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Environmental effects of the December 28, 1908, Southern Calabria–Messina (Southern Italy) earthquake

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Abstract   The review of all available contemporary documents, i.e., technical and photographic reports, newspapers, and other archive material, of the 1908, M 7.1, Messina–Reggio Calabria earthquake has allowed to recognize and classify a large number (365) of independent environmental effects of the earthquake and the subsequent tsunami. The effects have been categorized as slope movement, ground settlement, ground vertical movement and coastal retreat, liquefaction, ground crack, hydrological anomaly, gas emission, light, and rumble. No undisputable evidence of surface faulting has been pointed out. Nevertheless, the widespread and rather homogeneous subsidence of the coastal area of Messina (40–70 cm) might have been caused by slip along a NNE–SSW-trending, east-dipping fault, corresponding to the here proposed Messina Lineament. Likewise, slips along the Reggio Calabria, Armo and Motta San Giovanni faults, suggested by coastal subsidence and slides, ground cracks, and leveling data, cannot be ruled out. A large part of the achieved information has allowed to evaluate the epicentral intensity and local intensities at 74 sites, by applying the environmental seismic intensity scale ESI 2007. This study has led to the most comprehensive picture of the distribution and characteristics of coseismic environmental effects of that earthquake, a crucial knowledge to better estimate the future impact of a similar earthquake on a region that has seen a broad, and often poorly concerned, urban and infrastructural development since then.

Keywords   1908 Southern Calabria–Messina earthquake · Earthquake environmental effects · ESI scale · Earthquake scenario · Southern Italy

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1 Introduction

On December 28, 1908, an earthquake of ca. 7.1 magnitude hits the Messina Straits (Southern Italy), a region (Fig. 1) where seismic events have been frequent and severe already in ancient times. In fact, according to the historical catalogues (Guidoboni et al. 2007; Rovida et al. 2011), despite largely incomplete before 1600 (Barbano et al. 2014), the region was hit by frequent strong earthquakes (e.g., Comastri and Mariotti 2008; Guidoboni et al. 2008; Pantosti et al. 2008; Bottari et al. 2010 and references therein). The main events reported in the historical catalogues are as follows: around 91 BC (Reggio Calabria, IX–X MCS), 17 AD (Reggio Calabria–Eastern Sicily?, VIII–IX MCS), 361–363 (Messina Straits, X MCS), 853 (Messina, IX–X MCS), 1172 (Messina, VIII MCS), 1494
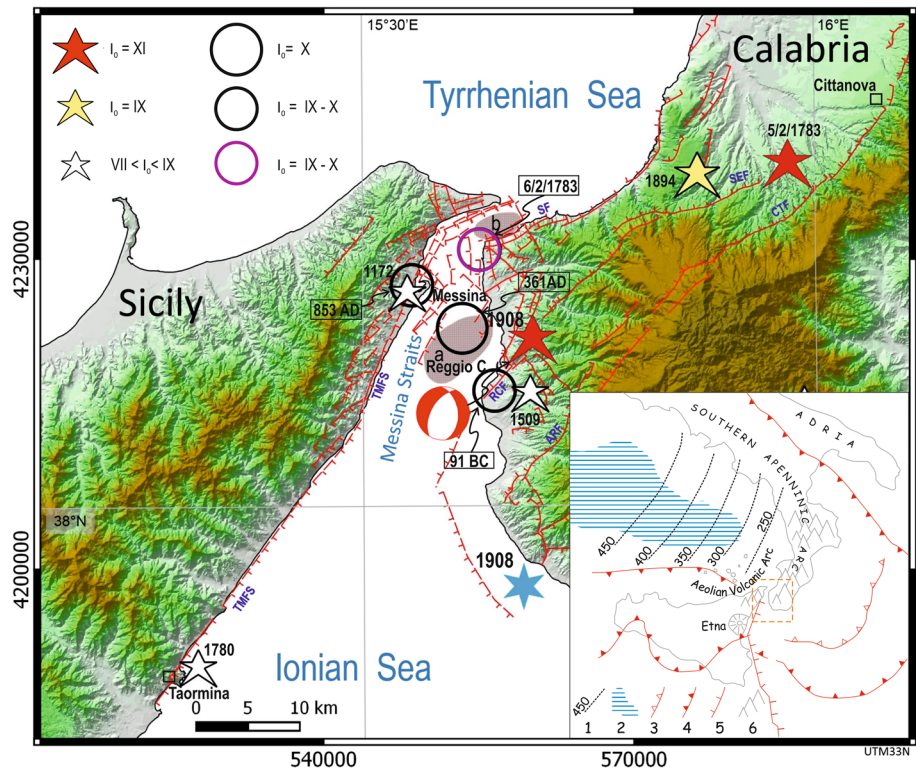

Fig. 1 Messina Straits region with the main capable faults (from ITHACA database, http://sgi. isprambiente.it/GMV2/index.html; see also Comerci et al. 2013a) and epicenters of historical earthquakes (*stars* CPTI11, Rovida et al. 2011, which report main events of seismic sequences since 1000 AD; *circles* CFTI 4.0 catalogue, Guidoboni et al. 2007, for events before 1000 AD and the February 6, 1783, aftershock event (*violet circle*). The *blue star* is the epicenter of Michelini et al. (2006). Focal mechanism from Amoruso et al. (2002). Patches (*a*) and (*b*) in the Straits are the epicentral areas according to Omori (1909) (*a*) and Baratta (1910) (*a, b*). *ARF* Armo Fault, *CTF* Cittanova Fault, *RCF* Reggio Calabria Fault, *SF* Scilla Fault, *SEF* S. Eufemia Fault, *TMFS* Taormina–Messina Fault system. Only faults relevant for this work are shown. *Inset* tectonic sketch based on Patacca and Scandone (2004) and Doglioni et al. (2012). *1* Isobaths of Southern Tyrrhenian slab; *2* Tyrrhenian back-arc basin (oceanic crust); *3* External Calabrian Arc; *4* Quaternary thrust front of Apennines, Calabria, and Sicily; *5* Hyblean–Maltese Escarpment; *6* Calabrian–Peloritan orogenic belt

(Messina, VII–VIII MCS), 1509 sequence (area of Reggio Calabria, VIII MCS), 1659 (Southern Calabria, X MCS), 1783 sequence (Southwestern Calabria, X–XI MCS), 1894 (Southern Calabria, IX MCS), 1905 (Southwestern Calabria, XI MCS), and 1907 (Southern Calabria, VIII–IX MCS). Despite the long experience of seismicity, the 1908 earthquake left a wake of destruction and a death toll of at least 80,000 (e.g., Mercalli 1909; Baratta 1910; De Stefano 1987), never historically documented before in the Mediterranean region. The tsunami that followed contributed significantly to the disaster in terms of both damage and victims. This was also the first event in Italy with a seismological documentation (e.g., Omori 1909; Rizzo 1909, 1911) and a systematic (although still spatially incomplete) description of its effects by a number of eminent scientists of the time, including the still today renowned Mario Baratta and Giuseppe Mercalli.

Among the effects registered by the researchers cited above and many others, a relevant position was taken by the geological, and more in general environmental, manifestations accompanying the event. The collection and organization of such wealth of information, as recorded in scientific, technical, and, to a lesser part, journalistic sources, is the key topic of this paper. Indeed, this paper shows that the panorama of geological effects seen in 1908 can significantly contribute to the future scenario of seismic damage, in addition to that induced by seismic shaking, as observed in many recent seismic events worldwide, from Haiti to Chile, Italy, Greece, Spain, New Zealand, China, and Japan (e.g., Eberhard et al. 2010; Hayes et al. 2010; Lekkas 2010; Mavroulis et al. 2010; EERI 2011; Fritz et al. 2011; Mori et al. 2011; Vittori et al. 2011; Udo et al. 2012; Di Manna et al. 2012; Pavlides et al. 2013; Harp et al. 2013; Silva et al. 2013). Consequently, they need to be considered in order to define a realistic seismic hazard scenario.

Coseismic environmental effects (insofar named earthquake environmental effects (EEEs), following Michetti et al. 2007) fall into two main categories: primary effects, such as surface faulting and tectonic uplift/subsidence; secondary effects, such as landslides, ground cracks, liquefactions, hydrological anomalies, and tsunami (e.g., Michetti et al. 2007). As a whole, they contribute to substantiate the environmental seismic intensity (ESI) evaluation, and some of them are also diagnostic for the assessment of the local ESI (Michetti et al. 2007), as described ahead (Sect. 7). Besides, several EEEs (the primary effects and, between the secondary ones, mostly landslides, liquefactions, and sinkholes) are significant also in terms of hazard, for the consequences they can cause to society, in terms of casualties and economic losses.

Earlier collections of geological effects are found in Caciagli (2008) and in CEDIT catalogue (Martino et al. 2014). The comprehensive database presented here (see Appendix in Supplementary material), based on the review of all the known contemporary sources, has allowed to (a) reconstruct the intensity distribution by applying the ESI scale; (b) provide useful hints about what to expect in terms of effects on the environment from the repetition of a strong earthquake in this region, which is fundamental to a better focused preventive action in this densely populated region; (c) contribute to the still open issue of which fault(s) reactivated during this event.

In fact, about the latter point, the activated seismogenic structure remains elusive one century after the earthquake, despite the many studies focused on the seismogenic fault, based on geological/geomorphological investigation, the interpretation of the historical seismograms, and the inversion of geodetic data (e.g., Omori 1909; Schick 1977; Caputo et al. 1981; Gasparini et al. 1982; Ghisetti 1984, 1992; Mulargia and Boschi 1983; Bottari et al. 1986, 1989; Capuano et al. 1988; Boschi et al. 1989; De Natale and Pingue 1991; Valensise and Pantosti 1992; Tortorici et al. 1995; Monaco and Tortorici 2000; Pino et al.

2000, 2009; Amoruso et al. 2002; Catalano et al. 2003, 2008; Valensise et al. 2008; Argnani et al. 2009a; Bonini et al. 2011; Polonia et al. 2012; Aloisi et al. 2013).

