Gavardo)	BS		45.583	10.467	6-7	6-7	6-7
Vobarno	BS		45.644	10.500	6-7	6-7	6-7
Gavardo	BS		45.583	10.439	5	6-7	6
Barbarano Gardone Riviera	BS		45.615	10.553	6-7	6	5-6
Cisano (Bardolino)	BS		45.595	10.537	6-7	6	5.6
Provaglio Val Sabbia (Cedessano)	BS	MS	45.689	10.431	6-7	6	6
Brescia	BS		45.544	10.214	6	6	5-6
Fasano del Garda (Gardone Riviera)	BS		45.617	10.567	6	6	5.6
Muscoline (Chiesa)	BS		45.563	10.461	6	6	6
Nuvolento	BS		45.546	10.387	6	6	6
Vallio Terme	BS		45.61	10.393	6	6	6
Campazzi	VR		45.533	10.733	7-8	5-6	5-6
Badia Calavena	VR		45.565	11.154	5-6	5-6	5
Bagnolo Mella	BS		45.43	10.184	5-6	5-6	5
Nozza	BS		45.703	10.387	5-6	5-6	5
Belluno Veronese (Brentino Belluno)	VR		45.686	10.900	5-6	5	5
Chiampo	VI		45.544	11.283	5	5	5
Colà (Lazise)	VR		45.472	10.743	5	5	5
Desenzano del Garda	BS		45.464	10.547	5	5	5
Ferrara di Monte Baldo	VR		45.676	10.854	5	5	5
Garda	VR		45.576	10.709	5	5	5
Gardone Riviera	BS		45.622	10.566	5	5	5
Preseglie (Sottocastello)	BS	MS	45.667	10.395	5	5	5
Sirmione	BS		45.489	10.609	5	5	5
Torri del Benaco	VR		45.612	10.691	5	5	5
Villa (Salò)	BS		45.592	10.508	5	5	5
Collebeato	BS		45.582	10.214	4-5	5	5
Caprino Veronese	VR		45.605	10.795	4	5	4-5
Gargnano	BS		45.681	10.655	4	5	5
Iseo	BS		45.659	10.054	4	5	5
Manerba del Garda	BS	MS	45.550	10.557	4	5	5
Pesina	VR		45.599	10.756	4	5	5
Peschiera del Garda	VR		45.438	10.694	4	5	4-5
Isola del Garda (Gardone Riviera)	BS		45.593	10.586		5	5
Valdagno	VI		45.651	11.304	4-5	4-5	4-5

Table 1 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI11	*I* MCS	*I* EMS
Verona	VR		45.438	10.994	4-5	4-5	4-5
TN			45.757	11.001	4	4-5	4-5
Bedizzole	BS	MS	45.510	10.421	4	4-5	4-5
Brentino	VR		45.642	10.873	4	4-5	4-5
Castel d'Azzano	VR	MS	45.353	10.945	4	4-5	4-5
Castiglione delle Stiviere	MN		45.387	10.493	4	4-5	4-5
Cerea	VR		45.194	11.213	4	4-5	4-5
Guastalla Nuova	VR		45.404	10.793	4	4-5	4-5
Toscolano Maderno	BS		45.639	10.610	4	4-5	4-5
Montichiari	BS		45.413	10.393	4	4-5	4-5
Vicenza	VI		45.549	11.549	4	4-5	4
Riva del Garda	TN		45.887	10.844		4-5	4-5
Bassano del Grappa	VI		45.767	11.734	F	F	F
Chiavari	GE		44.317	9.322	3	F	F
Barbarano Vicentino	VI		45.409	11.540	5-6	4	4
Arsiero	VI		45.803	11.354	4	4	4
Este	PD		45.228	11.656	4	4	4
Livigno	SO		46.539	10.135	4	4	4
Brenzone (Magugnano-Marniga)	VR	MS	45.705	10.766	4	4	4
Pavia	PV		45.189	9.160	4	4	4
Pisogne	BS		45.806	10.109	4	4	4
Posina	VI		45.790	11.262	4	4	4
Recoaro Terme	VI		45.703	11.221	4	4	4
Trento	TN		46.064	11.124	4	4	4
Valli del Pasubio	VI		45.739	11.261	4	4	4
Cazzano di Tramigna	VR		45.472	11.204	F	3-4	3-4
Cologna Veneta	VR		45.309	11.385	3-4	3-4	3-4
Spinea (Orgnano)	VE	MS	45.490	12.165	3-4	3-4	3-4
Cavalese	TN		46.291	11.460	3	3-4	3-4
Darfo Boario Terme	BS	MS	45.880	10.183	3	3-4	3-4
Ponti sul Mincio	MN		45.411	10.686	3	3-4	3-4
Rovereto	TN		45.888	11.037	3	3-4	3-4
San Giovanni Ilarione	VR		45.523	11.236	3	3-4	3-4
Soave	VR		45.418	11.248	3	3-4	3-4
Treviso	TV		45.669	12.244	2	3-4	3-4
Fimon	VI		45.469	11.509	3-4	3	3
Poiano (Verona)	VR		45.472	11.016	3-4	3	3
Bolca	VR		45.594	11.208	3	3	3
Castelvero (Vestenanova)	VR		45.562	11.207	3	3	3

Table 1 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI11	*I* MCS	*I* EMS
Cerro Veronese	VR		45.574	11.042	3	3	3
Chiavenna	SO		46.322	9.402	3	3	3
Illasi	VR		45.466	11.183	3	3	3
Lonigo	VI		45.387	11.388	3	3	3
Miane	TV		45.942	12.091	3	3	3
Milano	MI		45.464	9.190	3	3	3
Modena	MO		44.647	10.925	3	3	3
Monteforte d'Alpone	VR		45.420	11.285	3	3	3
Padova	PD		45.407	11.876	3	3	3
Parma	PR		44.801	10.329	3	3	3
Sant’Andrea d'Alfaedo	VR		45.627	10.952	3	3	3
Sondrio	SO		46.171	9.872	3	3	3
Tregnago	VR		45.512	11.166	3	3	3
Vestenanova	VR		45.573	11.228	3	3	3
Treviri [Germany]						3	3
Velo Veronese	VR		45.605	11.096		3	3
Fontaniva	PD		45.636	11.756	2	2	2
Piacenza	PC		45.052	9.693	3	NF	1

3.3. The October 30, 1901 earthquake

The October 30, 1901 earthquake [I_0=VIII MCS, M_w=5.7: CPTI11 (Rovida *et al.*, 2011)] produced the strongest intensity attribution over the western bank of Lake Garda. The state of the knowledge of this event emerging from the Catalogo dei Forti Terremoti in Italia [Italian Strong Earthquake Catalogue: CFTI (Boschi *et al.*, 1995, 1997, 2000)] is mainly based on press reports, seismological compilations (Baratta, 1901; Cancani, 1902; Cavasino, 1935), and some coeval issues (bulletins and registers from the meteorological stations of Salò, Chiavari, Cremona, Milano, Moncalieri, and Parma, in northern Italy).

The intensity map of the reference database is composed by 191 localities, mainly distributed over the flat areas around Lake Garda (Fig. 4a). The maximum intensity of VIII MCS was assigned to Salò and to the village of Navezze (Fig. 4a) that is, remarkably, quite far from the epicentral area.

Out of the 57 damaged localities (I_s>V-VI), 44 are mainly based on journalistic reports, 12 are listed in the coeval compilation of Cancani (1902), and only 1 is documented by an archival source [a meteorological register: Boschi *et al.* (2000)]. The relative scarcity of data and the consideration that just a very little information is related to localities affected later also by the 2004 earthquake, suggested the possible improvement of the background material (Camassi *et al.*, 2011).

