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EARTHQUAKE DAMAGE SCENARIOS AND SEISMIC HAZARD OF MESSINA, NORTH-EASTERN SICILY (ITALY) AS INFERRED FROM HISTORICAL DATA

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A study aimed at evaluating earthquake damage scenarios and seismic hazard of Messina using historical data, is presented. The analysis of coeval reports allowed us to reconstruct the seismic history of the city and to obtain a homogeneous earthquake site catalogue based on intensity assessed by the European Macroseismic Scale 1998. In the last 1200 years Messina was destroyed once (1908, intensity X-XI EMS) and suffered effects estimated between intensities VII and IX EMS many times (e.g. 853, 1169, 1494, 1509, 1599, 1693, 1783, 1894, 1909). Destruction or severe damage which affected the city are mainly related to earthquakes occurring in the Messina Straits and Southern Calabria, while slighter, moderate effects are usually due to shocks taking place in the seismogenic sources of SE Sicily, Gulf of Patti and Northern Calabria. The damage scenarios of the most relevant events, delineated using coeval urban plans of the city, showed that damage distribution is strongly conditioned by the different soil response. A probabilistic seismic hazard assessment was obtained by using site observed intensities: The expected intensity in a time span of 50 years (i.e. maximum intensity characterised by at least 10% exceedance probability in 50 years) is IX EMS; the expected intensity in a time span of 300 years (10% exceedance probability in 300 years) is X EMS.

Keywords: Historical seismicity; damage scenarios; seismic hazard; Messina; Italy.

1. Introduction

In recent years several methods such as the standard technique originally proposed by Cornell [1968] have been used in the framework of the GNDT (National Group for the Defence against Earthquakes) activities in order to draw probabilistic seismic hazard (PSHA) maps in Italy [Slejko *et al.*, 1998]. These approaches are commonly biased by the assumption of homogeneous seismogenic zones having uniform seismic rates and attenuation models, which in practice determine the concealing of the site differences and by uncertainty on basic information and relevant parameters affecting final hazard estimates [D'Amico and Albarello, 2003].

In order to overcome these restrictions, the Messina (northeastern Sicily) PSHA has been estimated using site observed intensity, according to the methodology described by Magri *et al.* [1994] and Albarello and Mucciarelli [2002]. In this procedure the seismic history of each site, reconstructed from macroseismic data, is the basic information considered for PSHA. Unlike the standard technique, no *a priori* hypothesis is requested about statistical properties of seismicity (e.g. Poissonian distribution) and geometry of seismogenic areas. Furthermore, coherently with the essential character of macroseismic information, this methodology aims at the definition of PSHA in terms of expected macroseismic intensity [D'Amico and Albarello, 2003].

For this purpose, a new intensity dataset for Messina has been compiled, through the analysis of historical sources quoted in the most recent studies [Boschi et *al.*, 1995, 1997, 2000; Monachesi and Stucchi, 1997] and in some seismological compilations such as Perrey [1848], Mercalli [1897], De Rossi [1889] and Baratta [1901]. Further sources, mainly newspapers and local chronicles, have been used especially for the strongest earthquakes. To achieve homogeneity in the dataset, the collected information regarding earthquake effects have been used to estimate intensities according to the European Macroseismic Scale 1998 [EMS, Grünthal, 1998].

The great amount of collected information has also been used to reconstruct the urban damage scenarios of the main events in the last millennium.

2. Geological Setting and Urban Development: An Outline

The city of Messina is located within an important tectonic structure, the Messina Straits, which divides the southern Apennines from the Sicilian-Maghrebian Chain [Lentini *et al.*, 1995, 2000]. This area is crossed by a NNE-SSW trending normal fault system (Fig. 1), whose activity is testified by the significant and recent uplift of the area, as well as by the frequent strong seismicity occurring in historical times [Valensise and Pantosti, 1992; Monaco and Tortorici, 2000].

From the geological point of view, the inhabited centre is essentially built on an alluvial plain constituted by Holocene and recent sediments of alluvial fans and stream beds, and by beach deposits [Lentini *et al.*, 2000]. The river beds inside the urban area have been covered and adapted to road arteries following the urban expansion in 1950s. Other loose soils, such as the Messina Sands and Gravels (Middle Pleistocene), outcrop in the hilly western sector of the city, i.e. in the area of the Great Monumental Cemetery, the Matagrifone's Fortress and near the Capuchin Plain (Fig. 2a).

Formations with different geotechnical properties outcrop further west: The crystalline rocks of the Aspromonte Unit and the Tortonian-early Messinian

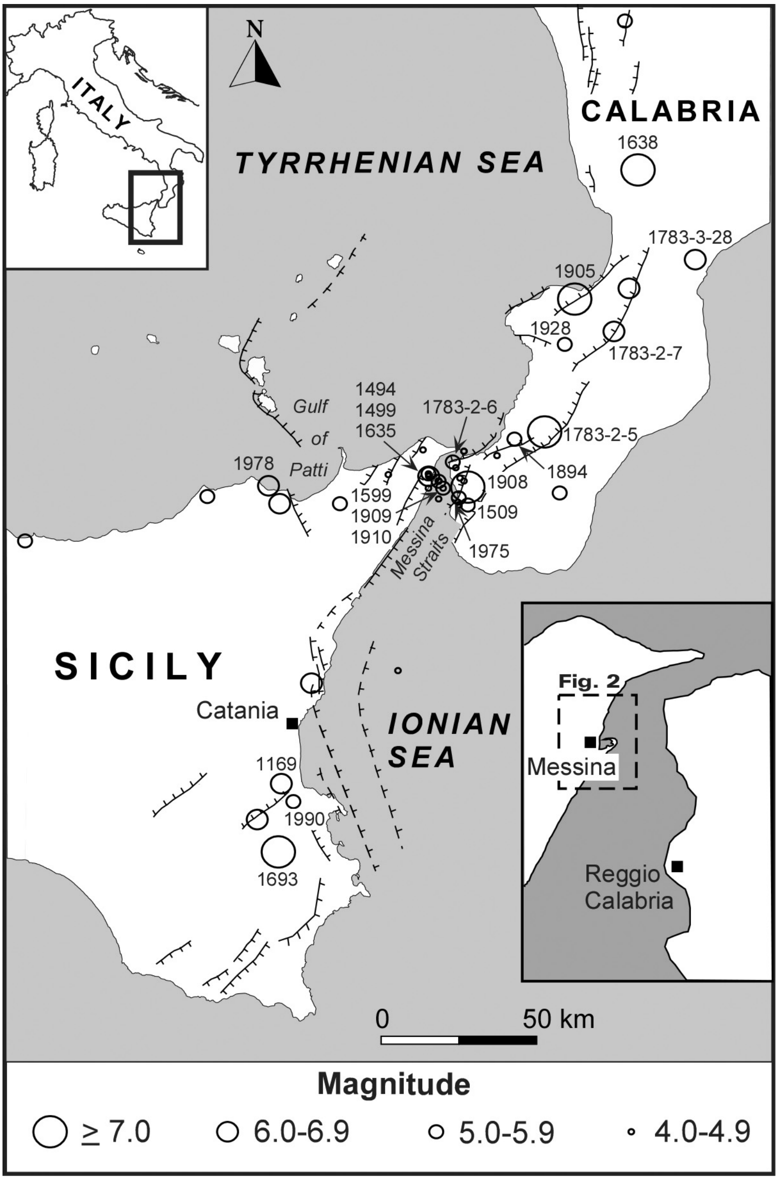


Fig. 1. Location of historical earthquakes which have damaged the city of Messina [data from Gruppo di Lavoro CPTI, 2004]. Earthquakes discussed in the text are marked by date. Main tectonic structures are redrawn from Monaco and Tortorici [2000].

sedimentary deposits, essentially constituted by conglomerates and cemented coarse sands [Gargano, 1994].