According to the worldwide and regional fault parameter databases (e.g., Wells and Coppersmith 1994; Pavlides and Caputo 2004), to the ESI scale (Michetti et al. 2007) and also to the historical evidence in the Southern Apennines (e.g., Serva et al. 2007) and Calabria (e.g., Jacques et al. 2001), a magnitude ~7 earthquake, such as the 1908 event, should have been associated with surface faulting for a length of at least several tens of kilometers, which was not reported by any witness. Consequently, some authors have proposed a causative blind low-angle seismogenic fault (Valensise and Pantosti 1992; Valensise et al. 2008; Bonini et al. 2011). Alternatively, this lack of evidence can be explained by a fault rupture emerging at the sea bottom of the Messina Straits (e.g., Argnani et al. 2009a; Polonia et al. 2012), or even, although less probable, because it was missed by surveyors who were not looking for fault ruptures and visited only the most accessible spots of the epicentral area.

Actually, in the mesoseismal area, there are several faults with geological and geomorphological evidence of recent activity, i.e., scarps and escarpments that are the cumulated effect of repeated surface faulting events (Fig. 1). So, the reported EEEs were also investigated considering their location with respect to these faults and reviewing in detail all accounts (e.g., ground ruptures and subsidence) possibly related to primary coseismic effects.

2 Tectonic framework of the 1908 earthquake

The structural setting of the region enclosing the Messina Straits is widely debated. This tectonic depression (Fig. 1), rather narrow in its northernmost part (ca. 3 km) and widening southwards, appears bounded on its western side (Sicily) by a system of more or less manifest NNE–SSW-trending coastal faults from Taormina to Messina and ENE–WSW faults north of this city. On the Calabrian side, the border faults are quite evident in the northernmost part (e.g., Scilla Fault), while a complex grid of offshore and inland faults shape the coast southward (among which, Reggio Calabria Fault and Armo Fault).

In general terms, the earthquake occurred within the southernmost part of the Southern Apenninic Arc (Patacca et al. 1993; Patacca and Scandone 2004; inset in Fig. 1), and more precisely in the Calabrian–Peloritan orogenic belt, whose formation started around the end of the Paleogene, when important rollback processes began to develop along the subducting western margin of Adria. The rapid flexure-hinge retreat of the lower plate determined the opening of the Western Mediterranean and Tyrrhenian back-arc basins and the simultaneous forward migration of the thrust belt-foredeep system (e.g., Malinverno and Ryan 1986; Patacca and Scandone 1989; Doglioni 1991; Doglioni et al. 1999). The Ionian slab is presently imaged by deep earthquakes and tomography (e.g., Selvaggi and Chiarabba 1995; Wortel and Spakman 2000; Lucente et al. 2006; Margheriti et al. 2008; inset in Fig. 1).

The Messina Straits tectonic depression is located in the zone separating the faster SE-retreating slab beneath Calabria and the Sicilian continental lithosphere, which is subjected to a compressive regime along the northern offshore of Sicily. Being a transfer zone between these two geodynamic settings, the Messina Straits displays extension and dextral transtension (Doglioni et al. 2012; references therein). Since Upper Pliocene on either side of the Straits a thick sets of gravels and sands deposited, prograding toward the center of the Messina Straits (Guarnieri et al. 2004; Argnani et al. 2009a), indicating the presence of a preexisting depression.

The whole Southern Apenninic Arc underwent, during the Quaternary and Holocene, a regional uplift with concurrent extension and downfaulting (Dumas et al. 1982; Ghisetti 1984; Monaco and Tortorici 2000; Dumas et al. 2005), still active today and well constrained by geological data (Valensise and Pantosti 1992; Antonioli et al. 2006; Ferranti et al. 2007, 2008).

The concurrent uplift and extension has been interpreted as a consequence either of an asthenospheric flow into the gap resulting from a slab detachment (e.g., Wortel and Spakman 2000; Goes et al. 2004) or an asthenosphere wedging beneath the decoupled crust (Gvirtzman and Nur 2001). According to Patacca and Scandone (2004), during the final stage of the foreland-to-hinterland thrust migration, a breaching process caused a generalized uplift in the axial part of the mountain chain (1.8–2.2 cm/year in the Southern Apennines and around 0.5 in Sicily).

To distinguish the contribution of regional uplift from that of the local tectonics is a difficult task: according to Westaway (1993), 1.67 mm/a of post-Middle Pleistocene uplift is partitioned between 1 mm/a c.a. due to regional processes and the residual to aggregated displacement on the major faults of Southern Calabria (Scilla, Reggio Calabria-S. Eufemia, and Cittanova–Armo Faults; see Fig. 1). The uplift in the Calabrian sector seems to have been faster than in the Sicilian coast close to Messina (Antonioli et al. 2006), implying active tectonics in the Straits. Holocene slip-rate estimates in the western Calabrian and eastern Sicilian coasts are provided by several authors (Firth et al. 1996; Stewart et al. 1997; Pirazzoli et al. 1997; De Guidi et al. 2003; Antonioli et al. 2004, 2006; Ferranti et al. 2007). Noteworthy, coseismic contribution to the total uplift rate during the Late Holocene has been estimated in Sicily (1.7–2.3 mm/a south of the Messina Straits) by De Guidi et al. 2003 and in Calabria (ca. 2.1 mm/a along the eastern coast of the Straits) by Ferranti et al. 2007.

Finally, the kinematics of the 1908 earthquake is consistent with the back-arc Quaternary tectonic activity of the whole Apennines; in particular, the Calabrian arc has undergone a greater shortening, with a corresponding maximum back-arc extension in the southern Tyrrhenian Sea (Scrocca et al. 2003a). Active NW–SE extension is confirmed by seismicity and seismic reflection profiles (Scrocca et al. 2003b; Doglioni et al. 2004, 2012; Pondrelli et al. 2004, 2006; Argnani et al. 2009a; Polonia et al. 2012), focal mechanisms of crustal earthquakes (e.g., Chiarabba et al. 2005; Ferranti et al. 2008; D'Amico et al. 2010, 2011), structural studies (e.g., Tortorici et al. 1995; Monaco and Tortorici 2000; Jacques et al. 2001), and geodetic velocities (D'Agostino and Selvaggi 2004; Goes et al. 2004; Serpelloni et al. 2005, 2010; Devoti et al. 2008; D'Agostino et al. 2011).

3 The 1908 event

The December 28, 1908, earthquake (Mw 7.1, epicentral intensity MCS XI; Rovida et al. 2011) was the most destructive disaster of the twentieth century in Italy. The impact of the earthquake was particularly catastrophic along the southwestern Calabrian coast and along the northeastern coast of Sicily (Baratta 1910; Boschi et al. 1995; Barbano et al. 2005; Guidoboni and Mariotti 2008). Reggio Calabria and Messina were almost totally destroyed. Few minutes after the earthquake, both sides of the Messina Straits were inundated by a disastrous tsunami, whose effects often overprinted those directly caused by the earthquake. The run-up reached 11.70 m at Sant'Alessio, in Sicily, and 13 m at Pèllaro, in Calabria (Platania 1909a, b) (see Sect. 6.1). Most authors have suggested a tectonic source for the tsunami (e.g., Gerardi et al. 2008; Argnani et al. 2009b), while Billi et al. (2008, 2010) believe the tsunami was triggered by an underwater landslide in the Ionian Sea, offshore Taormina.

The earthquake and the tsunami waves caused a great number of victims (at least 80,000, according to De Stefano 1987 and references therein). The exact number is unknown because the Messina municipal archive was destroyed by a fire and also the vital records of Reggio Calabria were lost. According to Mercalli (1909), in Messina, the victims were 65,000, corresponding to 42 % of inhabitants (counted at the end of 1900), while in Reggio district were more than 25,000, corresponding to 44.9 %. Based on the distribution of damage on buildings and man-made structures, the macroseismic epicenter was located north of Reggio Calabria (Fig. 1). However, the precision of this location suffers of the wide marine area inside the epicentral region and the paucity of information from the mountainous regions inland.

In most reconstructions (e.g., Omori 1909; Baratta 1910; Ryan and Hezen 1965; Schick 1977; Bottari et al. 1986; Boschi et al. 1989; Cello et al. 1982; De Natale and Pingue 1991; Valensise and Pantosti 1992), based on the available seismological and geodetic data, the epicenter was located offshore in the Messina Straits. Successively, Michelini et al. (2006) have proposed its location in the southern part of the Straits, close to the Calabrian coast, while Pino et al. (2000) have determined a northward direction of the rupture propagation.

The main shock occurred at 5 h 20 m 27 s (CET) of December 28, based on the registration of the microseismographer *Vicentini* of the Messina seismic Observatory (Rizzo 1909, 1911). Only the first portion of the movement traced by the nib along the vertical component is significant, because the shock affected the functioning of the markers (causing the immediate rupture of the two horizontal nibs and the entanglement of the vertical component nib with the chronographer). Nevertheless, according to Oddone (1909), in the seismogram, it is possible to distinguish a second shock, occurred five minutes after the first shock, before the interruption of the registration. Baratta (1910) collected many descriptions of the main shock, often in contrast among them. According to the Director of the Messina seismic Observatory, there was a sequence of quakes started with a first pulse NNE–SSW oriented, followed by a stronger shock, ESE–WNW directed, and a third, even stronger, series of vibration along the NNE–SSW direction (Rizzo 1909).

Such observations seem to indicate a seismic cycle composed by subevents, related to the activation of different faults or fault segments.

Only 11 historic seismograms are available for the waveform analysis, registered in 6 stations (5 in Germany and 1 in Russia). Unfortunately, their quality, spatial distribution (between 12° and 16° from the epicenter, except the Russian one), and azimuthal coverage (<9°, except the Russian one) are modest, limiting the possibilities of sound seismological analyses (Pino et al. 2000; Pino 2008). As well, several authors have modelled the seismogenic fault plane and its slip (see references in Aloisi et al. 2013) based on the geodetic survey of Loperfido (1909), who revisited in the months following the event many benchmarks (121) of an earlier survey both in Sicily (around Messina) and along the Calabrian coast. Despite the invaluable information it provides, this survey is presumably affected by local effects and is demonstrated not to deliver a unique solution (Aloisi et al. 2013).

The focal mechanism of the earthquake was mainly normal, with the fault plane oriented NNE–SSW. The dip of the ruptured plane (east or west) is still debated (Pino et al. 2009; references therein).