Table 2 - Macroseismic intensities of the November 16, 1898 earthquake. Revised intensities are given in EMS and MCS; the latter are compared with the MCS intensity values included in DBMI11.
SC = Special Cases: MS = Multiple settlement: settlement whose traditional place name refers to a set of small settlements in a limited area, including small islands. The code represents a warning for the user.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI11	*I* MCS	*I* EMS
Barghe	BS		45.679	10.408		6	5-6
Comero	BS		45.707	10.315		6	5-6
Preseglie (Sottocastello)	BS	MS	45.667	10.395	5	6	5-6
Salò	BS		45.606	10.522	6	6	5-6
Avenone Villa e Spessio	BS		45.747	10.365		5-6	5
Collio	BS		45.810	10.334	4	5-6	5
Barbarano Gardone Riviera	BS		45.615	10.553	4	5	4-5
Lumezzane (San Sebastiano)	BS	MS	45.649	10.262		5	4-5
Memmo	BS		45.810	10.319		5	4-5
Bovegno	BS		45.792	10.271	4	4-5	4-5
Gardone Val Trompia	BS		45.688	10.184	4	4-5	4-5
Idro	BS	MS	45.739	10.481	4	4-5	4-5
Nave	BS		45.587	10.286		4-5	4-5
Brescia	BS		45.544	10.214	4	4-5	4-5
San Zeno Naviglio	BS		45.49	10.215	4	4	4
Gussago	BS	MS	45.587	10.156	4	3-4	3-4
Adro	BS		45.622	9.961	3	3	3
Toscolano Maderno	BS		45.639	10.610		3	3
Pisogne	BS		45.806	10.109	3	3	3
Serle	BS		45.565	10.365	3	3	3
Pezzoreo	BS		45.761	10.217		F	F
Bagnolo Mella	BS		45.43	10.184	NF	NF	1
Bardolino	VR		45.542	10.726		NF	1
Castelletto di Brenzone	VR		45.686	10.750		NF	1
Castenedolo	BS		45.470	10.300	NF	NF	1
Castione della Presolana	BG		45.908	10.036		NF	1
Chiari	BS		45.538	9.931	NF	NF	1
Darfo Boario Terme	BS	MS	45.880	10.183	NF	NF	1
Frontignano	BS		45.419	10.039		NF	1
Leno	BS		45.366	10.219		NF	1
Limone sul Garda	BS		45.813	10.792		NF	1
Loveno	BS		46.064	10.249		NF	1
Lozio	BS	MS	45.986	10.261		NF	1
Martinengo	BG		45.570	9.768		NF	1
Ospitaletto	BS		45.555	10.075		NF	1
Parzanica	BG		45.738	10.035		NF	1

Table 2 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI11	*I* MCS	*I* EMS
Prestine	BS		45.930	10.313		NF	1
Rezzato	BS		45.512	10.318	NF	NF	1
Tignale (Gardola)	BS		45.738	10.721	NF	NF	1
Torri del Benaco	VR		45.612	10.691		NF	1
Travagliato	BS		45.523	10.080	NF	NF	1
Trescore Balneario	BG		45.693	9.843	NF	NF	1
Trieste	TS		45.656	13.784		NF	1

3.3.1. Updating the information dataset

Our investigation started from the careful collection and analysis of the informative background of CFTI studies (Boschi *et al.*, 2000) and was then extended both to bibliographic and archival level (Fig. 5a). The critical revision of the original seismic postcards (UCMG, 1892-1901) was a very useful resource to expand the number of reports and to improve intensity assignments of this earthquake. We reviewed and completed the assessments of Cancani (1902), who formerly estimated the intensity of 151 localities basing on the postcards. A large number of local news reports was collected and carefully analyzed. As a whole we retrieved earthquake accounts from 100 localities till now ignored or scarcely noticed by scientific reports. The final number of localities account increased up to 291.

Localities with the new MCS intensity assignment are listed in Table 3, together with the previous values; EMS assignments are listed too.

The most damaged area was limited to the neighbourhood of Salò and to the hamlets of Val Sabbia, albeit the information about this area is scarcely detailed. The maximum intensity (VII-VIII MCS) is now assigned to the localities of Pompegnino and Campoverde (in the close surroundings of Salò: Fig. 4b), where two buildings entirely collapsed, several others experienced a partial collapse, and many houses were severely damaged by downfall of chimneys and ceilings, and by large cracks in the walls. On the whole, 14 localities, including Salò, suffered effects well described by the VII MCS degree (spread downfall of chimneys and tiles, extensive cracks in the walls of many houses, some partial collapse of roofs and walls).

Damage descriptions regarding other 20 localities do not allow a reliable discrimination between VI and VII intensities, due to contradictory or confused records. In this case we estimated the coeval seismological sources or contemporary reports being more reliable than legal documents, used to dispose benefits, published a long time after the earthquake.

The damaged area includes approximately 50 localities with intensities VI and V-VI, and some sporadic damage such as fall of some chimneys, fall of plaster pieces, fall of loose stones, cracks in walls, and vague descriptions. The accounts are in agreement with the effects felt by population, describing a frightening shock and a general escape outdoors. The village of Navezze is included in this group of localities, confirming that the former intensity estimation (*I*=VIII) from the CFTI studies (e.g., Boschi *et al.*, 2000) was strongly overestimated. The information related to Navezze, in fact, pertained only the fall of part of a frieze of the San Vincenzo church

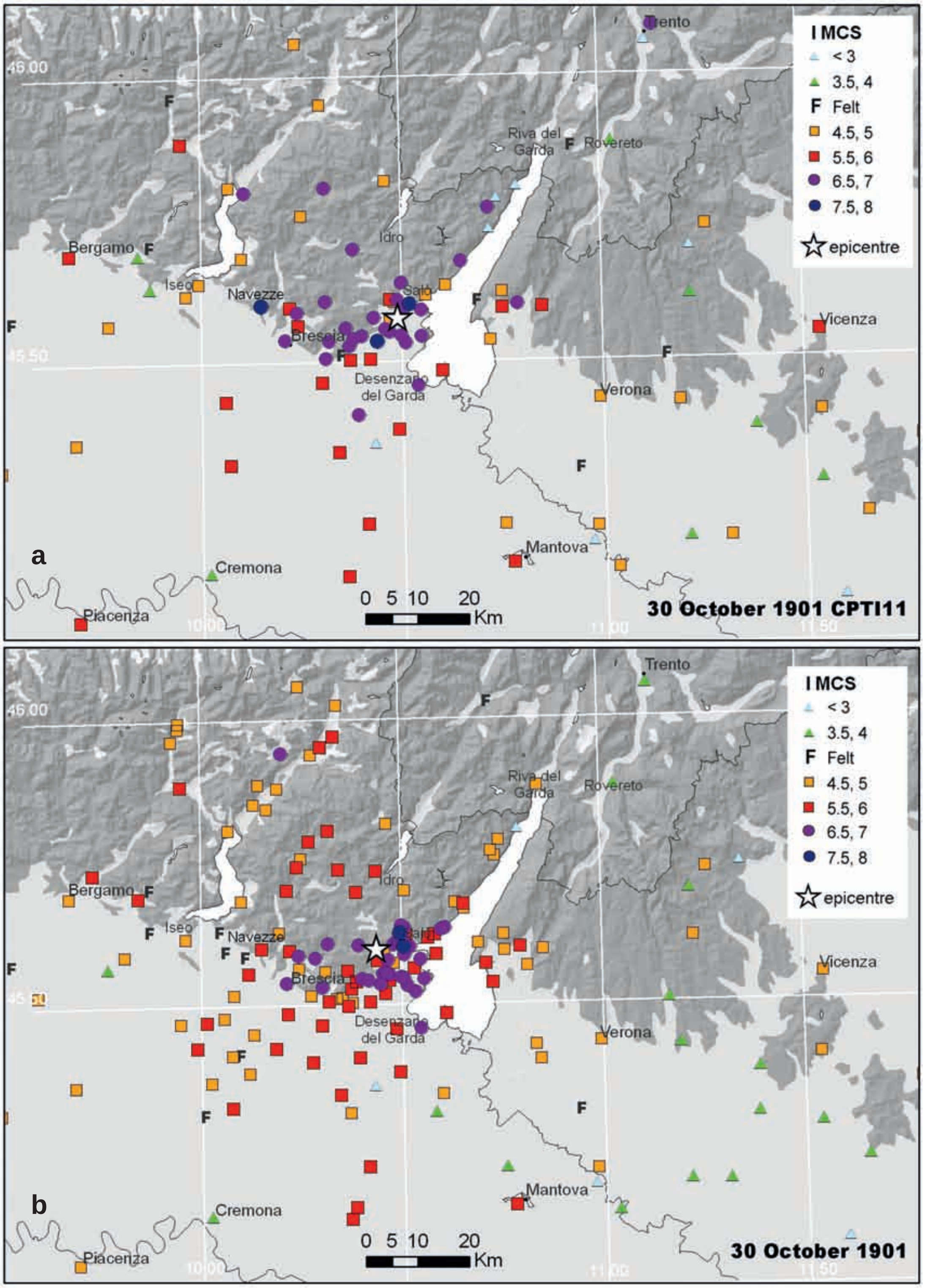

Fig. 4 - Comparison between the maps of CFTI (Boschi *et al*., 2000) (a) and the present revision (b) of the 1901 earthquake. Star indicates the macroseismic epicentre location calculated with the new data by the Boxer 4.0 code (Gasperini *et al*., 2010).