The different seismic response and vulnerability of the city is strictly related to its urban development through time with respect to the geolithological

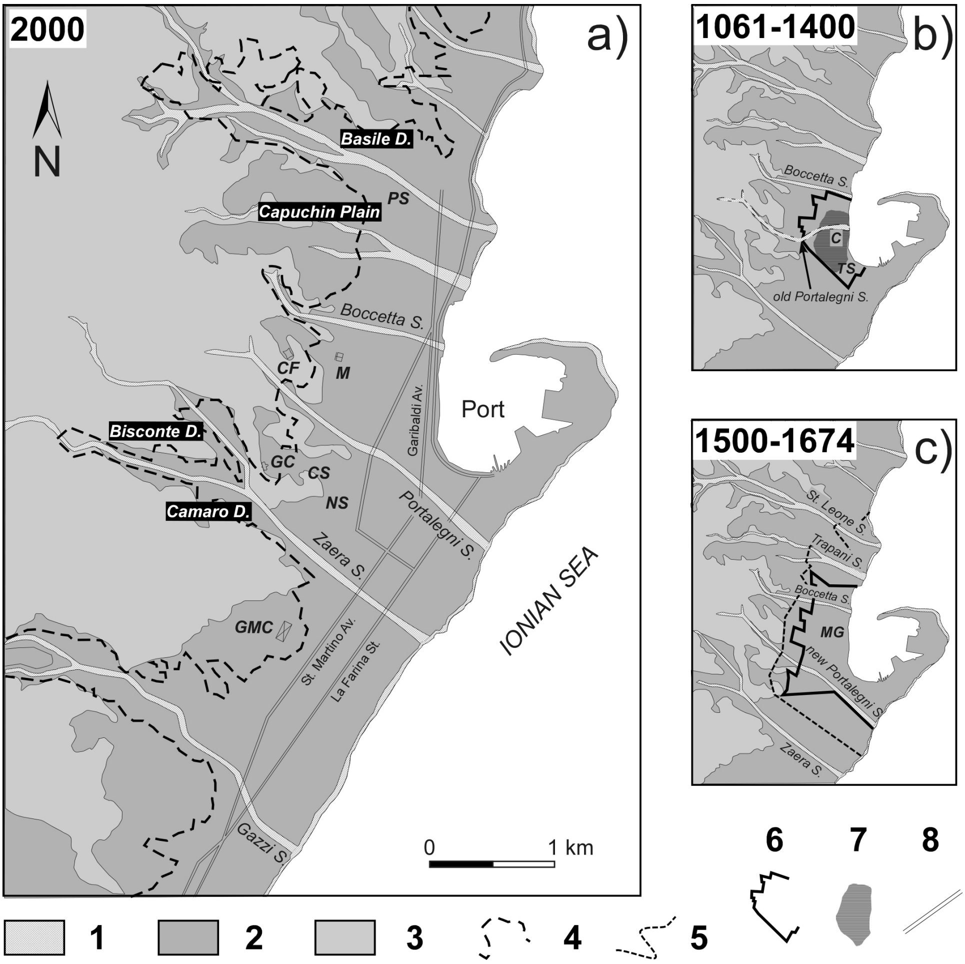


Fig. 2. (a) Simplified geological map of Messina [modified from Gargano, 1994]: (1) recent alluvial and beach deposits (Holocene); (2) soft rocks (Messina Sands and Gravels — middle Pleistocene); (3) hard rocks (bedrock, Aspromonte Unit and early Tortonian-Messinian terrigeneous deposits); (4) limit of the present urban area; (5) limit of Messina before the 1908 earthquake; (6) medieval town walls; (7) extension of the city between 5th BC and 11th AD cent.; (8) main roads. (b) Extension of the urbanised area during the Norman and Aragonese dominations. The old Portalegni stream crossed the ancient walls of the city and flowed into the port just behind the Cathedral (C). (c) Extension of Messina from 1500 to the anti-Spanish rebellion. Note that the talweg of Portalegni was diverted and flowed into the sea south of the port. New suburbs developed beyond the new city walls along the Boccetta, S. Leone, Portalegni and Zaera streams, giving the city a digitated configuration. Abbreviations: CF = Castellaccio Fortress; CS = Casazza Street; GC = Gonzaga Castle; GMC = Great Monumental Cemetery; *M* = Matagrifone Fortress; MG = ancient *Marina* gate damaged during the 1638 earthquake; NS = Noviziato Street; PS = Palermo Street; TS = Terranova Suburb.

characteristics, to different construction types and to the dramatic changes in the urban setting following the largest earthquakes.

The Messina settlement dates back to Greek times: the first colony was named Zancle (i.e. falcate for the shape of its natural inlet). In short, the following changes are relevant for lithological and building vulnerability of Messina:

(i) Until the 15th century the city expanded between the Boccetta and Portalegni streams (Fig. 2b). The latter crossed the ancient walled city and flowed into the port just behind the Cathedral [Sisci, 1990].

(ii) From 1500 until the anti-Spanish rebellion (1674), the city developed between the Trapani stream to the North and the new Portalegni stream to the South (Fig. 2c), whose bed was diverted along the new walls built by the Spanish King Charles V for defence purposes [Ioli Gigante, 1986].

(iii) After the 1783 seismic sequence that heavily damaged the city, it was then badly restored using inhomogeneous rubble stones and poor quality mortar for new constructions.

(iv) The reconstruction following the destructive 1908 earthquake entailed the old structure being partially modified in order to make room for a new urban scheme [Borzì, 1912; Longo, 1933]. This took place in accordance to the introduction of the first seismic code prescribing the use of reinforced concrete structures, floors to replace the arches, prohibition of abuse of projections, orthogonal roads cut off by squares, 1–2 storey buildings, etc. [Ministero dei Lavori Pubblici, 1913].

(v) The expansion of the urban plan of the city after World War II along the coast-line and, more recently, along the stream beds. In particular vulnerability conditions may also exist in the modern city due to RC frame edifices built without consideration of the seismic code and the diffuse practice of increasing the height of masonry buildings.

3. Damaging Events in the Seismic History of Messina

The strongest earthquakes which hit the area since the 17th century have recently been studied by Boschi *et al.* [1995, 1997, 2000] but they provide intensities expressed in the MCS scale. For the city of Messina the historical accounts report very detailed descriptions of damage to monumental buildings, while for ordinary buildings generic information is usually provided. Therefore, we have re-analysed the historical sources with the aim of re-evaluating intensity on the EMS scale, classifying damage according to its level and vulnerability class of buildings, also using pictures and paintings showing damage effects, as well as locating it on the contemporary urban plans of the city.

To this end, an historical-cartographic search has also been performed. For the 1693 and 1894 earthquakes, we have used maps of the 17th and late 19th centuries found in the historical Messina archive [ASCM, 17th and 19th cent.]. For the 1783 earthquake, we have selected a map of 1718 [Dufour, 1992] and for the 1905 and 1908 earthquakes we select another map issued in 1902 [Trasselli, 1987].

The earthquakes which have damaged Messina are briefly described hereinafter, with particular emphasis on their impact on the urban framework and together with the seismic scenarios reconstructed for the main events.

3.1. *February 4, 1169 earthquake*

The earthquake, with estimated magnitude $M_{aw} = 6.6$, struck all eastern Sicily and part of southern Calabria causing considerable damage [Boschi *et al.*, 2000]. All the most important villages and towns in eastern Sicily were heavily damaged [Barbano *et al.*, 2001]. Several permanent phenomena on the ground were observed in a wide area from the Ionian coast to the middle of Sicily. In Messina, a tsunami causing a wave about 5 metres high (*20 palms*) [Falcando, 12th cent.] was observed; the sea first drew back and then the run-up overcame the city walls, inundating the streets [Fazello, 1558; Caruso, 1737–1745]. Boschi *et al.* [2000] have found some 12th and 13th centuries archive documents relating to the rebuilding of houses and shops in the castle, suggesting that they were damaged by the seismic event. It is difficult, on the basis of the available information, to ascribe the damage to an intensity value; the site intensity I_s = VI-VIII EMS has been attributed to the damage.