4 The collection of earthquake environmental effects

The following paragraphs illustrate the evidence of primary and secondary EEEs induced by the 1908 earthquake, based on the accounts of contemporary testimonies. As to be

expected, the surveyors were generally more interested in the effects on people and their constructions than on the natural environment. However, 509 contemporary testimonies were collected related to 365 environmental effects, documented in newspapers, magazines, the Official Gazette, and tens of reports, several of them compiled by true authorities of that time on this subject, such as Mercalli, Baratta, and Omori. All the descriptions are summarized in the table in Appendix. The most relevant geological and geophysical documental sources were Baratta (1909a, b, 1910), Cortese (1923), Crema (1909, 1921), Di Stefano (1909), Franchi (1909), Galli (1910), Gor'kji-Meyer (2005, translated from the original Russian text of 1909), Luiggi (1909), Martinelli (1909), Marzolo (1909), Mercalli (1909), Miller (1909), Morris (1909), Novarese (1909), Occhiuto (1909a, b), Oddone (1909), Oldham (1909) Omori (1909), Perret (1909), Platania (1909a, b), Rezzadore (1914), Ricciardi (1909, 1910), Riccò (1909a, b), Rizzo (1911), Sabatini (1909), Società Fotografica Italiana (1909), and Taramelli (1909). Moreover, the 121 topographic elevation changes obtained by Loperfido (1909), via a geometric levelling survey repeated after the shock, were re-examined and located.

Once found in the original sources, each described effect was classified into a "category of effect" and "type of effect." The following categories were considered: *slope movement, ground crack, ground lowering and uplift (also measured by means of geometric levelling), ground settlement, coastline retreat, sinkhole, liquefaction, hydrological anomaly, gas emission, earthquake light,* and *acoustic effect.* Their statistical distribution is reported in Fig. 2. Also, 423 tsunami effects were classified, such as run-up, wave ingression, erosion, and sedimentation, that are being described in another dedicated paper under preparation.

Sometimes, the interpretation and selection of the most appropriate category for an effect has not been straightforward, and the above classes are to be interpreted in a broad
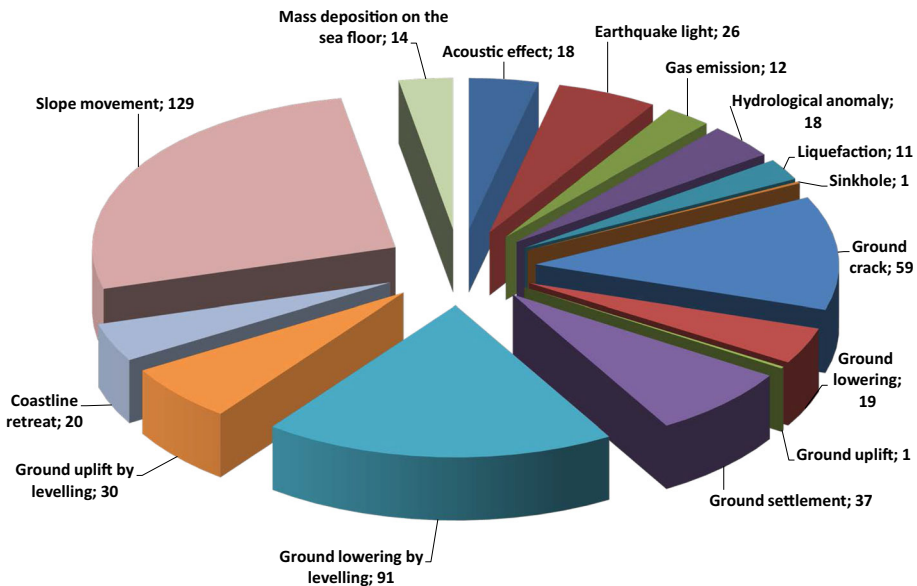

Fig. 2 Classification of the 486 collected effects induced by the 1908 earthquake on the environment and their statistical distribution. 365 effects derive from contemporary accounts, while 121 (91 + 30) are the data from the geometric levelling survey carried out by Loperfido (1909)

sense. In fact, the descriptions in the contemporary sources were often vague enough, or sometimes uncertain even when a mechanism was explicitly proposed in the text (e.g., landslide when describing ground sink, although other possibilities could not be ruled out). In the reading of reports, and even more evident in newspapers and books, it is clear that the descriptions very often suffer of the knowledge/beliefs of the times, also of the scientists, or the will of the journalists to impress the readers by exaggerating or multiplying events, often of second hand.

All the original accounts are reported in the Appendix, both in Italian and English. In the table, all the relevant sources are given for each occurrence, together with its most likely location in WGS84 coordinates, location reliability, information reliability, and local ESI, when evaluable.

In general, the geographical distribution of the 365 independent effects appears strongly uneven (Figs. 3, 4, 5), largely due to the irregular pattern of investigation conducted then by the surveyors. Evidently, they concentrated their efforts in the many settlements along the coastal area, severely hit but still accessible, often from the sea. In fact, in that ragged morphology, many slides blocked the roads, making complex and strenuous the access to the inland region, generally hosting only small and dispersed villages. Consequently, little
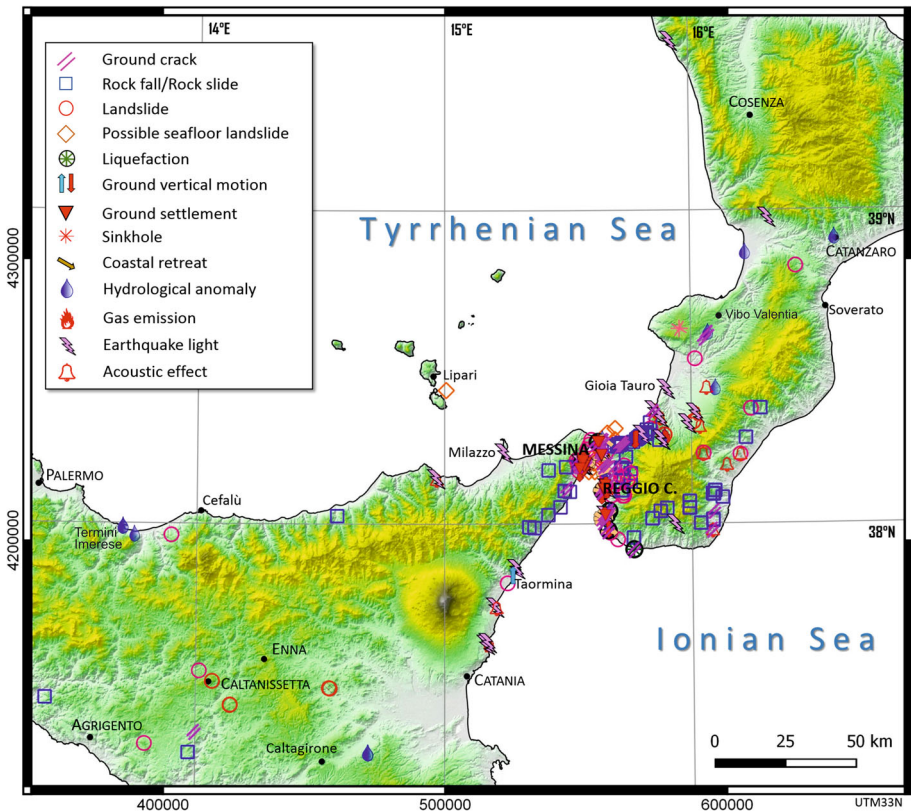

Fig. 3 Distribution of the 365 effects on the environment described by the contemporary sources. Their geographical distribution is uneven also because the surveyors focused on the more inhabited and more accessible areas
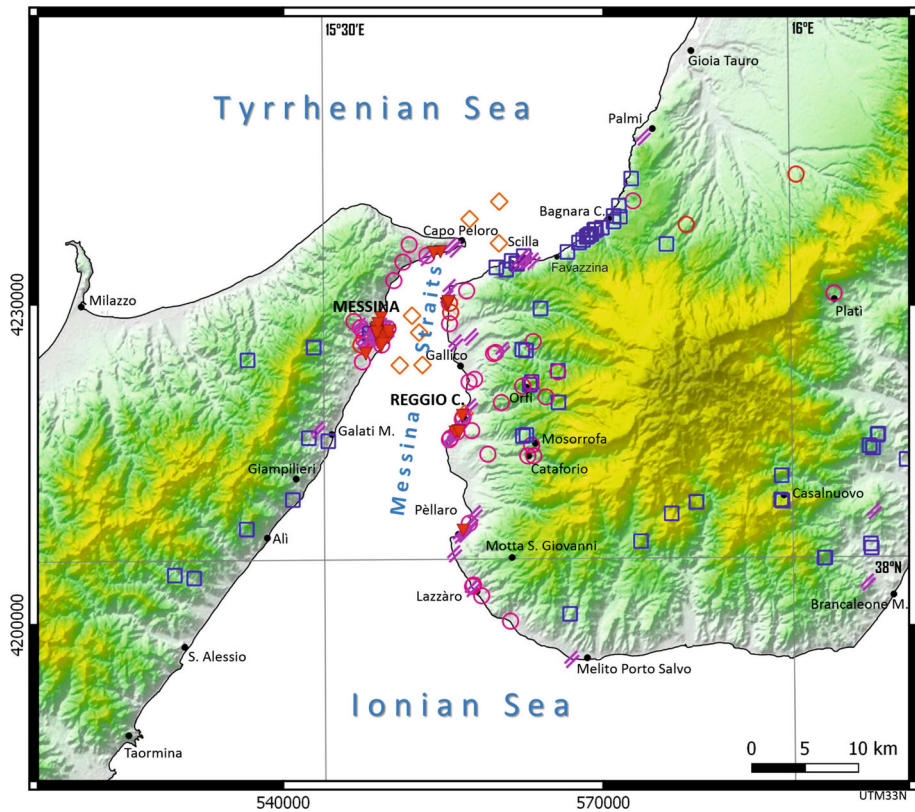
Fig. 4 Close-up view of rock falls/rock slides, landslides, ground settlements, ground cracks, and possible seafloor landslides in the epicentral area. Legend as in Fig. 3

is known about damage and environmental effects away from the coastal areas and the main settlements.

The *Location reliability* is represented by four classes of spatial approximation ranging in the following intervals: 0–100 m, 0–1 km, 0–10 km, >10 km.

Out of the 365 effects, 198 occurred in Calabria, 152 in Sicily, 1 at Valletta (Malta), and 14 at sea (probable mass depositions on the seafloor). Most of the collected effects (104) fall in the Messina town area. Excluding those occurred in Messina and Reggio Calabria (137 in total), the number of inland effects in Calabria (165) is much larger than that in Sicily (48).

Most of the reported effects are slope movements, as evident focusing on the epicentral area (Fig. 4).