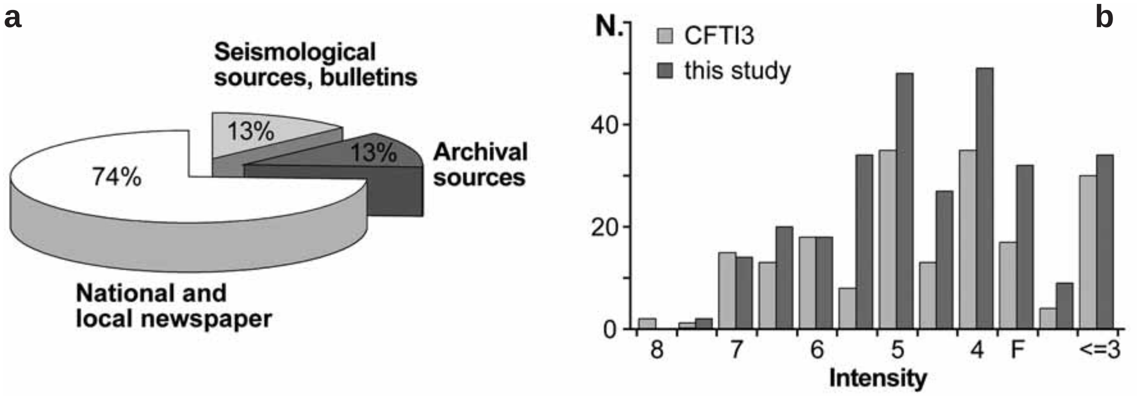

Fig. 5 - Distribution of the coeval sources (a) used by the present study [data from Camassi *et al*. (2011)]. Comparison between observations reported in the CFTI (Boschi *et al*., 2000) and the present study (b).

that is clearly insufficient to justify a high intensity to the whole locality.

Our revision contributed to improve the intensity map by increasing the number of observations from 191 to 291 and producing a more uniform distribution of the intensity points (Fig. 5b and Table 3).

4. The November 24, 2004 earthquake

The most recent significant event that struck the Lake Garda area is the November 24, 2004 moderate earthquake (I_0=VII-VIII, M_w=5.2), located at 45.68° N 10.52° E, with an estimated depth ranging from 5 to 10 km (ISIDe Working Group, 2010). About 200 aftershocks, with magnitudes ranging from 0.2 to 3.6 and clustered in a restricted area north of Salò (Fig. 2), were instrumentally recorded in the aftermath of the main shock (Augliera *et al.*, 2006). The earthquake was felt in the whole northern Italy and also part of Switzerland, Austria, and Slovenia. The maximum intensity, VII-VIII MCS, was observed in two villages of Val Sabbia valley, Clibbio and Pompegnino, where some buildings suffered partial collapses and several others were affected by heavy structural damage (Bernardini *et al.*, 2005). The damaged buildings were mostly old masonry houses, either already in bad state or inappropriately restored before the earthquake (Dimova *et al.*, 2005). Churches and belfries also suffered severe damage. Reinforced concrete structures incurred next to no damage. As a whole, the damaged area was restricted to the south-western side of Lake Garda and to the Val Sabbia (Fig. 6 and Table 4) and this damage pattern reflects roughly the same distribution already observed during the past events.

In order to explain the distribution of the major damage spots in Val Sabbia, ambient noise measurements were carried out in localities along the Chiese River (Barghe, Sabbio Chiese, Vobarno, and Salò) to define the resonance frequency of the loose deposits. The analysis showed seismic amplification at a local scale in the range of critical frequencies for masonry buildings (Franceschina *et al.*, 2009), strongly correlated with the presence of loose deposits of glacio-fluvial origin. Therefore the damage pattern can be explained by local amplification effects,

Table 3 - Macroseismic intensities of the October 30, 1901 earthquake. Revised intensities are given in EMS and MCS; the latter are compared with the MCS intensity values included in DBMI11, based on Guidoboni *et al*. (2007) study. SC = Special Cases. MS = Multiple settlement: settlement whose traditional place name refers to a set of small settlements in a limited area, including small islands. The code represents a warning for the user. SS = Small settlement: settlement the size of which is too small to supply a significant building sample for intensity assessment. AL= Absorbed locality: a locality absorbed into a larger one. The code is a warning for understanding the seismic history

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Campoverde (Caccavero)	BS		45.606	10.506		7-8	7
Pompegnino	BS		45.631	10.498		7-8	7-8
Botticino (Mattina)	BS		45.536	10.302	7	7	6-7
Bovezzo	BS		45.592	10.244	7	7	6-7
Calvagese della Riviera	BS		45.541	10.447	7-8	7	6-7
Gazzane	BS		45.621	10.504		7	6-7
Soprazocco	BS		45.583	10.467		7	6-7
Agneto	BS	SS	45.613	10.508		7	7
Castello	BS		45.560	10.464		7	7
Fontanelle	BS		45.553	10.500		7	7
Polpenazze del Garda	BS		45.551	10.507	7	7	7
Prevalle	BS		45.548	10.419		7	7
Salò	BS		45.606	10.522	8	7	7
San Felice del Benaco	BS		45.584	10.548		7	7
Villa	BS		45.592	10.508	7	7	7
Vobarno	BS		45.644	10.500	7	7	7
Toscolano Maderno	BS		45.639	10.610	5	5-6	5-6
Borno	BS		45.947	10.206		6-7	6
Brescia	BS		45.544	10.214	7	6-7	6
Moniga del Garda	BS		45.527	10.535		6-7	6
Nave	BS		45.587	10.286		6-7	6
Paitone	BS		45.551	10.402	6-7	6-7	6
Soiano del Lago	BS		45.539	10.514	6-7	6-7	6
Tormini	BS		45.610	10.482	5	6-7	6
Vallio Terme	BS		45.610	10.393		6-7	6
Caino	BS		45.612	10.317	6-7	6-7	6-7
Collio	BS		45.639	10.509		6-7	6-7
Desenzano del Garda	BS		45.464	10.547	7	6-7	6-7
Liano	BS		45.619	10.493		6-7	6-7
Longavina	BS		45.559	10.454		6-7	6-7
Maderno	BS		45.636	10.600	7	6-7	6-7
Manerba del Garda (Solarolo)	BS	MS	45.550	10.557	7	6-7	6-7
Morsone	BS		45.558	10.470	6-7	6-7	6-7
Muscoline (Chiesa)	BS	MS	45.563	10.461		6-7	6-7

Table 3 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Trobiolo	BS		45.614	10.504		6-7	6-7
Volciano	BS		45.613	10.495	7	6-7	6-7
Canneto sull'Oglio	MN		45.150	10.379	6	6	5-6
Castenedolo	BS		45.470	10.300	6	6	5-6
Castiglione delle Stiviere	MN		45.387	10.493	6	6	5-6
Nozza	BS		45.703	10.387	6-7	6	5-6
Rezzato	BS		45.512	10.318	6-7	6	5-6
Trescore Balneario	BG		45.693	9.843	3	6	5-6
Verolanuova	BS		45.326	10.076	6	6	5-6
Bagnolo Mella	BS		45.430	10.184		6	6
Caprino Veronese	VR		45.605	10.795	7	6	6
Garda	VR		45.576	10.709		6	6
Gavardo	BS		45.583	10.439	6-7	6	6
Ghedi	BS		45.405	10.276		6	6
Livemmo	BS		45.742	10.344		6	6
Memmo	BS		45.810	10.319	6-7	6	6
Nuvolento	BS		45.546	10.387	7	6	6
Nuvolera	BS		45.533	10.373	6-7	6	6
Serle	BS		45.565	10.365	6-7		6
Sirmione	BS		45.489	10.609		6	6
Longhena	BS		45.43	10.060	6	D	D
Portese	BS		45.596	10.553	6-7	D	D
Puegnago sul Garda (Castello)	BS	MS	45.567	10.510		D	D
Abbiategrasso	MI		45.398	8.916	5-6	5-6	5
Alzano Lombardo	BG		45.734	9.730		5-6	5
Asola	MN		45.221	10.413	5-6	5-6	5
Bardolino	VR		45.542	10.726	5	5-6	5
Bedizzole (Piazza)	BS	MS	45.510	10.421	5-6	5-6	5
Bovegno	BS		45.792	10.271		5-6	5
Breno	BS		45.957	10.303	5	5-6	5
Calvisano	BS		45.348	10.34	5-6	5-6	5
Carzago Riviera	BS		45.525	10.459		5-6	5
Castegnato	BS		45.561	10.117		5-6	5
Gardone Riviera	BS		45.62	10.566	5	5-6	5
Isola del Garda	BS		45.593	10.586		5-6	5
Marcheno	BS		45.707	10.214		5-6	5
Melegnano	MI		45.358	9.323		5-6	5
Molinetto	BS		45.503	10.366		5-6	5
Niardo	BS		45.976	10.336		5-6	5