3.2. *May 28, 1494 earthquake*

The earthquake has probably occurred in northeastern Sicily because it was not felt in Calabria [Boschi *et al.*, 2000]. In Messina the roofs of some houses collapsed as well as parts of the northern walls and the city gate known as *Giano* or *St Antonio* [Maurolico, 1562]; there were no victims [Pagliarino, 15th cent.; Maurolico, 1562]. The available information led us to estimate I_s = VII-VIII EMS.

3.3. *November 9, 1499 earthquake*

The most ancient account of this event is found in Maurolico [1562] who reports, probably on the basis of oral sources (the author was born in 1494), that in Messina *"Anno salutis 1499* [...] *die Novembris nono circa occasum solis fuit ingens terremotus, ceciderunt nonnulla ædificia"* [There was a great earthquake in November 9, 1499 towards the sunset, many buildings fell]. Since some collapses are reported, the intensity estimated is I_s = VIII EMS.

3.4. *February 25, 1509 earthquake*

The earthquake was felt in southern Calabria and in the Messina area [Boschi *et al.*, 2000]. According to Samperi [1644], damage was higher in Reggio Calabria than in Messina, so the catalogues [Postpischl, 1985; Gruppo di Lavoro CPTI, 2004] locate the epicentre in southern Calabria.

Pacca [16th cent.] describes the event thus: "In March 1509, in the city of Messina there was a huge earthquake, which continued 23 times for one day with great fear and surprise of the inhabitants. Many buildings fell together with the merlons and part of the walls of the castle of the city". By contrast Maurolico [1562] reports: "On February 25 1509, an earthquake shook Messina at one hour after sunset and then at five o'clock in the night another stronger shock frightened people who ran outdoors. Many people had abandoned the houses for fear of collapses and lived in tents, in the fields and in the gardens". These sources give a very different description of the effects, so I_s = VII-VIII EMS is assigned.

3.5. *June 8, 1599 earthquake*

Spanò-Bolani [1857] wrote that "the public buildings were damaged and a lot of them remained collapsing" both in Reggio Calabria and in Messina. Mongitore [1743], who quotes Samperi [1644], reports that inhabitants in Messina abandoned their houses because of the repeated shocks, from July to August. The collected information, however generic, indicates moderate damage consistent with I_s = VII-VIII EMS.

3.6. *August 12, 1635 earthquake*

Carrera [1636], describing the 1635 Etna eruption, reports that "in the hamlets and in Catania a slight earthquake was felt, which opened and ruined some buildings in Messina". From this information I_s = VII EMS has been estimated.

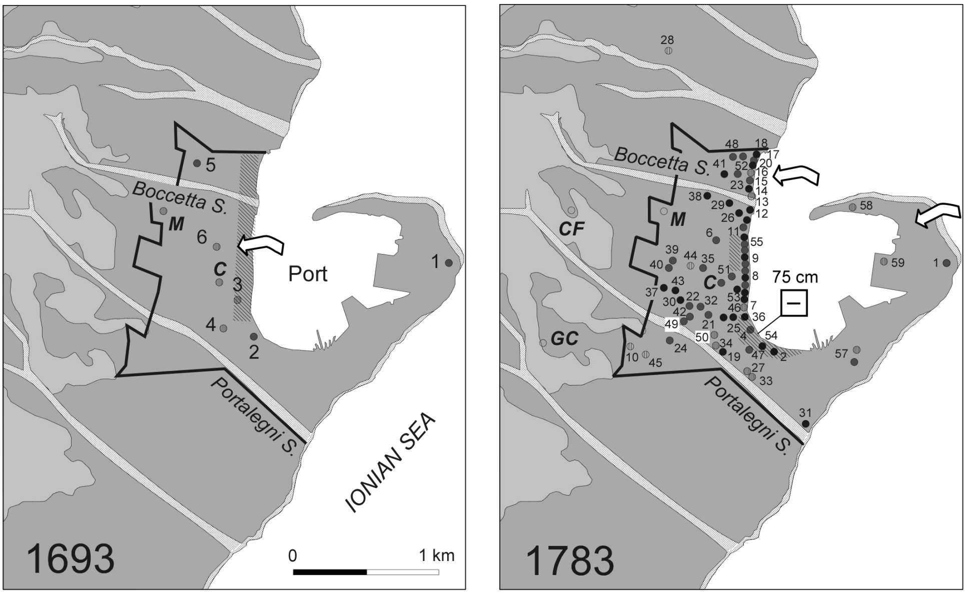
3.7. *March 27, 1638 earthquake*

Available sources report that an earthquake of $M_{aw} = 7.0$, hit northern Calabria, seriously striking more than 200 towns and causing thousands of casualties [Boschi *et al.*, 2000].

Samperi [1644] affirms that the event in Messina caused the collapse of part of the roof on the right wing of the Cathedral, damaging the Chapels and the Apostles' statues. Seven people died and others were wounded. The *Marina*'s Gate (Fig. 2c) was damaged, as testified by an inscription emplaced after the restoration [Trasselli, 1987]. Two houses collapsed [Vera relazione dello spaventevole terremoto…, 1638]. From this information I_s = VII-VIII EMS has been estimated.

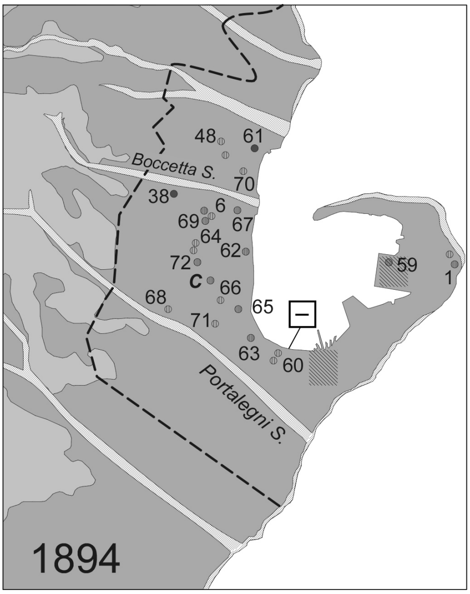
3.8. *January 9 and 11, 1693 earthquakes*

The January 9 foreshock [Barbano and Cosentino, 1981; Boschi *et al.*, 1995] caused severe damage in southeastern Sicily, whereas in Messina it was strongly felt (I_s = V EMS). On January 11 the main shock caused destruction and heavy damage in most localities of eastern Sicily [Boschi *et al.*, 1995]. In Messina some houses and churches collapsed and some others were tottering; in all, 12 people died [AGS, 1693; Burgos, 1693; Corrao, 1784]. According to Bottone [1718] the poor dwelling-houses collapsed and superb palaces cracked; some *Palazzata's* buildings failed and all the structure was in distress. A summary of damage is reported in Fig. 3(a). An hour after the earthquake, a fissure opened in the beach in front of the theatre, half a *palm* wide [Bottone, 1718]. According to two coeval reports, after the earthquake the sea receded 50 m (60 steps), leaving the *Cittadella* walls dry, and then the run-up overcame the wharf [Boschi *et al.*, 2000]. An I_s = VII-VIII EMS has been estimated.