5 Primary effects

The main evidence of coseismic primary effects is generally considered the ground elevation changes in Calabria and Sicily, measured by means of geometric levelling soon after the earthquake (Loperfido 1909; Costanzi 1910; De Stefani 1910). In Calabria, the 1909 campaign repeated the measures taken in 1907–1908, while in Sicily the reference levelling had
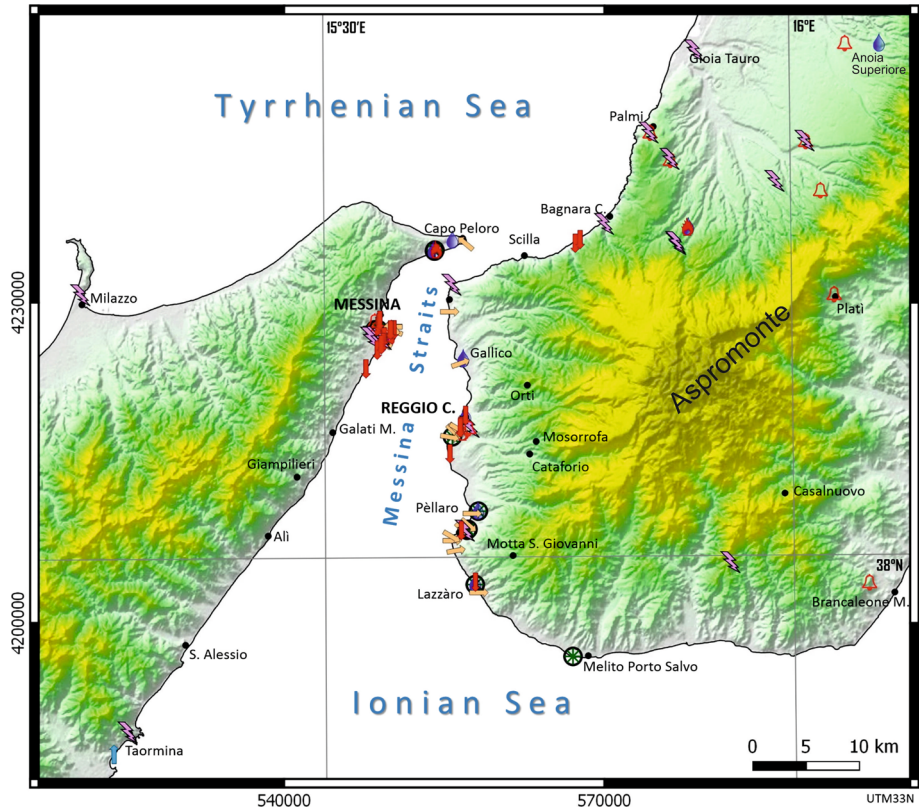
Fig. 5 Close-up view of ground vertical motions (ground lowering and uplift), coastal retreats, liquefactions, hydrological anomalies, gas emissions, earthquake lights, and acoustic effects in the epicentral area. Legend as in Fig. 3

been carried out in 1898–1899. The differences between the 1909 and the previous surveys are shown in Fig. 6. It is to be considered that many benchmarks, during the 1909 levelling, resulted damaged by the earthquake and many of them were also reached by the tsunami. Nevertheless, as a whole, along the Calabrian coast, there is a good coherence among the data, with the highest ground subsidence (up to 58 cm) in the Reggio Calabria area and a tapering of the elevation drop toward the two primary benchmarks at Gioia Tauro and Melito di Porto Salvo; at the railway stations of Saline and Melito di Porto Salvo was also measured an uplift exceeding 12 cm (Fig. 6). On the Sicilian side, where the levelling was along a transect orthogonal to the coast, stands out the constant drop in elevation of the 4 benchmarks in the coast of Messina (66–71 cm), compared to the overall stability of the inland benchmarks (among which only the easternmost point, 8A, showed a subsidence of 12 cm).

5.1 Historical accounts of possible tectonic subsidence and faulting

5.1.1 Tectonic subsidence

Basically, four areas underwent coseismic subsidence associated with ground fractures of possible tectonic origin, in Messina, Reggio Calabria, Pèllaro, and Lazzàro. Such
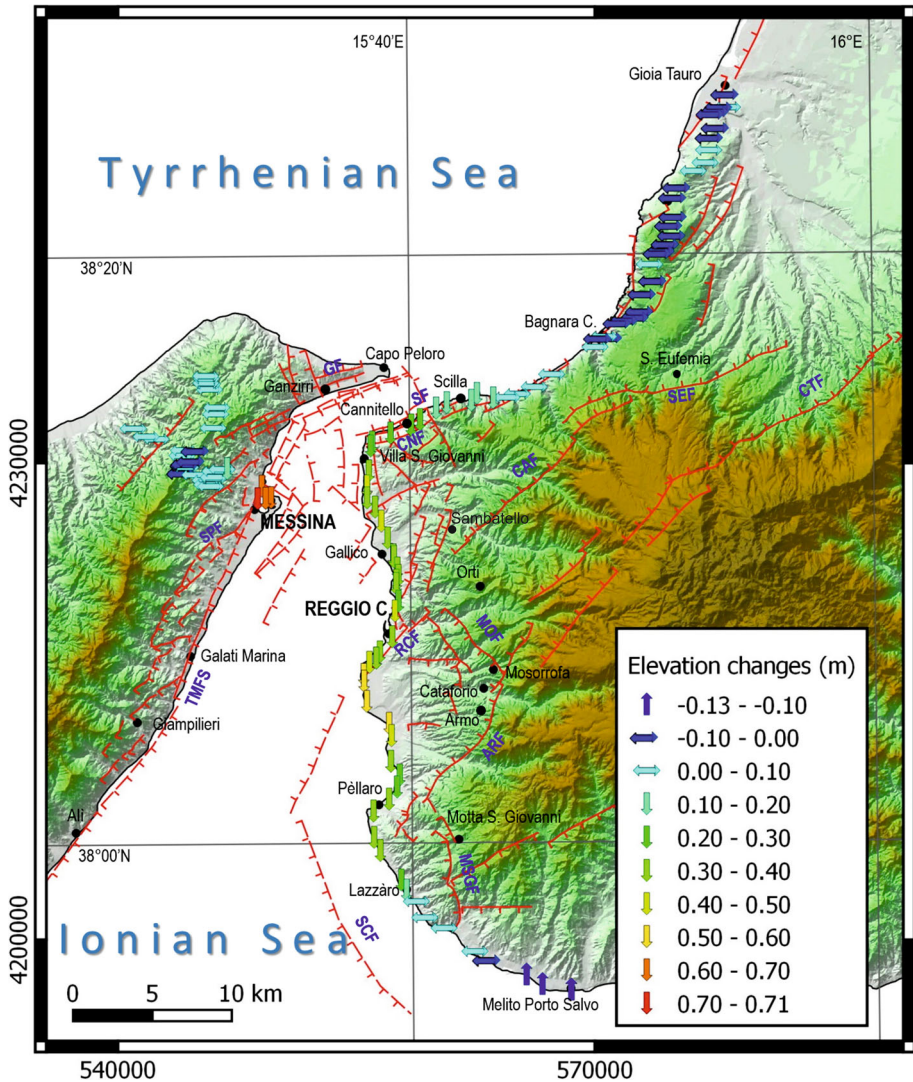
Fig. 6 Topographic elevation differences between the geometric levelling carried out by Loperfido in 1909 and the previous surveys carried out in Calabria (1907–1908) and in Sicily (1898–1899). In *red* are the faults (*thick solid lines* barbed on the downthrown side, *dashed* where inferred or submerged) after ITHACA (http://sgi.isprambiente.it/GMV2/index.html) (simplified): *ARF* Armo Fault, *CAF* Calanna Fault, *CNF* Cannitello Fault, *CTF* Cittanova Fault, *GF* Ganzirri Fault, *MOF* Mosorrofa Fault, *MSGF* Motta San Giovanni Fault, *RCF* Reggio Calabria Fault, *SCF* Southern Calabria Fault, *SEF* S. Eufemia Fault, *SF* Scilla Fault, *SPF* San Pietro Fault, *TMFS* Taormina–Messina Fault system. The sources for the faults are, among many, Atzori et al. (1983), Ciaranfi et al. (1983), Ghisetti (1992), Tortorici et al. (1995), Del Ben et al. (1996), Lentini et al. (2000), Guarnieri et al. (2004), Guarnieri and Pirrotta (2008), Aloisi et al. (2013)

deduction, comforted by the leveling data of Loperfido (1909), is based on some contemporary accounts of widespread *Ground Lowering*. In the Appendix, 19 events are classified as such; they are mostly located in Messina and along the Calabrian coast (Fig. 5).

Baratta (id 59 in Appendix) states that in Messina, a true ground subsidence took place at the mouth of the Portalegni Torrent. Franchi (id 7 in Appendix) reports that the State Railway Maintenance Office has found a constant lowering of 47 cm along the railtrack from the ferryboat station to the Zaera bridge, and the levelling of the Military Geographic Institute proves a sink of 37 cm of the whole lower part of the town. Platania (1909a) documents a remarkable and homogeneous lowering of the bridge of San Diego "falsabraga" (at the Citadel, in the sickle-shaped peninsula that bounds the harbor of Messina; Figs. 7, 8). Moreover, the San Raineri lighthouse, at the Saintest Saviour fortress (the easternmost tip of the peninsula), reportedly subsided of 51 cm (id 54). The same author (Franchi 1909; p. 138) puts forward a hypothesis (which he defines probable even if highly speculative) that "a true general lowering of the bedrock," in particular of the whole rocky sickle contour, took place. As a whole, a tectonic subsidence of 40–70 cm might be inferred, which affected the lower part of town, near the coast, from Fata Morgana Street (benchmark 6; Loperfido 1909) to south of the harbor, near the outlet of the Fiumara Portalegni. If so, the settlement due to liquefaction of unconsolidated fine-grained sediments, proposed by Bottari et al. (2010) to explain the damage to buildings in the sickled peninsula, may have superimposed onto the widespread subsidence along the coast.