Table 3 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Piadena	CR		45.130	10.368	6	5-6	5
Pompiano	BS		45.431	9.989		5-6	5
San Zeno Naviglio	BS		45.490	10.215		5-6	5
Tavernole sul Mella	BS		45.748	10.240		5-6	5
Trenzano	BS		45.475	10.013		5-6	5
Castrezzone	BS		45.548	10.469		5-6	5-6
Clusone	BG		45.888	9.950	6	5-6	5-6
Concesio	BS		45.60	10.220		5-6	5-6
Fasano del Garda	BS		45.628	10.582		5-6	5-6
Gargnano	BS		45.681	10.655	7	5-6	5-6
Lavenone	BS		45.739	10.438		5-6	5-6
Lonato	BS		45.462	10.484		5-6	5-6
Mantova	MN		45.152	10.775	6	5-6	5-6
Montichiari	BS		45.413	10.393	6-7	5-6	5-6
Navezze	BS		45.604	10.151	8	5-6	D
Raffa	BS		45.569	10.531		5-6	5-6
Ronchi	BS		45.627	10.511	6-7	5-6	5-6
Sopraponte	BS		45.597	10.440		5-6	5-6
Albese con Cassano	CO		45.797	9.164		5	4
Crema	CR		45.362	9.686	5	5	4-5
Bagolino	BS		45.822	10.465	5	5	5
Barbarano Vicentino	VI		45.409	11.540	5	5	5
Bergamo	BG		45.694	9.670	5-6	5	5
Bogliaco	BS		45.673	10.657		5	5
Brusatasso	MN		44.983	10.785		5	5
Cascina Camerona	NO		45.384	8.755		5	5
Crespadoro	VI		45.619	11.227	4	5	5
Dello	BS		45.417	10.076		5	5
Dolcè	VR		45.600	10.853	5-6	5	5
Erba	CO		45.810	9.226	5	5	5
Gallarate	VA		45.659	8.793	6	5	5
Gandellino	BG		45.990	9.945		5	5
Gromo	BG		45.968	9.928	F	5	5
Gromo San Marino	BG		46.000	9.946		5	5
Lavone	BS		45.762	10.250	5	5	5
Lecco	LC		45.856	9.408	6	5	5
Lodi	LO		45.314	9.501	5	5	5
Lograto	BS		45.483	10.056		5	5
Lovere	BG		45.812	10.070	5	5	5

Table 3 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Lumini	VR		45.627	10.755	4-5	5	5
Mazzano	BS		45.518	10.351	F	5	5
Milano	MI		45.464	9.190	5	5	5
Mompiano	BS		45.569	10.243	6	5	5
Montecchio	BS		45.885	10.193		5	5
Offlaga	BS		45.386	10.118		5	5
Padova	PD		45.407	11.876	5-6	5	5
Parma	PR		44.801	10.329	6	5	5
Pavia	PV		45.189	9.160	5	5	5
Pesina	VR		45.599	10.756	6	5	5
Piacenza	PC			45.052	9.693	6	5
Riva del Garda	TN		45.887	10.844		5	5
Rivoli Veronese	VR		45.571	10.812		5	5
San Eufemia della Fonte	BS		45.522	10.273	5	5	
San Paolo (Pedergnaga-Oriano)	BS	MS	45.370	10.024		5	5
Sermerio	BS		45.774	10.725	7	5	5
Sommacampagna	VR		45.407	10.844		5	5
Sona	VR		45.433	10.832		5	5
Sondrio	SO		46.171	9.872	5	5	5
Sonico	BS		46.164	10.354		5	5
Torri del Benaco	VR		45.612	10.691	F	5	5
Travagliato	BS		45.523	10.080		5	5
Tremosine (Vesio)	BS	MS	45.792	10.745	D	5	5
Verona	VR		45.438	10.994	5	5	5
Vicenza	VC		45.549	11.549	5-6	5	5
Villa Carcina	BS		45.632	10.195		5	5
Villanuova sul Clisi	BS		45.600	10.456		5	5
Virle	BS		45.516	10.337		5	5
Visano	BS		45.316	10.368		5	5
Carate Brianza	MI		45.676	9.239	3	4-5	4
Abano Terme	PD		45.360	11.790	4-5	4-5	4-5
Adro	BS		45.622	9.961	4-5	4-5	4-5
Angolo	BS		45.892	10.145		4-5	4-5
Artogne	BS		45.849	10.165		4-5	4-5
Cadignano	BS		45.765	10.735		4-5	4-5
Capo di Ponte	BS		46.030	10.344		4-5	4-5
Capriano del Colle	BS		45.455	10.129		4-5	4-5
Casello	BS		45.509	10.376		4-5	4-5

Table 3 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Cavriana	MN		45.348	10.599		4-5	4-5
Cividate Camuno	BS		45.944	10.278		4-5	4-5
Colombaro	BS		45.578	10.479	5	4-5	4-5
Comezzano Cizzago (Cizzago)	BS	MS	45.473	9.948		4-5	4-5
Eno	BS		45.705	10.508		4-5	4-5
Garlasco	PV		45.196	8.922	4-5	4-5	4-5
Loveno	BS		46.064	10.249	5	4-5	4-5
Mirandola	MO		44.887	11.065	4	4-5	4-5
Monza	MI		45.584	9.274	4-5	4-5	4-5
Mornico al Serio	BG		45.591	9.809		4-5	4-5
Navazzo	BS		45.684	10.635		4-5	4-5
Olgiate Comasco	CO		45.785	8.968	5	4-5	4-5
Rogno	BG		45.857	10.133		4-5	4-5
San Gallo	BS		45.564	10.309		4-5	4-5
Sorgà	VR		45.214	10.980	5	4-5	4-5
Sulzano	BS		45.688	10.100	5	4-5	4-5
Treviglio	BG		45.521	9.593		4-5	4-5
Valli del Pasubio	VI		45.739	11.261	5	4-5	4-5
Soragna	PR		44.928	10.124	4-5	4	3
Certenoli	GE		44.379	9.296	3-4	4	3-4
Barlassina	MI		45.656	9.129	4	4	4
Bassano del Grappa	VI		45.767	11.734	3	4	4
Cassine	AL		44.750	8.527	5	4	4
Cavezzo	MO		44.838	11.028	3-4	4	4
Cerea	VR		45.194	11.213	4	4	4
Chiavari	GE		44.317	9.322	4	4	4
Chiavenna	SO		46.322	9.402	3-4	4	4
Cologna Veneta	VR		45.309	11.385	4-5	4	4
Colognola ai Colli	VR		45.432	11.193	5	4	4
Como	CO		45.810	9.084	4	4	4
Cremona	CR		45.136	10.024	4	4	4
Crespino	RO		44.982	11.885	3	4	4
Domodossola	VB		46.117	8.292	4	4	4
Este	PD		45.228	11.656	4-5	4	4
Ferrara	FE		44.836	11.618	4	4	4
Genova	GE		44.419	8.898	4	4	4
Gropello Cairoli	PV		45.177	8.991		4	4
La Spezia	SP		44.105	9.819	4	4	4

Table 3 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Lanzo d'Intelvi	CO		45.980	9.020		4	4
Lonigo	VI		45.387	11.388	4	4	4
Luzzara	RE		44.960	10.690	4	4	4
Marmirolo	MN		45.220	10.756	5	4	4
Martinengo	BG		45.570	9.768	5	4	4
Moglia	MN		44.933	10.912	4-5	4	4
Nonantola	MO		44.678	11.041	4	4	4
Novara	NO		45.446	8.623	5	4	4
Novellara	RE		44.845	10.731	4	4	4
Noventa Vicentina	VC		45.290	11.542	4	4	4
Pavullo nel Frignano	MO		44.334	10.834	5	4	4
Pieve del Cairo	PV		45.048	8.803	5	4	4
Recoaro Terme	VC		45.703	11.221	3	4	4
Rosasco	PV		45.250	8.580	5	4	4
Rovereto	TN		45.888	11.037	4	4	4
Rovigo	RO		45.070	11.790	5	4	4
Santuario di Oropa	BI	SS	45.627	7.981	4	4	4
Savona	SV		44.307	8.480	4	4	4
Sestri Levante	GE		44.270	9.394	4	4	4
Spinea (Orgnano)	VE	MS	45.490	12.165	4	4	4
Teglio	SO		46.172	10.067	4	4	4
Torino	TO		45.070	7.674	4	4	4
Tortona	AL		44.897	8.864	5	4	4
Tregnago	VR		45.512	11.166	F	4	4
Trento	TN		46.064	11.124	3	4	4
Treviso	TV		45.669	12.244	4	4	4
Trieste	TS		45.656	13.784		4	4
Varese	VA		45.818	8.825	4	4	4
Villimpenta	MN		45.141	11.034	5	4	4
Guidizzolo	MN		45.317	10.582		4	4-5
Vigevano	PV		45.317	8.856	4-5	4	4-5
Asso	CO		45.861	9.269	4	3-4	3-4
Legnago	VR		45.192	11.311	4-5	3-4	3-4
Lucca	LU		43.843	10.505	3	3-4	3-4
Modena	MO		44.647	10.925	3	3-4	3-4
Oneglia	IM	AL	43.888	8.052	4	3-4	3-4
Rovellasca	CO		45.667	9.052	4-5	3-4	3-4
Stienta	RO		44.940	11.544	4	3-4	3-4