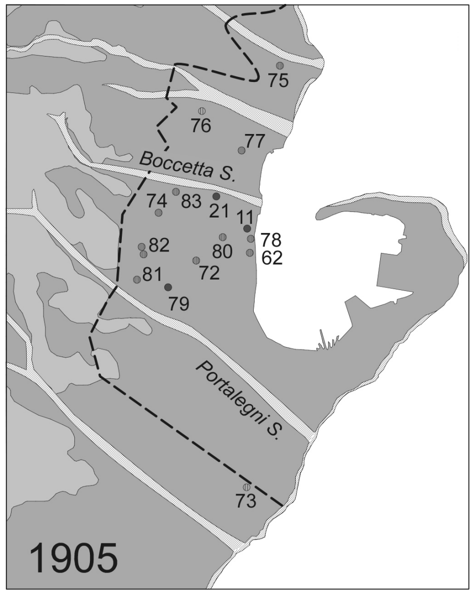


(a) (b)

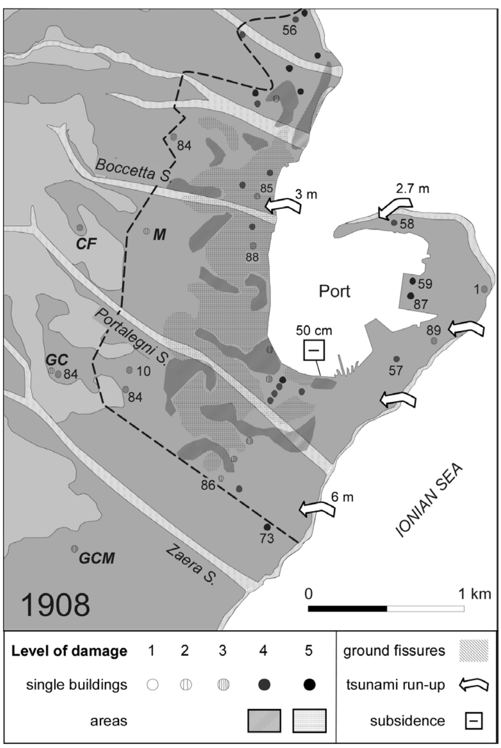
Fig. 3. Summary of damage in Messina following the main earthquakes (see text). Symbols and abbreviations as in Fig. 2; other monumental buildings are labelled by numbers. (a) 1693 earthquake; (b) 1783 earthquakes; (c) 1894 earthquake; (d) 1905 earthquake; (e) 1908 earthquake. 1 = Faro tower (St. Ranieri lighthouse); 2 = Royal Palace; 3 = Archbishopric; 4 = Seminary; 5 = St. Francesco Convent; 6 = Annunziata dei Teatini Ch.; 7 = Calvaruso Prince Palace; 8 = D'Alcontres Prince P.; 9 = Old Customs Door; 10 = Noviziato; 11 = St. Giovanni di Malta Ch.; 12 = Calapai house and Belviso Duke P.; 13 = Cannizzari P.; 14 = Pignatelli P.; 15 = Vittoria door; 16 = Placida d.; 17 = Flavia d.; 18 = Royal d.; 19 = St. Luca Ch.; 20 = Teresiani C.; 21 = St. Maria la Scala Ch.; 22 = St. Filippo Neri Ch.; 23 = St. Giovanni Ch.; 24 = Hospital; 25 = Mint; 26 = Carmine C.; 27 = St. Chiara Monastery; 28 = Cappuccini C.; 29, 30 = Royal boarding schools; 31 = St. Carlo Ch.; 32 = Anime del Purgatorio Ch.; 33 = St. Nicola Ch.; 34 = St. Barbara Ch.; 35 = St. Nicolò Ch.; 36 = Sacerdoti Hospital's; 37 = St. Teresa Ch.; 38 = Immacolata Ch.; 39 = St. Agostino Ch.; 40 = St. Gregorio Ch.; 41 = St. Leonardo Ch.; 42 = College of the Studies and St. Giovanni Battista Ch.; 43 = St. Antonio Abate Ch.; 44 = Monte di Pietà; 45 = Holy Spirit M.; 46 = St. Domenico Ch.; 47 = St. Elia Ch.; 48 = Casa Pia; 49 = St. Lorenzo Ch.; 50 = St. Caterina Valverde Ch.; 51 = Annunziata dei Catalani Ch.; 52 = St. Maria dell'Arco Ch.; 53 = St. Nicolò in the archbishopric Ch.; 54 = St. Maria La Rosa Ch.; 55 = Senatorial P.; 56 = St. Francesco di Paola Ch.; 57 = Cittadella; 58 = St. Salvatore fortress; 59 = Dry dock; 60 = Bonded warehouse; 61 = Cappellini alms house institution; 62 = Town hall; 63 = Messina d.; 64 = Police-headquarters; 65 = Boccabarile Street; 66 = Catalani St.; 67 = Alighieri boarding school; 68 = University Palace; 69 = Gymnasium and technical school; 70 = Revenue office; 71 = Royal technical and nautical Institute; 72 = Prefecture; 73 = Pasteria Pataria; 74 = Prison; 75 = Legnano St.; 76 = Polverari St.; 77 = Caio Gallo St.; 78 = Court-house; 79 = Agonia St.; 80 = St. Camillo St.; 81 = Gesù Maria delle Trombe St.; 82 = Monasteri St.; 83 = Latina St.; 84 = water reservoirs; 85 = Vittorio Emanuele Theater; 86 = Cammareri Villa; 87 = Maritime Protection; 88 = Bank of Sicily; 89 = English Cemetery.



(c)



(d)



(e)

Fig. 3. (*Continued*)

3.9. *The seismic sequence of February–March, 1783*

The 1783 seismic sequence, begun on February 5 ($M_{aw} = 6.9$), ruined many towns in Calabria and northeastern Sicily and caused large geomorphological changes [Barbano *et al.*, 1981; Boschi *et al.*, 1995]. The epicentres migrated from south to central Calabria. The strong shocks occurring on February 5 and 6 ($M_{aw} = 5.9$) caused extensive collapses and severe damage in Messina, especially to the buildings close to the sea. The zone of the *Palazzata* (Fig. 3b), a large group of buildings situated along the coast was mostly damaged between the Royal Palace and the Boccetta stream [Sarconi, 1784]. The *Gonzaga's* and the *Castellaccio* castles did not suffer heavy damage [Vivenzio, 1788]. Large ground fissures opened between the *Purgatorio* and *Customs* gates along the coast. The wharf and beach subsided 75 cm (3 *palms*) and the sea reached the fish-shop barrack. The casualties due to the tsunami were 28 [Spallanzani, 1795].

The following shocks on February 7 and March 28 "ended by ruining the remainder of the houses in Messina" [Spallanzani, 1795]. It is difficult to discriminate the damage scenario due to the February 5 and 6 earthquakes from the cumulative effects of the entire sequence. As a result the urban area on the alluvial plain between the Portalegni and Boccetta streams suffered the most damage (Fig. 3b). Gallo [1784] suggests that the effects of the second shock in Messina were stronger than the first one, so that I_s = VIII-IX and VII-VIII EMS can be estimated, respectively. On the whole, the seismic sequence caused around 700 causalities in Messina.

3.10. *November 16, 1894 earthquake*

Three strong shocks, the main of which occurred at 17:52 GMT ($M_{aw} = 6.0$), heavily struck southern Calabria [Boschi *et al.*, 2000]. Mercalli [1897] and Baratta [1901] report that in Messina there were no collapses or victims, but many buildings had serious cracks. Most damage occurred along the Portalegni and Boccetta streams and near the Cathedral (Fig. 3c).

The Town Hall suffered notable structural damage; the Revenue office was affected by new cracks and the pre-existing ones widened [Riccò, 1907]. The *Luce, Liberale* and *Immacolata* Churches were seriously damaged [Giornale di Sicilia, 1894a]; the *Faro* tower cracked [Mercalli, 1897]. In the dry dock and west of *Lazzareto* along the beach, pre-existing ground fissures widened and a sinking of 15 cm occurred in the basin and in the Customs the ground subsided [Faggiotto, 1895]. I_s = VII EMS has been estimated.