Notably, the tidal gauge in the Messina harbor, although destroyed by the tsunami and restored afterward, appears to have recorded a comparable subsidence (ca. 40 cm, becoming rather quickly 55 cm toward the end of 1909; Fig. 1 in Cannelli et al. 2013). The lowered coastal area appears bounded to the west by a rather sharp morphological rise, whose rectilinear edge has been named here Messina Lineament (MEL, Fig. 8). This lineament, located slightly east of the San Pietro Fault (Ghisetti 1992) and the Messina Fault of Ferranti et al. 2008, appears to correspond to the NNE-trending active fault across Messina reported in Ghisetti 1979, Ciaranfi et al. 1983, Neri et al. 2006, part of the Taormina–Messina Fault system (TMFS in Figs. 1, 6) running all along the Sicilian coast from south of Taormina to north of Messina. MEL has been traced here based on its morphological evidence, particularly clear on the shaded relief image (inset of Fig. 8) obtained from the SurfIt 10-m resolution DEM (Tarquini et al. 2012).
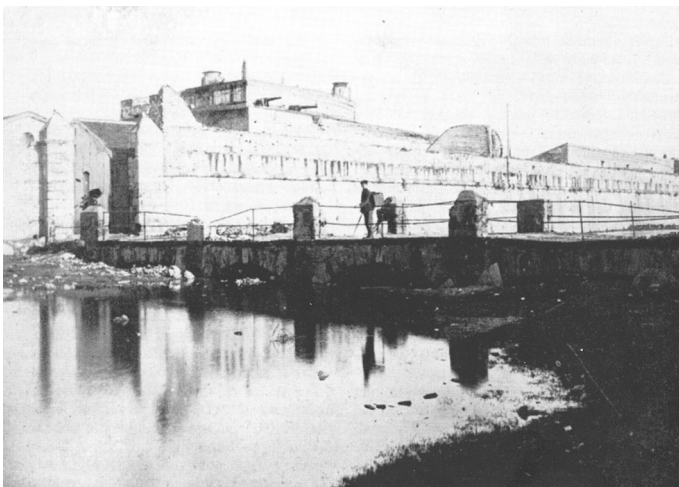

Fig. 7 Lowering of the San Diego "falsabraga" bridge, at the Citadel (Fig. 8), in the sickle-shaped peninsula of Messina (Platania 1909a). Note the almost completely submerged arches
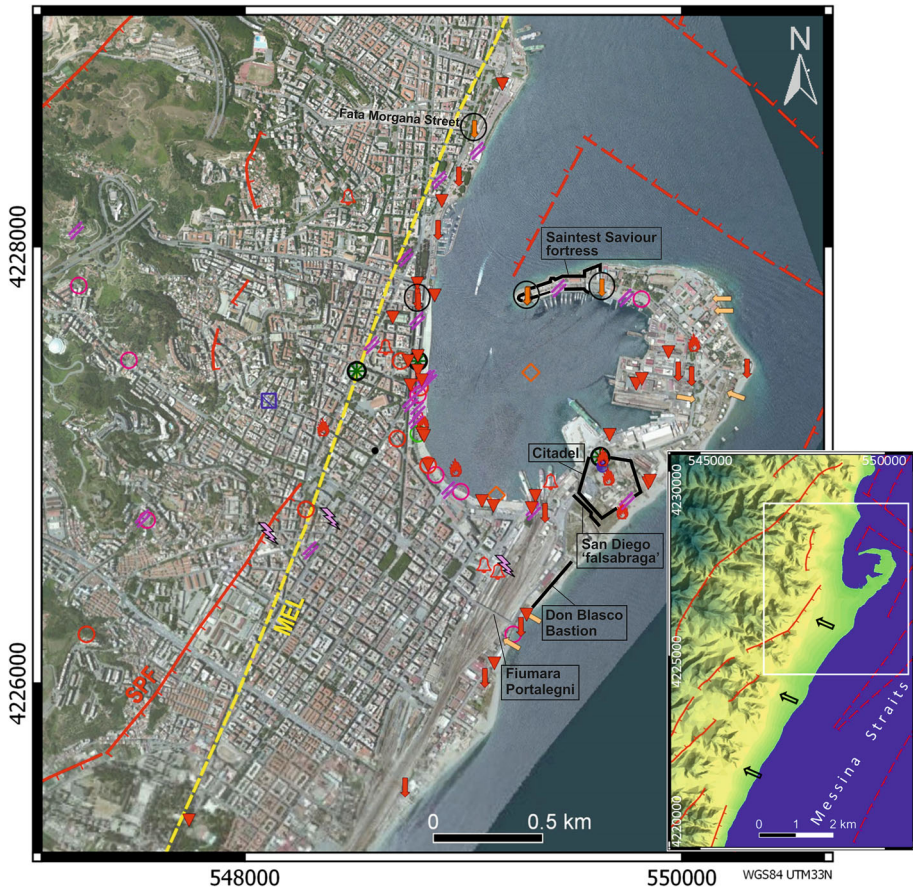
Fig. 8 EEEs occurred in Messina (Legend as in Fig. 3). Many of these EEEs are related to slope movements that involved a large part of the town's seacoast. The flat coastal area east of the NNE–SSW dashed *yellow line* (called here Messina Lineament, MEL) was affected by a widespread subsidence of about 0.5 m, indicated by Loperfido (1909) measurements (*4 encircled arrows*) and pointed out at many locations by independent observers. A possible tectonic origin cannot be ruled out here. SPF: San Pietro Fault. *Inset* DEM showing the morphology of the coastal area around Messina. *Arrows* point to the "Messina Lineament." *White box* encloses the area of main figure. Satellite image from Bing Maps. Inland faults from Ghisetti (1992), Lentini et al. (2000), and Guarnieri et al. (2004). Faults in the sea area around the "sickle" from Finetti and Del Ben 1985 (in Bottari et al. 2010)

A large subsidence was also noted in the town of Reggio Calabria (Fig. 9), associated with ground fracturing and a retreat of the coastline. The largest lowering took place along the coast, from the port, where it was estimated to be between 90 cm and over a meter (id 182 in Appendix), to south of it. Novarese (id 185 in Appendix) states that near the Old Port, south of the new one, the beach retreated for 20–30 m and ground fractures took place, parallel to the beach, in the ground close to the sea.

Many other accounts are available of fracturing parallel to the coastline and accompanying the coastal retreat, especially along the Marina Road and in the wharf area (id 169, 170, 171, 174, 178, 179, 180, 181, 184, 186, 190, in Appendix), along a rectilinear stretch of coast, about 2 km long, parallel to the northeast–southwest-trending Reggio Calabria Quaternary fault (RCF in Figs. 6, 9; Atzori et al. 1983; Tortorici et al. 1995; Aloisi et al. 2013).

Fig. 9 EEEs occurred in Reggio Calabria. Most of these EEEs (erosion, subsidence, landslides, collapses) were reported along the seacoast. Faults from Atzori et al. (1983). The inferred shape of the Punta (Cape) Calamizzi that disappeared in 1562, likely because of a landslide induced by coastal erosion, is shown

About the causes of the observed ground sink, it must be recalled that the same area underwent severe effects of the tsunami, and also the ground shaking could have triggered or accelerated sliding phenomena (this is the opinion of Mercalli 1909; Baratta 1910) that certainly had already affected this sector of the coast. This is, for example, the likely cause of the drowning of Punta Calamizzi, the old port of Reggio Calabria, in 1562, although the deviation of the Calopinace stream may have caused a rapid erosion of that sandy promontory. Much less likely is the sometimes invoked seismic cause, as no earthquakes are known in the region for that period.

However, despite the lack of any unequivocal evidence, to which might have contributed the subsequent tsunami waves, the location of many effects so close to the Reggio Fault leaves at least a suspect of reactivation, possibly reinforced by the tectonic

subsidence shown by the leveling of Loperfido (Fig. 6). Many EEEs classified in Appendix as ground lowering, coastline retreat, landslide, and ground crack might be actually associated with tectonic subsidence.

Moreover, the strips of land disappeared underwater at Pèllaro and Lazzàro (id 247, 248, 249, 250, 252, 258, 262, 263) could be also related to tectonic subsidence, even if Sabatini and Novarese (id 241) interpreted this phenomenon as a consequence of seaward land slip (Fig. 4), and the huge tsunami waves certainly eroded, at least in part, the shore (see Sect. 6.1). At Lazzàro, Platania (id 265) reported a possible evidence of ground lowering of about 1 m (Fig. 5).

Finally, it must be recalled the only case of ground uplift, apart those in southern Calabria measured by Loperfido (1909), which occurred near the beach of Giardini, just south of Taormina, as reported by Oddone (id 129): "We cannot speak of a general lowering of the beach, instead, it looks that at Giardini di Taormina, the coast has raised of some tens of centimeters." Noteworthy, this area rests on the footwall of the Taormina Fault, part of the Taormina–Messina Fault system.

5.1.2 Surface faulting

Some reports describe ground ruptures that are potentially evidence, even if dubious, of slip along capable faults (Appendix; Fig. 6). An example is the effect (Appendix, id 245) described by Sabatini (1909) at Pèllaro: "In the vineyards above the city hall, many ground fractures were still visible during my last visit on April 29, 1909. These fractures, for the most already closed …, could be followed for many meters, up to 10 cm wide. Originally, many of them were more than 50 cm wide and several meters deep. Most of them, but not all, were parallel to the coast. Somebody told me that they could be followed up to Motta San Giovanni and showed me, with surprise, that marine sand bordered the fracture rims". So, liquefaction took place, which actually could alone explain the large fractures observed. If, instead, tectonic fractures really took place and reached Motta San Giovanni, their end-to-end length would have reached about 5 km. Actually, a set of secondary Quaternary faults is known running from the area of Pèllaro to Motta San Giovanni (Fig. 6), but does not exist any sound supporting evidence of reactivation. The same conclusion can be drawn for the several other accounts along the Calabrian coast, e.g., at Villa San Giovanni, Sambatello, between Cannitello and Scilla (e.g., id 216, 236, 238, 239, 282, 283, and 284). At Reggio Calabria, many report fractures, also relevant, in particular in the marina area (id 169, 170, 175, 178–181), but the descriptions do not allow a reliable attribution to tectonics. Interestingly, Taramelli (1909) describes fractures, N70E striking, located in the area of case Laganà (id 190), at the base of the fault scarp related to the Reggio Calabria Quaternary fault.