Table 3 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Vercelli	VC		45.322	8.418	3	3-4	3-4
Vimercate	MI		45.614	9.370	4-5	3-4	3-4
Asolo	TV		45.801	11.914	3	3	3
Asti	AT		44.899	8.206		3	3
Belluno	BL		46.146	12.222	3	3	3
Bologna	BO		44.498	11.340	2	3	3
Carpenedolo	BS		45.363	10.430	3	3	3
Castel d'Ario	MN		45.188	10.975	3	3	3
Crevalcore	BO		44.722	11.147		3	3
Fossano	CN		44.550	7.721	3	3	3
Ispra	CO		45.816	8.617	4	3	3
Lendinara	RO		45.084	11.598	3	3	3
Luino	VA		45.997	8.747		3	3
Montespluga	SO		46.490	9.336	3	3	3
Ovada	AL		44.637	8.642		3	3
Pisa	PI		43.716	10.401	4	3	3
Ponzone	AL		44.588	8.459	3	3	3
Retinella	RO		45.047	12.178	3-4	3	3
San Donà di Piave	VE		45.633	12.572	3	3	3
Santa Giustina	BL		46.081	12.042		3	3
Sant'Ulderico	VC		45.749	11.347		3	3
Sarzana	SP		44.111	9.961	2-3	3	3
Spotorno	SV		44.226	8.417	3	3	3
Varzo	VB		46.207	8.249		3	3
Bolladore	SO		46.326	10.326	6	3	3-4
Limone sul Garda	BS		45.813	10.792		2-3	2-3
Bormio	SO		46.468	10.372	2-3	2-3	3
Bra	CN		44.698	7.849	2	2	2
Comacchio	FE		44.694	12.183	2	2	2
Imperia	IM		43.885	8.027	2	2	2
Pistoia	PT		43.932	10.913	2	2	2
Baveno	VB		45.909	8.503		F	F
Belgioioso	PV		45.160	9.313	F	F	F
Brunate	CO		45.820	9.095	F	F	F
Cantù	CO		45.739	9.131	3	F	F
Carpesino	CO		45.820	9.226		F	F
Cavalese	TN		46.291	11.460	F	F	F
Corenno Plinio	CO		46.090	9.310		F	F

Table 3 - continued.

Locality	Prov.	SC	Lat °N	Lon °E	DBMI04	I MCS	I EMS
Cremella	LC		45.739	9.303	F	F	F
Grumello del Monte	BG		45.635	9.873	4	F	F
Guastalla	RE		44.921	10.654	F	F	F
Massa Marittima	GR		43.050	10.889	F	F	F
Merate	LC		45.698	9.420	4	F	F
Novi Ligure	AL		44.764	8.788	5	F	F
Passirano	BS		45.599	10.063		F	F
Paullo	MI		45.417	9.398		F	F
Pordenone	PN		45.964	12.660	4	F	F
Presa Ticino	MI		45.668	8.684		F	F
Provaglio d'Iseo (Fontane-Zurane-Gresine)	BS	MS	45.635	10.048		F	F
Quinzano d'Oglio	BS		45.313	10.008		F	F
Redona	BG		45.709	9.873	F	F	F
Reggio nell'Emilia	RE		44.697	10.631	4	F	F
Rodengo-Saiano	BS		45.590	10.111		F	F
Salsomaggiore Terme	PR		44.816	9.979		F	F
San Salvatore Monferrato	AL		44.995	8.566		F	F
Tione di Trento	TN		46.035	10.725		F	F
Valletti	SP		44.377	9.526	F	F	F
Vaprio d'Adda	MI		45.576	9.528	F	F	F
Varano	VA		45.774	8.704	F	F	F
Venezia	VE		45.438	12.335	F	F	F
Viadana	MN		44.929	10.522	F	F	F
Vigasio	VR		45.317	10.942	F	F	F
Sestola	MO		44.229	10.771		NF	1
Siena	SI		43.321	11.328		NF	1

together with the presence of a widespread intrinsic vulnerability of the buildings.

5. Hypothesis on the 1901 earthquake source

In the case of the 1901 event, the magnitude is sufficient to assure the reliability of the application of the Boxer code (Gasperini *et al*., 2010) developed for the assessment of the location, the physical dimension and the source orientation of large ($M \geq 5.5$) historical earthquake using intensity data. The recent version (Boxer 4.0) of the code locates and sizes earthquakes by means of seven different methods: the simplest of these methods calculates the barycentre of the

Table 4 - Macroseismic intensities of the November 24, 2004 earthquake. Intensities are given in MCS (from Bernardini *et al*., 2005) and EMS (this paper).

Locality	LAT °N	LON °E	*I* MCS	*I* EMS
Clibbio (Sabbio Chiese)	45.637	10.457	7-8	7
Pompegnino (Vobarno)	45.630	10.498	7-8	7
Morgnaga (Gardone Riviera)	45.617	10.558	7	6-7
Pavone (Sabbio Chiese)	45.650	10.437	7	6
Roè (Roè Volciano)	45.623	10.493	7	6
Salò	45.606	10.522	7	6
Carpeneda (Vobarno)	45.649	10.471	6-7	6
Gazzane (Preseglie)	45.658	10.380	6-7	6
Il Vittoriale (Gardone riviera)	45.625	10.567	6-7	6
Prandaglio (Villanuova C.)	45.623	10.443	6-7	6
Sabbio Chiese	45.656	10.419	6-7	6
Fostagna (Gavardo)	45.601	10.419	6	6
Gardone Riviera	45.622	10.566	6-7	6
Gavardo	45.583	10.439	6	6
Gazzane (Roè Volciano)	45.622	10.504	6	6
Moniga del Garda	45.526	10.534	6	5
Muscoline	45.563	10.461	6	5
Odolo	45.644	10.386	6	5
Padenghe sul Garda	45.506	10.508	6	5
Puegnago sul Garda	45.567	10.510	6	5
Quarena (Gavardo)	45.603	10.442	6	5
Sabbio Sopra	45.661	10.415	6	5
San Felice del Benaco	45.584	10.548	6	6
Sopramonte (Gavardo)	45.597	10.440	6	5
Tormini (Roè Volciano)	45.610	10.482	6	5
Toscolano Maderno	45.639	10.610	6	6
Vobarno	45.644	10.500	6	5
Volciano (Roè Volciano)	45.613	10.495	6	6
Barghe	45.679	10.408	5-6	5
Bedizzole	45.510	10.421	5-6	5
Botticino	45.542	10.323	5-6	5
Brescia	45.544	10.214	5-6	5
Calvagese della Riviera	45.540	10.447	5-6	5
Carzago Riviera	45.525	10.459	5-6	5
Castello (Serle)	45.577	10.351	5-6	5
Castenedolo	45.470	10.300	5-6	5
Casto	45.696	10.321	5-6	5
Cisano (San Felice del Benaco)	45.595	10.537	5-6	5

Table 4 - continued.

Locality	LAT °N	LON °E	*I* MCS	*I* EMS
Concesio	45.601	10.220	5-6	5
Degagna (Vobarno)	45.681	10.506	5-6	5
Gargnano e frazioni	45.681	10.655	5-6	5
Manerba sul Garda	45.550	10.557	5-6	5
Marcheno	45.707	10.214	5-6	5
Marone	45.737	10.093	5-6	5
Marzago (Provaglio)	45.686	10.420	5-6	5
Moglia (Vobarno)	45.658	10.471	5-6	5
Montichiari	45.413	10.393	5-6	5
Montirone	45.444	10.232	5-6	5
Muslone (Gargnano)	45.711	10.693	5-6	5
Nave	45.587	10.286	5-6	5
Nuvolento	45.546	10.386	5-6	5
Nuvolera	45.533	10.373	5-6	5
Preseglie	45.667	10.394	5-6	5
Prevalle	45.548	10.418	5-6	5
Provaglio Val Sabbia	45.690	10.431	5-6	5
Raffa (Puegnago)	45.569	10.531	5-6	5
Rezzato	45.502	10.345	5-6	5
San Biagio (Gavardo)	45.588	10.463	5-6	5
San Giacomo (Gavardo)	45.594	10.479	5-6	5
Teglie (Vobarno)	45.663	10.463	5-6	5
Treviso Bresciano	45.712	10.462	5-6	5
Vallio Terme	45.610	10.393	5-6	5
Vestone	45.709	10.401	5-6	5
Villanuova sul Clisi	45.600	10.455	5-6	5
Agnosine	45.649	10.355	5	5
Anfo	45.767	10.494	5	5
Armo (Valvestino)	45.771	10.595	5	5
Bagnolo Mella	45.429	10.184	5	5
Bagolino	45.822	10.465	5	5
Barbariga	45.405	10.054	5	5
Bardolino	45.542	10.726	5	5
Bione	45.665	10.345	5	5
Borgosatollo	45.476	10.241	5	5
Bovegno	45.792	10.271	5	5
Caino	45.611	10.317	5	5
Calcinato	45.455	10.416	5	5

Table 4 - continued.