3.11. *September 8, 1905 earthquake*

The earthquake ($M_{aw} = 7.1$) produced severe damage in central Calabria [Rizzo, 1907]. In Messina the Prefecture Building and many houses were cracked, a few heavily damaged; several streets were obstructed by debris. Pieces of mouldings fell in many churches [L'Ora, 1905]. The area between the Cathedral and the Boccetta stream and near the Portalegni stream suffered the most damage [L'Ora, 1905; Giornale di Sicilia, 1905] (Fig. 3d). The earthquake was accompanied by an anomalous movement of the sea [Rizzo, 1907; Platania, 1908]. I_s = VII EMS has been estimated.

3.12. *December 28, 1908 earthquake*

This earthquake ($M_{aw} = 7.2$), the most catastrophic event occurring in the 20th century in Italy, caused extensive destruction over an area surrounding southern Calabria and northeastern Sicily [Boschi *et al.*, 2000]. The earthquake, tsunami and fires destroyed around 90% of the existing buildings in Messina; 65 000 people perished, namely 42% of the population [Mercalli, 1909]. The worst damage effects occurred along the *Palazzata* north of the Town Hall (Fig. 3e), unlike the 1783 earthquakes when the "Maritime Theatre" suffered more extensive damage in the southern part (Fig. 3b). Baratta [1910] suggests that the cause of such a discrepancy may be attributed to the bad state of building maintenance of the *Palazzata* northern sector after the 1783 events, since these were too expeditiously restored.

The zone between the Cathedral square and the Civic hospital, as well as the Boccetta neighbourhood, were completely destroyed [Baratta, 1910]. Along *St. Martino* and *St. Sebastiano* streets near the Matagrifone's Fortress, the damage was less serious. Two houses, the Cammareri and Lanzara Villas, which have been built shortly before the 1908 earthquake, by using good quality materials and inserting ties, were undamaged [Luiggi, 1909]. This observation highlights how the poor quality of the building materials in Messina, usually inhomogeneous rubble stones, together with the widely adopted constructive techniques "*a sacco*" (bare stones with poor quality mortar), have significantly influenced the damage distribution. Recent and ancient buildings showed significant structural defects, such as the lack of iron connections among various parts [Bassani *et al.*, 1909; Baratta, 1910].

The western part of the city, built on more compact terrains, experienced minor damage [Baratta, 1910; Rezzadore, 1914; Cavasino, 1935]: For instance, the *Gonzaga* Castle and some surrounding edifices, suffered slight damage. A tsunami began a few minutes after the earthquake causing further damage and causalities [Platania, 1909; Sabatini, 1910]. Near the Harbour-office, along *Vittorio Emanuele* Street, and near the *St. Salvatore* fortress the run-up was about 3.0 m high, whereas the run-up at the Portalegni mouth raised about 6 m [Platania, 1909]. Several ground fissures opened near *Marina* Street [Baratta, 1910] and subsidence (about 50 cm) of the beach and wharfs also occurred. The overall picture of the effects is consistent with I_s = X-XI EMS.

3.13. *The earthquakes after 1908*

After the 1908 earthquake, several events caused minor damage in Messina throughout the last century (Table 1). On January 23, 1909 [Corriere di Catania, 1909] a

Table 1. Messina site catalogue ($I_s \geq$ V)]. I_o is the epicentral intensity and M_{aw} equivalent moment magnitude; data from the parametric Italian catalogue [Gruppo di Lavoro CPTI, 2004]; (*) data from Postpischl [1985]. I_{as} is the observed MCS intensity from the database associated with the parametric Italian catalogue. I_s observed EMS intensities; I_c is the calculated intensities using epicentral intensities, epicentral distance and the cubic attenuation law by Magri *et al.* [1994].

Year Date	Epicentral area	I_o	M_{aw}	I_{as}(MCS)	I_s(EMS)	I_c	Main references
853 08 31	Messina	IX-X	6.3	IX-X	VIII-X	9.5	Guidoboni and Traina [1996]
1169 02 04	Eastern Sicily	X	6.6	VII	VII-VIII	5.5	Falcado [12th cent.]; Fazello [1558]
1230 04 05	Reggio Calabria	V-VI	4.6	—	—	5.5	—
1310	Villa S. Giovanni	VII	5.2	—	IV-V	7.0	Mongitore [1743]
1390 09 19*	Reggio Calabria	V	4.3	—	V	—	Maurolico [1562]
1448	Messina	VI	4.8	—	V	5.0	Gallo [1756–58]
1456 12 05	Central-southern Italy	X	6.6	V	V	—	Samperi [1644]; Gallo [1756–58]
1494 05 29	Messina	VII	5.2	VIII	VII-VIII	7.0	Samperi [1644]; Maurolico [1562]
1499 11 09	Messina	VII-VIII	5.4	VII-VIII	VIII	7.5	Samperi [1644]; Maurolico [1562]
1509 02 25	Southern Calabria	VIII	5.6	VII	VII-VIII	8.0	Samperi [1644]; Maurolico [1562]
1513 08 25	Messina	VI	4.8	—	V	6.0	Gallo [1756–58]
1542 12 10	Syracuse area	X	6.6	V	IV-V	5.5	Arcovito [19th cent.]
1549 04*	Messina	V	4.3	—	V	—	Aguilera [1737–1740]
1599 06 08	Messina	VII	5.2	VII	VII-VIII	7.0	Samperi [1644]; Fiore [1691]
1613 08 25	Naso	VIII	5.6	VI	VI	4.5	Gallo [1879–1881]
1635 08 12	Messina	VI-VII	5.0	VI-VII	VII	6.5	Carrera [1636]
1638 03 27	Calabria	XI	7.0	VII	VII-VIII	6.5	Vera relazione [1638]
1659 11 05	Central Calabria	X	6.5	V	IV-V	6.0	Mongitore [1743]
1693 01 09*	Eastern Sicily	VIII-IX	6.0	V	V	—	AGS [1693]
1693 01 11	Eastern Sicily	XI	7.4	VIII	VII-VIII	7.0	Burgos [1693]; Boccone [1697]
1706 03 19	Reggio Calabria	V-VI	4.6	V-VI	V-VI	5.5	Carbone-Grio [1884]
1715 02 21	Reggio Calabria	V-VI	4.7	—	—	5.5	—
1716 12 01	Catania	VII	5.2	V	IV-V	3.5	Hoff von [1840]

Table 1. (*Continued*)