In Messina, apart from the many ground ruptures in the wharf area and surroundings, including the northern beach (Appendix, id 84), fracturing evidence supporting fault reactivation is meager. The pervasive ground cracking, in many places also masked under the fallen buildings, had certainly several concurring causes, from liquefaction, differential compaction, sliding to, possibly, faulting, leaving poor chances to point out the latter mechanism. Instead, major and continuous coseismic fault slip away from the coastline, where less destruction occurred, would have been likely noted. Baratta (1910) only cites a few cracks and superficial slides (id 94) in the hills surrounding Messina. However, the *Gazzetta Ufficiale del Regno d'Italia* (id 95) reports that large fractures were seen in the mounts paralleling the coast south of Messina by the director of the Etnean Observatory.

Evidence possibly related to tectonics is the sinking of parts of the carriageway skirting the Lake Pantano before Ganzirri, associated with long fractures, liquefaction phenomena, and hydrogen sulfide emissions. The lake is actually bounded on the north side by a fault (GF in Fig. 6). The occurrence of ground cracks, ground sinking, water gushes, and gas emissions in the same area (id 107, 108, 109, 110, 111, and 113 in Appendix) is reported by Franchi (1909), Mercalli (1909), Oddone (1909), Ricciardi (1909), Sabatini (1909), Taramelli (1909), and Baratta (1910).

6 Secondary effects

6.1 Tsunami and coastline retreat

Run-up data (210) of the tsunami were gathered from several sources (Franchi 1909; Mercalli 1909; Novarese 1909; Omori 1909, 1913; Platania 1909a, b; Sabatini 1909; Baratta 1910). The maximum value of run-up along the Calabrian coast was 13 m, at Pèllaro (10 km south of Reggio Calabria), where the waves reached 600 m inland (Fig. 10), while along the Sicilian coast the maximum run-up value of 11.70 m was measured at Sant'Alessio (40 km southwest of Messina). The run-up was measured over 8 m in 23 points (Fig. 11), 7 along the Calabrian coast (at Reggio Calabria, Pèllaro, and Lazzàro) and 10 along the Sicilian coast, from ca. 10 km south of Messina (at Galati Marina) southward (Alì Terme, Nizza di Sicilia, Sant'Alessio, Giardini Naxos); such effects have been used for ESI estimations, as described in Sect. 7. A reported run-up of 10 m faraway at Calabernardo, south of Syracuse, is certainly unreliable and is disregarded.

The tsunami effects, which included also erosion phenomena along a large part of the Straits coast, superimposed onto the shaking and tectonic effects, masking or obliterating many of them. As a whole, there are 20 accounts of coastline retreat (Fig. 5), as a result of the cumulated effects of the earthquake and the tsunami waves. Of them, 13 occurred on the Calabrian and 7 on the Sicilian coasts (6 in Messina).

Fig. 10 Postcard (courtesy of A. Zagari) depicting the devastating effects of the tsunami in Pèllaro (photograph: E.B. Giarmoleo)
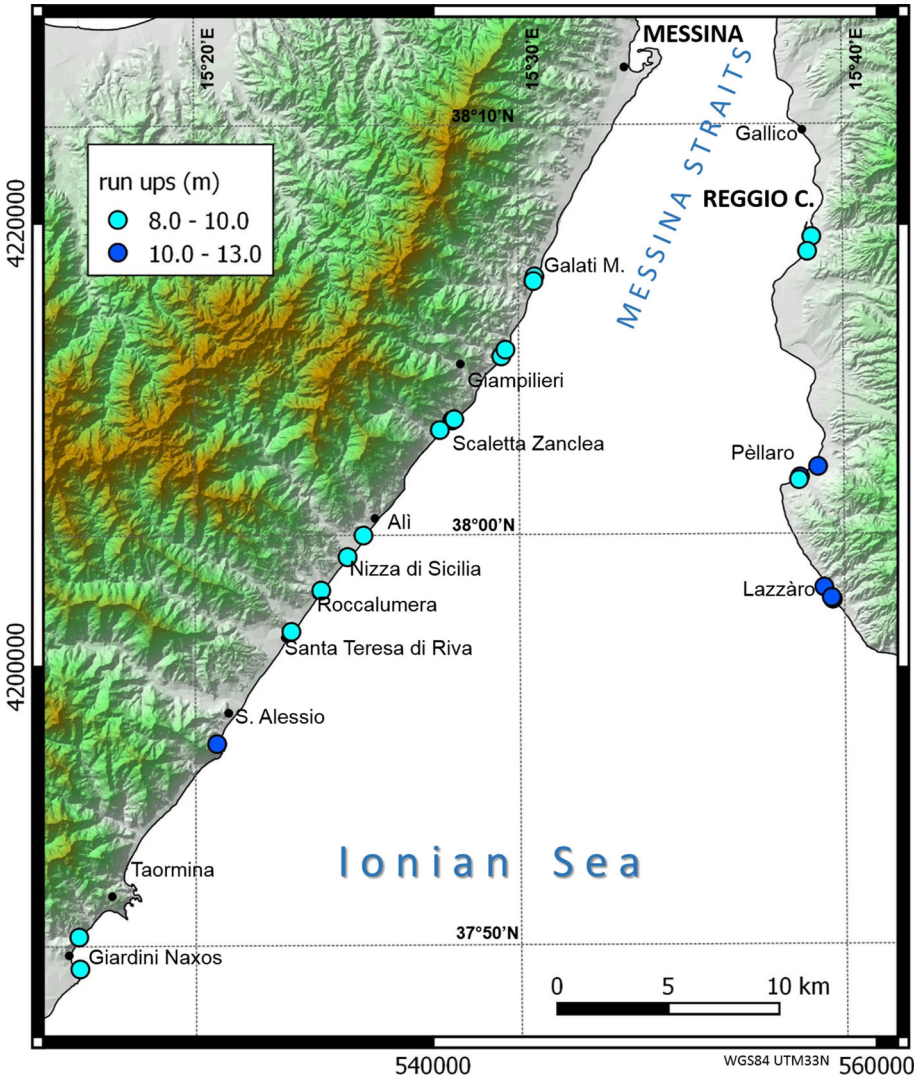
Fig. 11 Run-ups (only ≥8 m) reported for the tsunami that followed the 1908 earthquake

At Lazzàro, where the run-up reached 10 m, the coastline retreated up to 175 m (Fig. 12). Here, the landscape changed abruptly (see id 258, 262, and 263 in Appendix). In fact, Novarese (id 262) reports: "… a tsunami wave covered the village and while receding it swallowed its southern part. Here, not only disappeared a strip of beach, but also a part of the alluvial terrace, raised 6–7 m, sank in the sea, leaving a deep inlet north of the mouth of the Lazzàro torrent. The provincial road disappeared for a length of more than 600 m. And everywhere along the beach can be observed most clearly as the ground is collapsed into the sea over a strip of variable width that reaches its maximum exactly south of Lazzàro." Based on the subsidence evidence reported by Platania (id 265), it is possible to assume that a combination of earthquake shaking, subsidence, and tsunami waves affected the Lazzàro coast, determining its broad retreat.

Fig. 12 At Lazzàro, the coastline retreated up to 175 m as a result of the cumulated effects of subsidence, earthquake shaking, and tsunami waves. After Novarese (1909), modified

6.2 Slope movements

Slope movements (143) represent the most numerous class (39 % of the total) among the identified effects (see also Comerci et al. 2013b). Of them, 42 were reported in Sicily, 87 in Calabria, and 14 at sea (Figs. 3, 4). About the latter, depth soundings taken soon after the earthquake in the Straits area detected clear rise of the seafloor at 7 sites (Appendix, id 15, 16, 17, 158, 159, 164, 188), where underwater mass depositions of sediments likely took place. Moreover, also the interruptions (burial or cut) of communication cables laid on the seafloor between Milazzo and Lipari, Gazzi and Gallico, Malta, and Zante (id 155, 156, 161, 162, 163, 165, 166) are attributed to underwater landslides or turbidity currents (Ryan and Hezen 1965).

Inland, the landslides distributed on different lithologies and many of them were reactivations of preexisting slope movements. They are singled out here into two main categories, based on the stiffness of the involved lithology/ies: slope movement in rock (coherent and stiff lithology) and slope movement in soil (sand, clay, and loose material in general). The lithology was inferred from their most likely location in the Calabrian and Sicilian sheets of the Geological map of Italy at the scales 1:50,000 and 1:100,000 (http://www.isprambiente.gov.it/site/en-GB/Cartography/Geological_and_geothematic_maps/default.html). Figures 3 and 4 show the location of all the slope movements described by the contemporary surveyors: 62 were in rock and 67 in soil; the ones underwater likely involved mostly loose sediments.

Most of the descriptions do not allow a clear recognition of the type of slope movement. There are only a few well-documented cases, sometimes photographed by the contemporary authors. In many sites (precisely mapped by Baratta 1910 and illustrated in Società Fotografica Italiana 1909) between Bagnara and Favazzina, altered gneiss slid along the steep slopes, interrupting the railway line (Figs. 4, 13); along this cliff, the sliding was influenced by a clear topographic effect (Murphy 1995). Between Scilla and Cannitello,
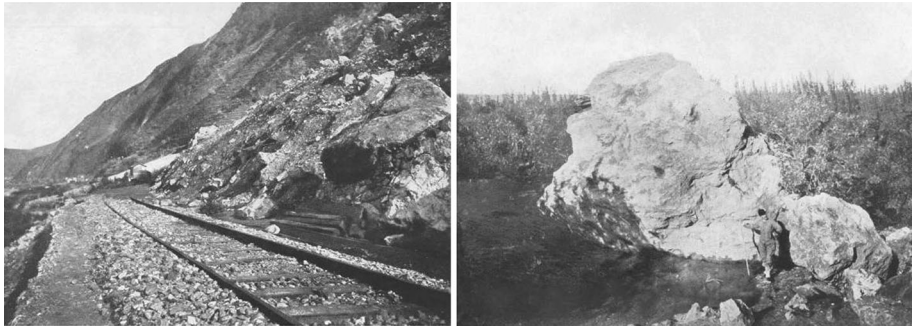
Fig. 13 Rockslides and rockfalls occurred along the railway line in Favazzina (Fig. 4), between Scilla and Bagnara Calabra (Società Fotografica Italiana 1909)

Mercalli took a picture of a considerable landslide, as well as of the rock avalanche that damaged the small village of Ortì Superiore, near Reggio Calabria (Fig. 14). A photograph taken from a different viewpoint of the landslide near Scilla was published by Sieberg (1923; Fig. 15). An earth slide fell on the mule track between Catdforio and S. Salvatore, east of Reggio Calabria (Fig. 16), killing three muleteers with their animals (Taramelli 1909).