Locality	LAT °N	LON °E	*I* MCS	*I* EMS
Calmasino	45.521	10.753	5	5
Capovalle	45.753	10.545	5	5
Capriano del Colle	45.455	10.129	5	5
Carpenedolo	45.363	10.430	5	5
Costa e Mignone (Gargnano)	45.731	10.636	5	5
Costermano	45.587	10.744	5	5
Darfo Boario Terme	45.880	10.183	5	5
Desenzano del Garda	45.464	10.546	5	5
Erba	45.810	9.226	5	5
Flero	45.485	10.178	5	5
Garda	45.576	10.709	5	5
Gardone Val Trompia	45.688	10.184	5	5
Gussago	45.587	10.156	5	5
Idro	45.734	10.459	5	5
Lavenone	45.740	10.438	5	5
Lavone (Pezzaze)	45.762	10.245	5	5
Lazise	45.506	10.733	5	5
Lodrino	45.720	10.277	5	5
Lumezzane	45.649	10.262	5	5
Magasa (Valvestino)	45.782	10.617	5	5
Maguzzano (Lonato)	45.485	10.502	5	5
Malcesine	45.764	10.809	5	5
Manerbio	45.354	10.140	5	5
Marmentino	45.755	10.286	5	5
Mocasina (Calvagese della Riviera)	45.530	10.439	5	5
Orzinuovi	45.402	9.924	5	5
Paitone	45.551	10.402	5	5
Palazzolo sull’Oglio	45.598	9.883	5	5
Pavone del Mella	45.303	10.211	5	5
Persone (Valvestino)	45.773	10.575	5	5
Peschiera del Garda	45.438	10.694	5	5
Polaveno	45.661	10.124	5	5
Polpenazze del Garda	45.550	10.506	5	5
Pompiano	45.431	9.989	5	5
Portese (S. Felice Benaco)	45.596	10.553	5	5
Rivoltella (Desenzano del Garda)	45.462	10.563	5	5
Ronco (Gussago)	45.596	10.136	5	5
Saiano (Rodengo Saiano)	45.589	10.111	5	5

Table 4 - continued.

Locality	LAT °N	LON °E	*I* MCS	*I* EMS
Sale Marasino	45.710	10.112	5	5
San Zeno di Montagna	45.440	11.178	5	5
Soiano del Lago	45.539	10.514	5	5
Sulzano	45.688	10.099	5	5
Tavernole sul Mella	45.748	10.240	5	5
Torri del Benaco	45.612	10.691	5	5
Turano (Valvestino)	45.760	10.596	5	5
Verolanuova	45.326	10.076	5	5
Verona	45.438	10.994	5	5
Zone	45.762	10.117	5	5
Zumiè (Capovalle)	45.755	10.545	5	5
Bellano	46.043	9.302	4-5	4-5
Bergamo	45.694	9.670	4-5	4-5
Cavaion Veronese	45.539	10.770	4-5	4-5
Cermenate	45.701	9.082	4-5	4-5
Collio	45.812	10.334	4-5	4-5
Como	45.809	9.084	4-5	4-5
Inverigo	45.739	9.219	4-5	4-5
Lecco	45.856	9.408	4-5	4-5
Lipomo	45.794	9.119	4-5	4-5
Lugagnano	45.433	10.890	4-5	4-5
Lurago d’Erba	45.751	9.221	4-5	4-5
Merate	45.698	9.420	4-5	4-5
Padova	45.406	11.876	4-5	4-5
Poncarale	45.460	10.173	4-5	4-5
San Fermo	45.480	9.919	4-5	4-5
San Zeno Naviglio	45.473	10.478	4-5	4-5
Sarezzo	45.651	10.203	4-5	4-5
Tavernerio	45.798	9.148	4-5	4-5
Valeggio sul Mincio	45.354	10.734	4-5	4-5
Venezia	45.438	12.335	4-5	4-5
Adria	45.055	12.058	4	4
Bovezzo	45.592	10.244	4	4
Genova	44.419	8.898	4	4
Ghedi	45.405	10.276	4	4
La Spezia	44.105	9.819	4	4
Leno	45.366	10.219	4	4
Milano	45.464	9.189	4	4

Table 4 - continued.

Locality	LAT °N	LON °E	*I* MCS	*I* EMS
Modena	44.647	10.925	4	4
Parma	44.801	10.329	4	4
Ravenna	44.417	12.198	4	4
Romano di Lombardia	45.519	9.755	4	4
Rovigo	45.070	11.790	4	4
Pisa	43.716	10.401	3-4	3-4
Torino	45.070	7.674	3-4	3-4
Bologna	44.498	11.340	3	3
Imperia	43.885	8.027	3	3
Copparo	44.894	11.830	2-3	2-3
Firenze	43.777	11.249	2-3	2-3
Ljubljana	46.058	14.503	F	3
Belluno	46.146	12.222	F	F
Cremona	45.136	10.024	F	F
Mantova	45.152	10.775	F	F
Piacenza	45.052	9.693	F	F

intensity points (as in the previous version Boxer 3.0, applied in the CPTI11 catalogue); otherwise, a combination of estimated and fixed parameters is used. Results are provided with associate errors in coordinates, orientation, depth, fault dimensions, and magnitude.

The fault of the 1901 event is not univocally defined by the code in position and azimuth. We expected that the new data would have improved the final parameter definition because of (i) the increase of the number of observations, (ii) the removal of the wrongly reported locations, and (iii) the larger quantity of data in epicentral area (see Table. 7), as suggested by Gasperini *et al.* (2010). However we observe that the associated errors to the parameters definition did not decrease after our revision.

Among all the Boxer solutions (Fig. 7 and Table. 5), we discharged the case_0, although compatible with the seismotectonic settings of the area (Castellarin and Cantelli, 2000), because calculated through the barycentric method on an incomplete intensity field due to the presence of the lake. The case_1, case_2 and coincident case_3 show an azimuth not compatible with the known structural settings and seem to be biased by the occurrence of soil motion amplification effects in the Val Sabbia.

The remaining case_4, case_5 and case_6 (Fig. 7), seem to be more likely solutions as they all display an azimuth slightly compatible with the structural settings of the area, similar dimensions and magnitude, and slightly different positions and orientations.

On the whole, the seismic source cannot be well depicted by the intensity observations both because of the lack in macroseismic data due to presence of the lake and, on the other side, the probable increment on intensity values due to site effects in Val Sabbia.