Year Date	Epicentral area	I_o	M_{aw}	I_{as}(MCS)	I_s(EMS)	I_c	Main references
1717 04 22	Castroreale	VII-VIII	5.4	V	V	5.5	Bottone [1718]
1717 06 15	Siracusa	V-VI	4.7	V-VI	V-VI	—	Gueneau de Montbéliard [1761]
1720 09 09*	Messina	V	4.3	—	VI	—	Gueneau de Montbéliard [1761]
1724 08 03	Villa S. Giovanni	VI	5.2	—	—	6.0	—
1729 06 29	Castroreale	VI-VII	5.1	Felt	V	4.5	Mongitore [1743]
1732 03 28	Castroreale	V-VI	4.6	V	V	4.0	Mongitore [1743]
1743 02 20	South Ionian Sea	IX-X	6.9	VII	VI-VII	—	Bologna [1743]
1743 12 07	Southern Calabria	VII-VIII	5.8	V	IV-V	4.0	Gallo [1879-1881]
1747 09	Villa S. Giovanni	VI	4.8	—	—	6.0	—
1770 06 08	Reggio Calabria	VI-VII	5.0	Felt	V-VI	6.5	Bologna [1770]
1777 06 06	Calabria	VII-VIII	5.5	V	IV-V	4.5	Hoff von [1841]
1780 03 28	Messina	VI	4.8	VI	VI-VII	6.0	Gallo [1784]
1780 04 10*	Northeastern	VII-VIII	5.4	—	V-VI	—	Gallo [1784]
1783 02 05	Southern Calabria	XI	6.9	VIII	VII-VIII	8.5	Gallo [1784]; Vivenzio [1788]
1783 02 06	Southern Calabria	VIII-IX	5.9	VIII-IX	VIII-IX	8.5	Gallo [1784]; Vivenzio [1788]
1783 02 07	Soriano Serre	X-XI	6.6	VI-VII	V	6.0	Gallo [1784]; Vivenzio [1788]
1783 02 07*	Messina	VII	5.2	—	VII	—	Gallo [1784]; Vivenzio [1788]
1783 03 01	Central Calabria	IX	5.9	VI	V	5.0	Gallo [1784]; Vivenzio [1788]
1783 03 28	Central Calabria	XI	6.9	VII-VIII	VII-VIII	5.5	Gallo [1784]; Vivenzio [1788]
1783 04 26*	Milazzo	VI-VII	5.0	V	V	—	Gallo [1784]; Vivenzio [1788]
1785 03 17	Reggio Calabria	VI-VII	5.0	—	V-VI	6.5	Bologna [1785]
1786 03 10	Northeastern	IX	6.0	VII	VI-VII	6.5	Bologna [1786]
1787 09 19	Messina	VI-VII	5.0	—	V	5.0	Gazzette de France [1787]
1789 02 07*	Messina	V-VI	4.6	—	V-VI	—	Gazzette de France [1789]
1817 10 19	Messina	VI	4.8	—	V	6.0	Gazzetta Piemontese [1817]
1818 02 20	Catania area	X	6.0	V	V	5.5	Longo [1818]
1823 03 05	Northern Sicily	VIII-IX	5.9	V-VI	VI	4.0	Ferrara [1823]
1836 05 04	Reggio Calabria	VII	5.2	—	—	6.0	—
1839 08 27	Reggio Calabria	VI	4.8	—	V	6.0	Gazzetta Piemontese [1839]
1841 03 20	Reggio Calabria	VII	5.2	—	V	7.0	Gazzetta Univ. di Foligno [1841a]
1841 08 15	Reggio Calabria	VI	4.8	—	IV	6.0	Gazzetta Univ. di Foligno [1841b]
1848 01 11	Augusta	VIII	5.5	III	V	4.0	Arcovito [19th cent.]
1851 04 11	Villa S. Giovanni	VI	4.8	—	VI	6.0	Gazzetta Piemontese [1851]

Table 1. (*Continued*)

Year Date	Epicentral area	I_o	M_{aw}	I_{as}(MCS)	I_s(EMS)	I_c	Main references
1852 05 13	Reggio Calabria	VII	5.2	—	—	7.0	—
1876 09 13	Reggio Calabria	VII	5.2	—	V	7.0	Gazzetta di Napoli [1876]
1894 11 16	Bagnara Calabra	VIII-IX	6.0	VII	VII	6.5	Giornale di Sicilia [1894a]
1894 11 20*	Bagnara Calabra	—	—	—	VI	—	Giornale di Sicilia [1894b]
1894 11 26*	Bagnara Calabra	—	—	—	VI	—	Giornale di Sicilia [1894c]
1897 02 11	South Sicilian Sea	VI	4.8	—	V	—	Agamennone [1897]
1898 08 12	Rometta	VI-VII	5.0	VI-VII	VI	6.5	Eredia [1909]
1905 09 08	Calabria	XI	7.1	VII	VII	6.5	Rizzo [1907]
1907 10 23	Southern Calabria	VIII-IX	5.9	V	V	6.0	Martinelli [1910]
1908 12 28	Southern Calabria	XI	7.2	X-XI	X-XI	10.0	Baratta [1910]
1909 01 23*	Villa S. Giovanni	VII-VIII	5.5	—	VII-VIII	—	Corriere di Catania [1909]
1909 06 02*	Villa S. Giovanni	V-VI	4.6	—	VI	—	Martinelli [1912]
1909 07 01	Calabro Messinese	VIII	5.5	VIII	VII-VIII	8	Martinelli [1912]
1909 09 22*	Villa S. Giovanni	V-VI	4.6	—	V-VI	—	Martinelli [1912]
1909 11 20	Villa S. Giovanni	VII	5.2	—	III	7.0	Martinelli [1912]
1910 11 18	Villa S. Giovanni	VII	5.2	—	VII	7.0	Martinelli [1913]
1912 12 22	Villa S. Giovanni	VII	5.2		—	7.0	—
1915 09 11	Reggio Calabria	VI	4.8	—	V-VI	6.0	Cavasino [1935]
1919 03 18	Villa S. Giovanni	V-VI	4.6	—	V	5.5	Cavasino [1935]
1928 03 07	Capo Vaticano	VII-VIII	5.9	VI-VII	VI-VII	4.5	Imbò [1929]; Cavasino [1935]
1932 05 22	Messina	V	5.1	V	V	5.0	Caloi [1942]
1938 04 13*	Southern Calabria	V	4.3	—	V	5.0	Agamennone [1938]
1949 12 09	Reggio Calabria	VI	4.8	—	—	6.0	—
1950 04 10	Messina	VII	5.2	—	V	7.0	La Sicilia [1950a]
1950 12 09	South Ionian Sea	VI	4.8	—	V	4.5	La Sicilia [1950b]
1961 03 24	Aspromonte	V-VI	4.6	V	V	5.5	Bollettino Sismico Definit. [1961]
1967 10 31	Mts. Nebrodi	VIII	5.5	IV	V	3.5	La Stampa [1967]
1975 01 16	Straits of Messina	VII-VIII	5.4	VI	VI	7.0	Bottari and Lo Giudice [1975]; Gazzetta del Sud [1975]
1978 03 11	Southern Calabria	VIII	5.4	V	V	4.5	Gazzetta del sud [1978a]
1978 04 15	Gulf of Patti	IX	6.1	VI	VI	6.0	Gazzetta del sud [1978b]
1985 05 13*	Southern Calabria	V	4.3	—	V	5.0	La Sicilia [1985]
1990 12 13	Southeastern Sicily	VII	5.7	IV	V-VI	3.5	La Sicilia [1990]; Boschi *et al.* [1997]

strong shock caused the collapse of already damaged buildings (I_s = VI-VIII EMS). Another strong shock on July 1, 1909, caused the collapse of various previously damaged buildings, with injuries and casualties (I_s = VII-VIII EMS). On November 18, 1910 an event caused "the collapse of many ruins and walls of the city" [Martinelli, 1912]. In 1928 another earthquake damaged Messina (I_s = VI-VII EMS) [Imbò, 1929; Cavasino, 1935].

Following the destructions of World War II and the reconstruction of the city in the 1950s, only three events provoked slight damage to the city.

During the 1975 earthquake [Bottari and Lo Giudice, 1975; Boschi *et al.*, 1997] only three houses in the *Bisconte* and *Camaro* districts (see location in Fig. 2a) were heavily damaged, but they were already in a very bad state of maintenance [La Sicilia, 1975]. In this case the observed damage scenario (I_s = VI EMS) was significantly lower than expected (I_c = 7–8 in Table 1, see next section). The 1978 earthquake [Barbano *et al.*, 1979; Boschi *et al.*, 1997] caused minor damage to the *Basile* town barracks and to some buildings along *Palermo* and *Noviziato Casazza* streets [Gazzetta del Sud, 1978b]. Finally, the 1990 event [Boschi *et al.*, 1997] caused the fall of some moulding and cracks in old buildings [La Sicilia, 1990] (I_s = V-VI EMS), significantly higher than expected ($I_c = 3$ in Table 1).