Several accounts of slope movements are available for the Messina urban area (see also Comerci et al. 2013b; Puglisi et al. 2013). Actually, Messina is the town with the largest number of effects of every type (Fig. 8), followed by Reggio, unsurprisingly, being these by far the two largest settlements. In Messina, the wharf area before the Palazzata was severely damaged (Fig. 17) and a large part of it collapsed because of the combined action of the seismic shaking and the tsunami. The whole coastal area suffered widespread damage and environmental effects. The Holocene loose alluvial deposits forming the coastal area and also the Pleistocene terraces on which a substantial part of the town was built were affected by widespread slope movements and lateral expansion triggered by the shaking (see also Murphy 1995). Several reports (e.g., id 2, 20, 64, 71, 75, and 366) describe a generalized ground movement toward the sea. Therefore, many of the accounted effects in Messina can be interpreted as a consequence of slope movements involving large part of the Messina seacoast.

Tectonic subsidence, described in Sect. 5.1, may have played a role also in triggering these secondary effects, due to slip along the hypothesized Messina Lineament (Fig. 8) and also near Ganzirri (Lake Pantano Grande).

The total area affected by landslides, defined as that of the minimum polygon enclosing all the mapped landslide localities of Fig. 3, is ca. 20,000 km^2. If this value is plotted on the graph of Keefer (1984), which scales the area affected by landslides with earthquake magnitude (Fig. 18a), the resulting magnitude matches neatly the one estimated for the 1908 earthquake. Therefore, the area distribution of the collected accounts on landslides is in good agreement with the Keefer's database.

Moreover, also the distance (216 km) of the known most remote landslide (in south-western Sicily) results in good agreement with the plot of Keefer (1984) of maximum distance of landslides from epicenter versus magnitude (Fig. 18b). Being unknown the type of the farthest landslide, the resulting magnitude value is bracketed between 7 and 7.2, again consistent with the magnitude estimate of the 1908 earthquake.
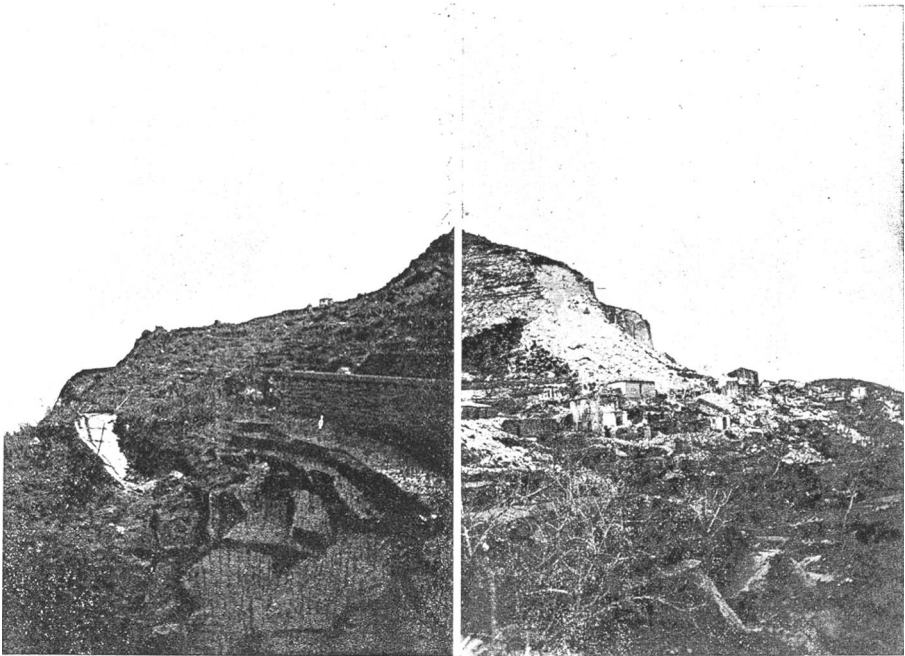
Fig. 14 *Left* A considerable landslide dislodged and disrupted the road between Scilla and Cannitello. *Right* The village of Ortì Superiore damaged by a rock avalanche. These photographs were taken by Mercalli in April 1909 (Mercalli 1909)
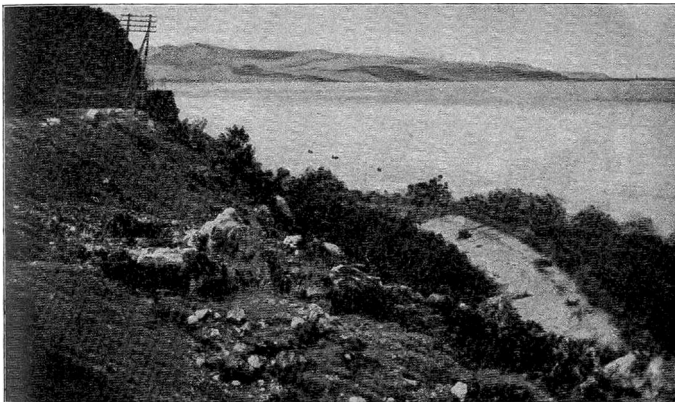

Fig. 15 Same landslide of Fig. 14 (*left*), occurred near Scilla, was photographed by F.A. Perret from a different view point (in Sieberg 1923)

The distribution of slope movements, as commonly observed (e.g., Keefer 1984; Rodríguez et al. 1999; Porfido et al. 2002), rarefies moving outward from the epicenter. The area significantly affected has a radius of ca. 40 km: 123 out of the 143 collected events (86 %) fall within this distance. This spatial distribution is coherent with a crustal
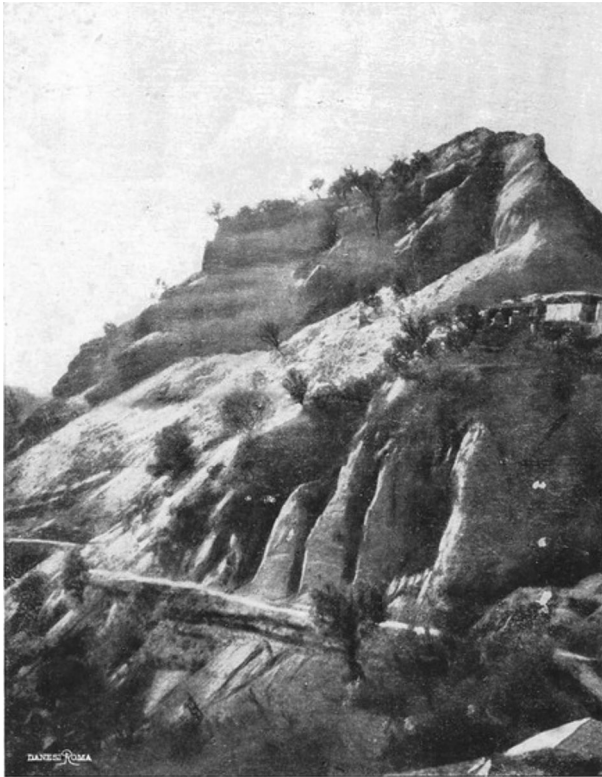
Fig. 16 An earth slide on the mule track between Cataforio and S. Salvatore (east of Reggio Calabria) killed three muleteers (Taramelli 1909)

seismic event such as the 1908 one should be; in fact, for deeper earthquakes, with focal depths ≥30 km, generally landslides propagate over much larger areas (Keefer 1984).

6.3 Ground ruptures and liquefaction

6.3.1 Ground cracks

The contemporary witnesses have cited many cases of fracturing, often not better described. In general, understanding now their true origin and significance is very difficult, if not impossible. In this work, whenever available, we have followed the interpretation of the first describers, classifying fractures either in the *Slope Movement* category, sometimes likely evidence of lateral spread, or interpreting them as features accompanying *Liquefaction*. The *Ground Crack* category (Figs. 3, 4) includes fractures (59 cases) of most likely secondary origin, i.e., consequence of the shaking, but without an established causing mechanism. Even if, as already stated, a plain evidence of surface faulting is always absent, some fractures could have been somehow related to a tectonic deformation. Anyhow, most of the effects classified as *Ground Crack* were actually also related to slope movements, lateral spread, or to a lesser extent, caused by differential compaction or deformation of artificial structures.

Fig. 17 Messina waterfront before the "Palazzata" was damaged by the combined action of the earthquake and the tsunami. Seismic shaking, liquefaction, and lateral expansion presumably induced the failure of the bearing structure of the wharf (photograph: L. Comerio 1908)
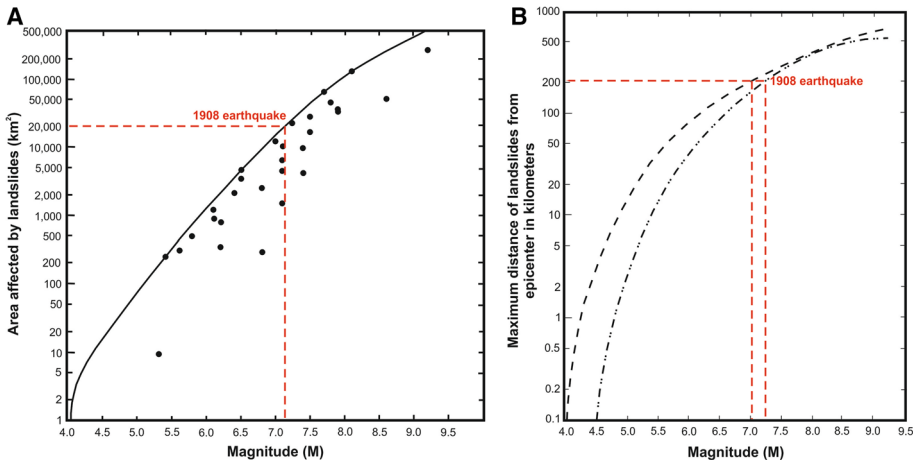
Fig. 18 A Areas affected by landslides versus earthquake magnitude (graph after Keefer 1984; *black dots* refer to Keefer's database), with the plot of the 1908 affected area (in *red*), showing a good fit with the actual estimated magnitude. **B** Maximum distance from epicenter of landslides versus earthquake magnitude (after Keefer 1984), with the plot of the 1908 most remote landslide. *Dashed line* is the upper boundary for disrupted falls and slides, and *dash-double-dot line* is the upper boundary for coherent slides

Fig. 19 Ground cracks at marina of Reggio Calabria (Società Fotografica Italiana 1909)

Most ground cracks were seen in Calabria (35), especially in the epicentral zone, along the Straits. Figures 19 and 20 report photographic evidence of ground fractures occurred along the *Marina* (seaside) of Reggio Calabria. The maximum distance of these features from the macroseismic epicenter exceeded 60 km (Figs. 3, 4), and one case was even reported in the middle of Sicily, more than 150 km away (Fig. 3).