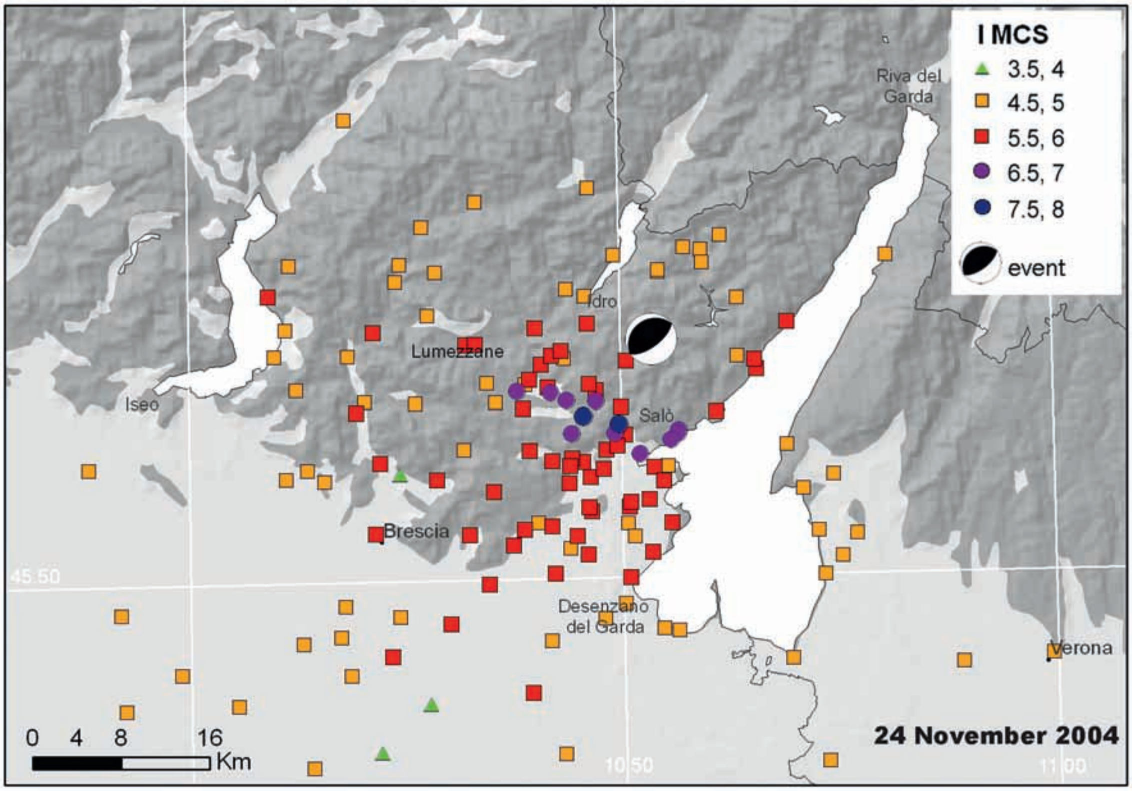

Fig. 6 - The 2004 event [redrawn from Bernardini *et al*. (2005)]. The fault plane solution is from Pondrelli *et al*. (2007) and indicates the instrumental epicentre.

Generally specking, the values of the calculated depth are all acceptable because the source must indeed rest above the brittle-ductile transition in the Alps [approximately 15-20 km: Viganò and Martin (2007)], that represents a lower limit for most of the Alpine crustal seismicity (e.g., Chiarabba *et al*., 2005). As for the 2004 event, also the 1901 rupture of the fault probably occurred in the Alpine metamorphic basement (e.g., Picotti *et al.*, 1995; Carulli and Slejko, 2009). The thin-skinned tectonics observed in the surface and mainly involving the Mesozoic to recent sedimentary cover is interpreted to be driven in depth by very few, large basement slices, the outermost of which is buried below the western bank of the Lake Garda (Picotti *et al.*, 1995). According to these structural considerations, the 1901 hypocentre position should fall on the same 2004 event basement ramp or, less likely, on a different parallel fault, anyway belonging to the same structural system and well described by the three accepted solutions.

These solutions suggest a shift of ~ 5 km toward NW of the DBMI11 macroseismic epicentre, due to the recent methods of estimation implemented in the Boxer 4.0 code.

It is noteworthy that the new finite fault solutions are close (approximately 6 km away) to the fault published in the Database of Individual Seismogenetic Sources (DISS Working Group, 2010) with a different azimuth (Fig. 7 and Table 5)

At this point it is questionable how plausible the fault plane representations are.

Table 5. - Parameters of the 1901 fault estimation.

Case	LAT °N ± σ [km]	LON °E ± σ [km]	DEPTH ± σ [km]	Mag.	AZIMUTH ± σ [°]	LENGTH [km]	WIDTH [km]
0	45.584 ± 0.958	10.490 ± 0.893	--	5.47	35.2 ± 11.7	6.090	5.482
1	45.642 ± 1.446	10.385 ± 1.719	4.487	5.46	119.0 ± 7.5	6.075	5.475
2	45.651 ± 1.578	10.377 ± 1.889	5.02 ± 0.24	5.47	123.2 ± 6.6	6.100	5.487
3	45.651 ± 1.526	10.377 ± 1.851	4.487	5.47	123.2 ± 6.6	6.100	5.487
4	45.594 ± 2.951	10.409 ± 2.650	16.24 ± 2.42	5.46	85.2 ± 8.6	6.075	5.475
5	45.598 ± 2.828	10.417 ± 2.612	14.32 ± 3.39	5.46	86.3 ± 9.6	6.074	5.474
6	45.604 ± 2.379	10.438 ± 2.347	7.26 ± 3.26	5.46	84.5 ± 13.7	6.076	5.475
DISS	45.63	10.51	6.5-9.0 (min-max)	5.7	231	7.0	5.0

The distribution of the intensity observations provides the location of the centre of strong shaking (Bakun *et al.*, 2011) rather than the location of the epicentre. Indeed, an important consideration has to be done on the real location of the sources, basing on the similarity among the intensity distributions of the studied earthquakes and accounting for the instrumental and macroseismic constraints provided by the recent 2004 event.

First of all, the instrumental assessment of the 2004 event location is somewhat critical due to the quite large distance of receiving stations from the epicentral area. As a consequence, different epicentre locations have been proposed in literature with a difference of about 4 km (Augliera *et al.*, 2006; Viganò *et al.*, 2008). Both the published instrumental solutions are however quite eccentric with respect to the macroseismic epicentre (Fig. 7). This fact may be explained by an irregular distribution of inhabited centres dependent on the morphology (mountains at N/NE and plain at S/SW) as well as by probable directivity effect of the seismic radiation. This latter hypothesis is supported by the evidence that the distribution of macroseismic observations around the instrumental location of the 2004 epicentre shows higher values towards SW and south directions, at the same distance from the epicentre respect to those in north and NE directions (Fig. 6). The shape of the ground shaking level elongated towards SW could be mainly dependent on the low dip angle of the fault, as demonstrated in Franceschina *et al.* (2009).

Rather than judging the eccentricity as an artefact produced by instrumental localization of the 2004 epicentre, the macroseismic review provided by this study allows to consider it as a real behaviour of the 2004 earthquake, and in general of the earthquakes of this area. For this reason, the calculated macroseismic epicentre should be considered as a somewhat shifted representation of the effective source. This hypothesis is compatible with and actually supported by the structural interpretation of the area.

Summarizing, the improvement of historical information does not identify a unique and well-defined source of the 1901 earthquake. The current state of knowledge of the area allows to slightly constrain the source; and more, the recorded data of the last earthquake, similar in many aspects to the one occurred in 1901, does not provide a clear picture of the rupture process and