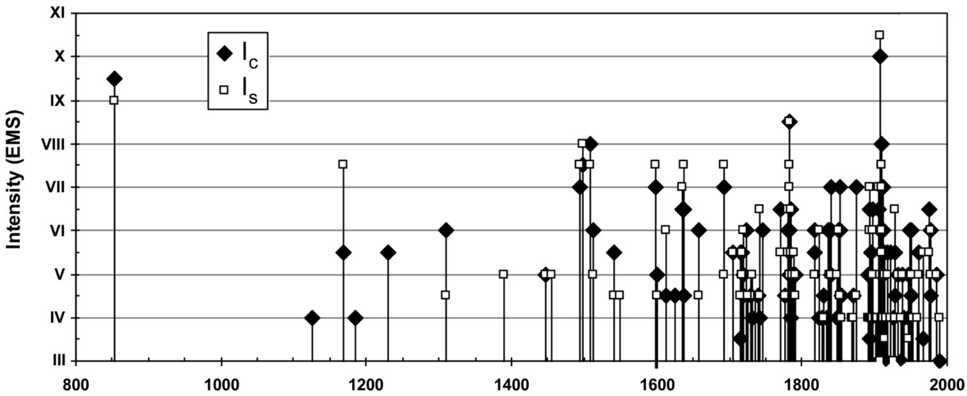
4. The Site Catalogue

In order to define the seismic history of Messina, 175 historical sources have been used. For the sake of brevity only the main 80 earthquakes which have produced effects greater or equal to intensity V EMS are reported in Table 1. The epicentres of earthquakes which have damaged Messina, are plotted in Fig. 1.

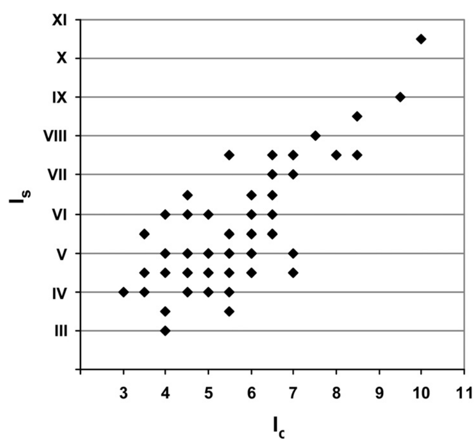
The analysis has allowed us to improve the macroseismic observations of the DOM4.1 (43 observations with $I_s \geq$ IV MCS) [Monachesi and Stucchi, 1997] and CFTI databases (31 observations with $I_s \geq$ IV MCS) [Boschi *et al.*, 1995, 1997, 2000] by adding new data. After assessing intensity by using the EMS, we obtained a site catalogue consisting of 115 observations with $I_s \geq$ IV EMS (Fig. 4). Many of the events are listed in the parametric catalogue of the Italian earthquakes [Gruppo di Lavoro CPTI, 2004] while others, mainly fore- and aftershocks or some minor events, are retrieved from the Postpischl [1985] catalogue. The first earthquake which appears in our site catalogue dates back to 853, when the city of Messina might have been seriously damaged [Boschi *et al.*, 2000].

There is a little evidence of earthquakes before this date in the area surrounding the Straits of Messina in 17 AD and around the middle of the 4th century AD [Guidoboni *et al.*, 1994, 2000], but no reliable information of damage effects for Messina is available.

Local seismic history is represented by the effects of a number N of earthquakes. Nevertheless, especially for older events, direct information about macroseismic effects can be missing. So in order to evaluate the completeness of the site catalogue and to improve its reliability for hazard purposes, calculated site intensities I_c have



(a)



(b)

Fig. 4. (a) Seismic history of Messina in the last 1200 years. (b) Comparison between observed site intensities EMS (I_s) and computed intensities (I_c).

been obtained using the parametric Italian catalogue [Gruppo di Lavoro CPTI, 2004] and the cubic attenuation model proposed by Magri *et al.* [1994]. This led us to include in our site catalogue another 18 earthquakes, without historical information, of which 7 events 5–6 $\leq I_c \leq 7$ (Table 1).

Like other Sicilian cities [Azzaro *et al.*, 1999; 2004; Barbano *et al.*, 2001], the seismic history of Messina shows a lack of information before the 16th century (Fig. 4). The catalogue seems historically complete since the end of the 19th century with regards to the events below the damage threshold ($I_s <$ V-VI EMS). Damaging earthquakes in Messina are very frequent since the city is located close to different, very active seismogenic zones [Meletti *et al.*, 2000a]. It suffered destructions in 1783 ($I_s =$ VIII-IX) and 1908 ($I_s =$ X-XI EMS) and it has been severely damaged (from VII to VIII EMS) many times.

5. Hazard Assessment

PSHA estimation has been calculated through the site catalogue using the procedure described by Magri *et al.* [1994]. This approach is based on the use of a discrete probability function $p_s(I_s)$ for each earthquake, which is the probability of each intensity degree I_s, to represent the observed site effects for that given event. By definition it holds that:

$$\sum_{\mathrm{I}=I_{min}}^{I_{max}} p_s(I_s) = 1. \tag{1}$$

The method has been developed to use the MCS scale but is equally valid if it is exported to any other macroseismic scale [Mucciarelli *et al.*, 2000].

The probability function $p_s(I_s)$ can be defined using available macroseismic data at the site. If, for instance, the uncertainty between the two possible intensity values VII and VIII is considered, the distribution function $p_s(I_s)$ is described by the following eleven elements array:

$$p_s(I_s) = [0, 0, 0, 0, 0, 0.5, 0.5, 0, 0, 0, 0], \tag{2}$$

for I_s ranging between the degrees II and XII EMS.

The probability distribution function is:

$$F_s(i \geq I_s) = \sum_{k=I}^{I_{max}} p_s(k), \tag{3}$$

and the probability that, at the site, the seismic intensity is greater than or equal to I_s [Magri *et al.*, 1994] is:

$$Pr[i \geq I_s] = F_s(I_s) = \sum_{k=I}^{I_{max}} p_s(k). \tag{4}$$

According to the authors, the average return period $RP(I_s)$ and the number $N(I_s)$ of earthquakes can be estimated for expected site intensity greater than or equal to I_s.

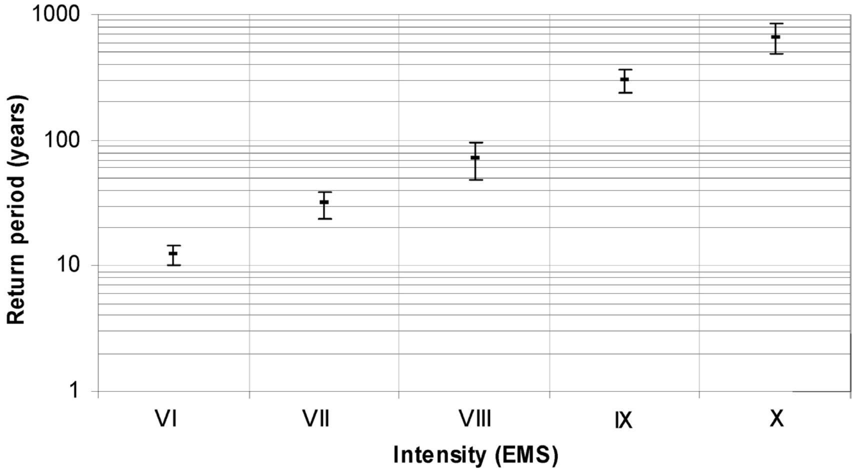
In this study, we simply use the estimated intensity and the RP for each intensity class is computed only when there are at least two events with the probability of being greater or equal to that given intensity. Furthermore, each intensity class is used independently of the others and has its own completeness threshold, computed using the methodology proposed by Mulargia *et al.* [1987]. In Table 2 the completeness starting year for each intensity class and the RP (Fig. 5a), are shown.