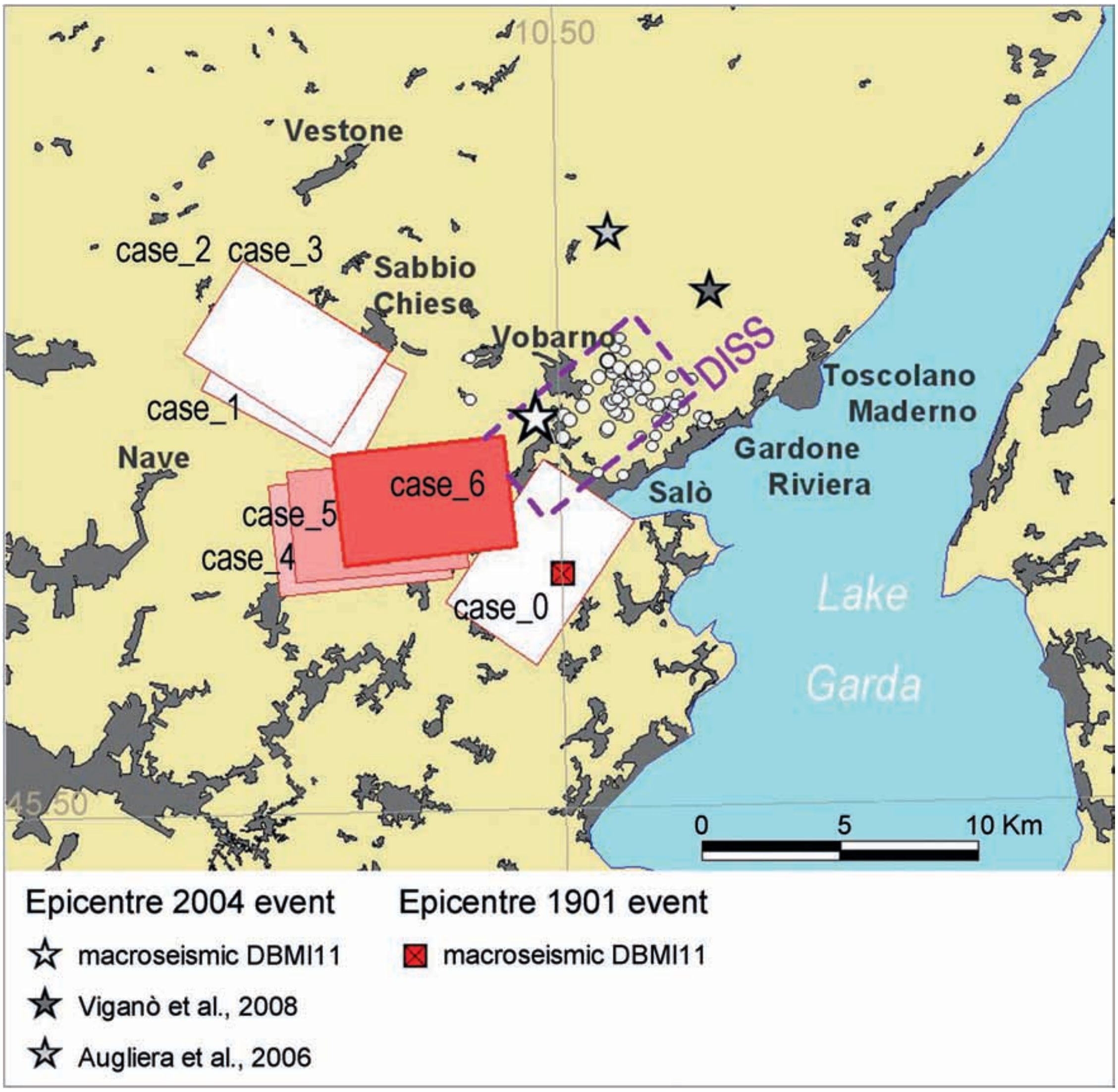

Fig. 7 - Instrumental epicentres (shaded stars) and the macroseismic epicentre DBM11 (empty star) for the 2004 event with aftershocks location (circles). For the 1901 event, red faults (case from 0 to 6) are calculated with the new data by the Boxer 4.0 code (Gasperini *et al*., 2010); the macroseismic epicentre DBM11 is also plotted together with the trace of the DISS fault.

highlights the more reliability of the macroseismic information, in this particular case.

6. Applicative outcomes from the revised macroseismic fields

The similarity among the intensity distributions of all the studied earthquakes allows addressing a series of issues that can be useful for predictive risk estimation.

(i) Despite the general intensity downgrade produced by our revision of the 1901 earthquake, the intensity values are still equal or larger (1.0 or 1.5 degree) than those of the 2004 event (Fig. 4b and Fig. 5b). The higher magnitude of the 1901 is therefore confirmed.

(ii) The town of Salò, the main centre on the western shore of Lake Garda, mostly recorded the higher values of intensities for all the studied events. This can be ascribed to the relative importance of Salò in the local territorial context, justifying that a systematic emphasis in the historical information is present. More important, the vulnerability level has grown due to the removal of the collective memory (Giustina and Treccani, 2004) and the town is characterized by an historic centre with critical vulnerability level (Pergalani, 1996). In addition, Salò is built on geotechnically poor terrains (e.g., Baroni, 1990) and probably, in case of earthquake, it will still record localized damages along the shoreline or in correspondence of the ancient landslide, always reactivated by the past events (Giustina and Treccani, 2004).

(iii) The distribution of the other high-intensity values displays discrepancies between the 2004 and 1901 events in some localities westwards of the epicentres. The higher intensity values recorded during the 2004 event in Val Sabbia, probably affected by local site condition amplifications (Franceschina *et al.*, 2009), are missing in case of the 1901 event, with the exception of Pompegnino where the damage was significant. It is hard to believe that these localities were not affected by local amplification effects also during the 1901 earthquake, because high intensities have been observed in Val Sabbia also for the 1826, 1892, and 1898 events (Camassi *et al.*, 2011). This fact remains an open issue: the lack in information due to the historical incompleteness is definitely plausible, but we speculate that as the 1901 event struck an area already affected by the two events happened in the previous 9 years, buildings therein were previously repaired or discarded, thus lowering the vulnerability of the area.

(iv) Finally, the particularly high levels of damage observed during the 2004 event in Val Sabbia could be ascribed to the particular conditions of the seismic vulnerability of housing stock, incremented in respect to the 1901 because of the buildings ageing.

The highlighted common features can be helpfully used for predictive purposes in this area, where the lack of well-defined seismic source (in terms of location and azimuth) makes difficult the generation of risk scenarios.

Nowadays the repetition of the 1901 event would lead to more than 60 damaged localities, in a densely urbanized area and with a large involved population; localities that could be severely hit with $I \geq$VII are about 20, with about 50,.000 people involved. The estimation is done using the proposed finite source of case_6 (Table 5), the well-tested intensity attenuation relationship (Faccioli and Cauzzi, 2006) and data on buildings from the national census survey (ISTAT, 2001).

Once again, the historical centres characterized by masonry buildings in a poor state of maintenance, especially in smaller towns, will mainly record greater losses. In general, most of the housing stock is at risk since it was built before the adoption of seismic norms, in 1984. In the municipalities that can be seriously damaged ($I \geq$VII) in case of the maximum historic scenario, only 15% of the total housing stock is built according to seismic protection criteria. Indirect damages could be outlined in the temporary cessation of production activities, in the expected decrease of tourist activity, and in the interruption of traffic that, for the morphology of the area, is absolutely non-redundant, and indeed limited to the main axis of flow in the valley

Table 6 - Improvements of the revised data.

Event	New observations	Wrongly reported locations	Modified intensity
January 5, 1892	4	1	37
November 16, 1898	22	1	8
October 30, 1901	106	5	101

and around the lake. Extended damage in Salò historic centre and in the oldest part of the small villages are expected, as well as local amplification in the valley zones (see: Franceschina *et al*., 2009).

7. Conclusions

Although it is the place of the most destructive event of northern Italy (the 1117 earthquake) the Alps-Po Plain margin is depicted by historical and instrumental data as a region with infrequent and generally moderate seismicity. Our historical knowledge of the area is considered complete only for the last four centuries and partially forced by the major urban centres. In this framework, we contributed with a detailed study of the main historical earthquakes in the Lake Garda area, where the most recent damaging event occurred on November 24, 2004.

We have revised the main historical earthquake that took place on the October 30, 1901 (M_w=5.5), together with some other minor events located in the same area, occurred on January 5, 1892 (M_w=5.0) and November 16, 1898 (M_w=4.6) (Table 6). The information data set considerably benefited from this revision: for the 1901 event the number of localities included in the new macroseismic field increased from the previous 191 to the current 291 with generally lower intensities. In the case of the two minor earthquakes, the search for new sources produced

Table 7 - Earthquakes of the area as formerly quoted in the CPTI11 catalogue (Rovida *et al*., 2011) and new parameters.

Event	MCS I_0		MCS I_{max}		N		New observations	Wrongly reported locations	Modified intensity
	CPTI	new	CPTI	new	CPTI	new			
January 5 1892	6-7	6-7	7-8	7	92	93	4	1	37
November 16 1898	5-6	6	6	6	23	43	22	1	8
January 5, 1892	6-7	6-7	7-8	7	92	93	4	1	37
November 16, 1898	5-6	6	6	6	23	43	22	1	8
October 30, 1901	8	7-8	8	7-8	191	291	106	5	101

N = number of intensity data points.

modest results in the light of their low intensity, but the critical reading of the known documents allowed significant change of some intensity attributions and correcting some misinterpretations (Table 7).

The revision was carried out both in MCS and EMS scale intensity: we generally observed that EMS values are lower than the MCS ones, especially in the V-VII intensity range, as already reported (i.e., Musson *et al.*, 2009), while, for lower intensity degrees, the two scales are practically coincident.

For the 1901 event we tested the capability of the earthquake parameter definition methods at the base of Boxer 4.0 code (Gasperini *et al.*, 2010). In the case of the 1901 event, the improvement of the data set does not assure a decrease of the errors in the parameters definition confirming the complexity of its observations pattern and corroborating the authors' caution on the lower magnitude limit of applicability of the method.

The comparison among the new macroseismic fields of the studied events shows similarities in the damage distribution that arouse important considerations:

(i) the 1901 event is confirmed to be the strongest known event in the area;

(ii) the location of the 1901 source is consistent with the activity of a buried basement thrust, with earthquakes likely nucleating along a low-angle ramp, even if the complexity of the intensity pattern does not enable a precise single source identification;

(iii) updated macroseismic data set led to more reliable source parameters for the larger event, suggesting a shift of the macroseismic epicentre;

(iv) also considering the great uncertainty in constraining the seismic source location, expected damage distribution will be mainly affected by the vulnerability level of the old masonry buildings;

(v) this could be particularly crucial for some small towns of the Val Sabbia where, in addition to the presence of historic settlements with particular high vulnerability level, local site amplification effects may be accounted for.

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