As long as the intensity threshold increases, the RP decreases its statistical significance because there are obviously less observations and consequently the confidence interval increases. The RP estimated by the site intensities is generally shorter than the ones obtained through the Cornell method [Slejko *et al.*, 1998].

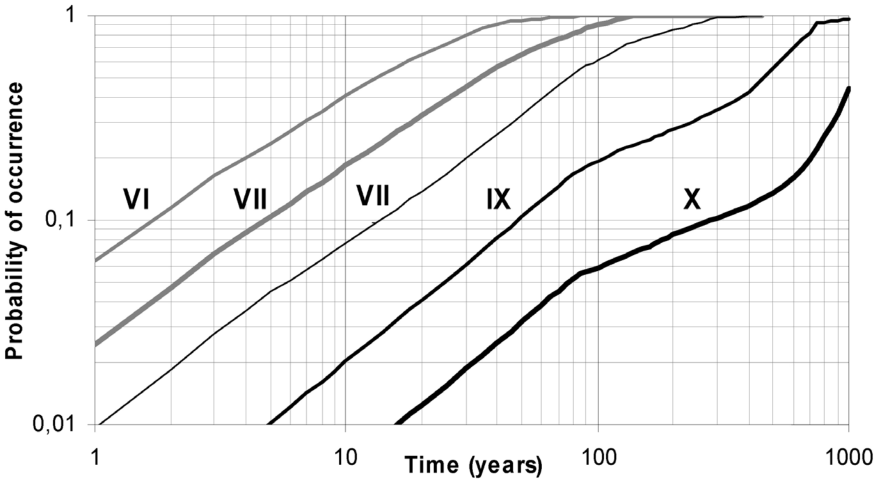
The latter, for instance, gives RP between 100 and 500 years for intensity VII [see Mucciarelli *et al.*, 2000], but our results estimate an RP of 31 years and 71 years

Table 2. Completeness starting year for each intensity class and corresponding average return period (years) with associated error.

Intensity	Complete since	Return period
VI	1599	12.4 ± 2.2
VII	1494	31.3 ± 7.7
VIII	1494	71.4 ± 23.5
IX	1169	299 ± 60.2
X	853	665 ± 180.4



(a)



(b)

Fig. 5. (a) Average return time with associated error for Messina; (b) Probability of occurrence for damaging earthquakes (from $I_s =$ VI EMS).

for intensity VII and VIII respectively, while the *RP* for intensity X EMS is longer than 660 years (Fig. 5a). This value is similar to the one estimated for Catania by Azzaro *et al.* [1999] with the Magri *et al.* [1994] method. Our result is comparable to that estimated by Ghisetti [1992] and Valensise and Pantosti [1992] on a geological basis, suggesting a recurrence time of 1000 years for events like the 1908 earthquake.

Mucciarelli *et al.* [2000] compared PSHA calculated by site intensities with the estimates compiled according to traditional PSHA approaches, obtaining significant differences for some sites.

To explain the differences they suggest that in the classical PSHA the stationary assumption of seismicity has a poor fit with reality and the definition of the seismogenic zones leads to a bias in the seismicity rate estimate. In accordance with these authors, we find a response for the site of Messina that is different from the average values predicted using attenuation relationships.

The obtained PSHA for Messina gives very low probability recurrence values for the highest intensities (Fig. 5b). The probabilities (*Pr*) within a future time span (50, 95, 300, 475 years) that at least one occurring earthquake able to produce on-site effects greater or equal to the intensities from VI to X EMS are shown in Table 3. The maximum intensity characterised by a probability of exceedance not less than 10% during an exposure time of 50 years is IX EMS. For the Catania site the same probability is obtained in 95 years (Table 3) [Azzaro *et al.*, 1999].

The maximum intensity characterised by a probability of exceedance not less than 10% during an exposure time of 300 years is X for both Messina and Catania (Table 3). The hazard assessment performed by GNDT [Meletti *et al.*, 2000b] through the Cornell method, displays instead higher probability for $I_s \geq$ X EMS for the Straits of Messina area in comparison to those obtained for the Catania area. Also in the last hazard estimate calculated by GNDT [Gruppo di Lavoro, 2004] the PSHA obtained for Messina is much higher than the one obtained for Catania, but a direct comparison is impossible because the values are in PGA.

Table 3. Hazard estimates computed through the site approach for Messina and Catania [from Azzaro *et al.*, 1999]. Values are expressed in terms of probability (*Pr*) that in a future time span (50, 95, 300, 475 years) at least one earthquake will occur that is able to produce on-site effects greater or equal to intensities from VI to X EMS.

Future time span	$Pr \geq$ VI	$Pr \geq=$ VII	$Pr \geq$ VIII	$Pr \geq$ IX	$Pr \geq$ X
		Messina			
50 years	0.95	0.64	0.33	0.10	0.03
95 years	0.99	0.88	0.59	0.19	0.06
300 years		0.99	0.92	0.31	0.10
475 years			0.99	0.51	0.13
		Catania			
50 years	0.84	0.53	0.23	0.06	0.02
95 years	0.99	0.86	0.44	0.11	0.03
300 years		0.99	0.83	0.28	0.10
475 years			0.96	0.48	0.17

6. Concluding Remarks

The detailed analysis of historical sources has provided a complete inventory of damage effects in Messina during the earthquakes which have frequently hit the region in the last millennium. Contemporary reports have been studied in order to reconstruct the seismic history of Messina, as well as to delineate the damage scenarios of most relevant events by mapping damage locations with reference to the existing urban settlement of the city. The application of the European Macroseismic Scale 1998 has allowed us to obtain a homogeneous dataset of intensities and to classify damage levels with respect to the building typology. Finally, the resulting site catalogue has been used for evaluating PSHA.

The main results of this study are the following:

- The site catalogue shows that only the 1783 and 1908 earthquakes caused destructive effects in Messina, while at many other times the city suffered significant or heavy damages. The average return period computed using site intensity observations for I_s = X EMS is 660 years, very similar to the one obtained for Catania [Azzaro *et al.*, 1999]. However, in comparison with other sites of southeastern Sicily [Barbano and Rigano, 2001], the seismic history of Messina is characterised by shorter return periods, ca. 30–70 years, for events with intensity values VII and VIII EMS. Scant information is available for the earthquakes of the first millennium.
- The analysis of the damage scenarios related to the earthquakes of 1783 and 1908, which produced the strongest effects in Messina (I_s = VIII-IX and X-XI EMS, respectively), has highlighted that recent alluvial terrains are exposed to high seismic hazard with respect to the crystalline bedrock or the Miocene Units. In particular, two zones are more severely damaged during minor events: The area between the Portalegni and Boccetta streams and that behind the Cathedral. The latter represents, as shown in the historical maps as far as the 15th century, the ancient Portalegni stream which was diverted for defence purposes (cf. Figs. 2b and c).
- For building vulnerability the study has put in evidence that destruction in the case of 1783 and 1908 earthquakes were generally increased by the low quality of constructions, by their bad state of maintenance and the cumulative effect of damage due to repeated shocks.
- After the reconstruction following the 1908 event and World War II no effects greater than I_s = VI EMS has affected the city. This aspect reveals the importance of the introduction of the seismic code after the 1908 earthquake.
- Besides the earthquake magnitude, the lithological features represent a factor that will certainly influence the damage distribution in future events. The greatest effects are expected in the old urban sector built on alluvium soils, which was more exposed in the past, as well as in the new zones developed along the coast and in the stream beds after World War II and in the 1950–1960s.
- Finally, the tsunamis which have inundated the city of Messina after the strongest earthquakes, such as those in 1169, 1693, 1783, 1905 and 1908 caused extensive

damage and claimed many victims. Similarly, liquefaction-induced features, ground fracturing and subsidence phenomena repeatedly observed in the port area and along the coastal sector of the city would worsen the damage extent in Messina under strong seismic events in the future.

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