6.3.2 Ground settlement

A fair number of accounts (37) has been classified as *Ground Settlement* (Figs. 3, 4, 8, 9, and Appendix), mostly related to localized phenomena of ground disruption and subsidence likely caused by liquefaction, slides, lateral spread, and differential compaction. Often, these ground settlement effects were associated with differential lowering and tilting of buildings and other artificial structures. Also, this class includes EEEs where the true mechanism behind them cannot be ascertained now. Most of them (26) were seen in Messina, 2 near Lake Pantano, 8 in Reggio Calabria and Villa San Giovanni, and 1 at Pèllaro (Fig. 4). As a whole, they occurred within 15 km from the macroseismic epicenter.

6.3.3 Liquefaction

Figure 5 reports the location of the observed liquefaction phenomena. Cases classified in *Ground settlement, Ground Cracks,* or even *Ground Lowering* could be actually related to liquefaction, but the related descriptions gave not enough positive evidence.

The cases reasonably interpreted as liquefactions (11) describe ejections of water, mud, and sand, generally along fractures. They are mostly located along the coastal areas, equally distributed between Sicily and Calabria, with a maximum distance from the macroseismic epicenter not exceeding 19 km. The tsunami's transient pressure changes during run-up and drawdown may have contributed to the occurrence of such phenomena along the Straits (e.g., Young et al. 2009).

Liquefactions (mud and hot water venting along cracks, with hydrogen sulfide) occurred at the northern tip of the eastern Sicilian coast, in an area of lagoons (Ganzirri or Pantano),

Fig. 20 Ground crack along Marina Street, Reggio Calabria (Baratta 1910)

where liquefaction was documented also during the great 1783 Calabria earthquake (Galli 2000), whose second major shock (February 6) took place along the Scilla Fault (Figs. 1, 6). Mercalli (id 108) reports: "… 4 to 5 h after the earthquake, in Ganzirri, in marshy land near the lake of the same name, were seen coming out of the ground with force masses of hot water with mud and pumice."

In Messina, cracks spewing water and sand are testified at the Citadel (where the water was reportedly hot and mixed with hydrogen sulfide) and along the Corso Garibaldi. The reports of *bollente* (literally "boiling") water might be questionable, possibly meaning "bubbling" instead, because of gas mixed in the water/mud mixture. However, at the railway station of Reggio Calabria, reportedly (id 171 in Appendix) "many injured persons were horribly scalded by the flowing stream" of boiling water, and south of Reggio Calabria, at Lazzàro, "a scaring column of boiling water, mixed with sand and large stones, killed a large part of the inhabitants looking for escape in the midst of the rubble" (id 261), while "In the surrounding plain between San Gregorio and Pèllaro some large hollows in the soil opened, from which they were seen coming out columns of smoke and of boiling water" (id 349). The truth of these accounts cannot be verified now; certainly, the underground water should have appeared lukewarm compared to the winter outside temperature, but not hot. It is more credible to suppose that gushes of warm water occurred similar to those observed for example during the Emilia Romagna earthquake of 2012 (Di Manna et al. 2012).

6.4 Hydrological anomalies

Only 18 accounts of *Hydrological Anomalies*, i.e., appearance or disappearance of springs, change in spring discharge and/or water temperature, turbid waters have been reported (Figs. 3, 5). Most of them are changes in spring discharge, followed by evident rises of water temperature. Such effects were recorded, in Sicily, up to a distance of 175 km from the macroseismic epicenter (change in springs discharge, increase in water temperature, and disappearance of springs; id 136, 137, 138), while in Calabria up to 117 km (disappearance of a hot spring; id 319). In Sicily are worth noting the increase in water temperature in the Lake Pantano (Ganzirri), where supposedly the waters warmed, killing the

oysters of the nursery (id 107), and the changes in the thermal springs of Termini Imerese (the ancient *Thermae Himaerae*), 175 km away from the epicenter. Here, a new hot spring (43 °C) had already appeared after a seismic event in 1906, with epicenter in Termini Imerese (intensity MCS VII) and disappeared after nine months. The same spring resurfaced after the 1908 event (id 136) and in three months dried up. A slightly rise in water table and temperature was also noted in brackish water wells nearby (id 137). A drinking water spring feeding the Termini aqueduct reduced its discharge and eventually dried (id 138). Southwest of Catania, another warm water spring, named *Fiume Caldo* (warm river), momentarily dried (id 139). In Calabria, at Maida Marina (near the Tyrrhenian coast, west of Catanzaro), already before the main shock, the springs dried and the water of the Angitola river "arose" (id 312). At Anoia Superiore, near the Cittanova Fault, a spring that had appeared after the 1905 earthquake and disappeared after one year reappeared on December 28, 1908, with an abundant flow (id 271).

6.5 Other effects

Other environmental effects recorded in the Appendix are gas emissions, sinkholes, earthquake lights, and acoustic effects (Figs. 3, 5).

6.5.1 Gas emissions

Of the 12 accounts of gas emissions, 7 are located in Messina (where the quality of the available information is the most accurate; id 18, 39, 42, 43, 53, 78, and 79), 1 near Lake Pantano (id 112), and 1 at Reggio Calabria (id 196), all reporting strong smell of hydrogen sulfide. In the Citadel of Messina were also observed flames, coming out from fractures (id 39), as well as at Santa Maria la Scala (90 km southwest of Messina; id 143). Other two accounts, reporting gas emissions in Palmi and San Procopio (id 302 and 309), are more doubtful; a survey conducted on the end of January 1909 (Riccò 1909a) at Palmi indeed confuted the hypothesis of hydrogen sulfide emissions.

6.5.2 Sinkholes

Only one case can be interpreted as a sinkhole (id. 314), located in Calabria far from the epicentral area (Fig. 3), near Spilinga, in the countryside of Vibo Valentia (called at that time Monteleone). Its distance from the macroseismic epicenter is nearly 60 km. After a century, despite the detailed description available, this sinkhole could not be found in the field; likely, it was filled soon after and did not remain active afterward. The outcropping rock is represented by altered Miocene calcareous sandstones.

6.5.3 Earthquake lights

Earthquake lights (EQL) are electromagnetic effects commonly observed during earthquakes, firstly classified by Montandon (1948). Almost all the reported cases of earthquake lights (26) were observed in localities facing the Straits (Fig. 3, 5), i.e., within the epicentral area (Ricciardi 1909; Baratta 1910; Galli 1910; Rezzadore 1914; Attanasio 1988). Many reported a *flare, flash, or lightning in the sky, sometimes reddish in colour and lasting a few seconds*, others instead something resembling an *aurora borealis,* others a *column of reddish fire. A strange light* was seen (id 160) above Sicily from Valletta

(Malta). There is also a report of *glittering points* in the sky, *perfectly alike falling stars* (id 167). Moreover, a *circle of fire* in the air was seen from near Bagnara (id 203) on the Calabrian coast. Occhiuto (1909b) tells of two testimonies, one describing *a cloud of fire in the middle of the sky*, the other one *a rain of fire from the opened sky* (id 362). Sabatini (1909) tells of *luminous electrical phenomena* preceding the shaking (id 352 and 354).

Light emissions are often reported associated with major-to-moderate seismic events (e.g., Theriault et al. 2014; references therein). Galli (1910) has made the first modern catalogue and classification of such phenomena, covering a period from 89 BC to 1910, including therefore also the 1908 effects. Fidani (2010) has made a detailed collection of possible EQL witnessed in the months preceding and following the 2009 L'Aquila earthquake (Vittori et al. 2011). The latter catalogue includes all known types of EQL: they distributed over a period of many months either before or after the earthquake, without a clear prevalence during the main shocks of the seismic sequence.

The causes of EQL are debated and can be manifold (e.g., Thériault et al. 2014). Whatever the trigger mechanism, anomalous air ionization could be the cause of most lightning phenomena. More localized luminosities may be caused by triboluminescence effects (due to rock friction along coseismic faults, or even major rock falls) or burning gas (methane) escaping from the ground along coseismic fractures and ignited by rock friction sparks. About timing of the EQL seen in 1908, no evidence of clearly precursory effects was reported. The anticipated arrival of light with respect to shaking (e.g., id 130) and rumble locally perceived can be easily explained being the speed of light considerably higher than any seismic or sound wave.

6.5.4 Acoustic effects

The causes of acoustic effects are several. Noise is produced by ground cracking and slipping along faults, falling of rocks, rattling, hitting, and collapse of buildings; furthermore, perceptible sound waves can be generated when the ground vibration during the passage of seismic waves is transferred to the air. The 18 collected acoustic effects (rumbles) are mostly distributed in Southern Calabria, several beyond (east of) the Aspromonte mountain chain (Figs. 3, 5). Most reports describe a kind of strong, dull roar, or also "the bursting of a thousand bombs," contemporaneous with the main shock. Prof. Oddone (in Ricciardi 1909) felt something similar to underground enormous explosions accompanying the main shock and also the aftershocks (id 99).

7 ESI 2007 intensity assessment

The EEEs of the 1908 earthquake have been used for assessing epicentral and local intensities through the ESI 2007 scale (Michetti et al. 2007; http://www.isprambiente.gov.it/en/projects/inqua-scale/environmental-seismic-intensity-scale-esi-2007). The ESI scale provides intensity values comparable to those of the MM and MSK scales, making use solely of EEEs, including also tsunami effects. It can permit to size an earthquake also where the human settlements are rare or absent or the other scales saturate, as it commonly occurs at the highest degrees.

ESI epicentral intensity can be estimated based on the total area affected by secondary effects, which is about 24,000 km^2, once excluded the not diagnostic effects (e.g., EQL and acoustic effects). This value decreases to about 20,000 km^2, if considering only the distribution of coseismic slope movements. In any case, such total area indicates an ESI

epicentral intensity equal to XI, in agreement with the I_0 MCS estimate (Locati et al. 2011; Guidoboni and Mariotti 2008). Since no clear pattern of surface faulting is known (see Sects. 5.1.2, 8), its typical parameters (surface rupture length, maximum displacement) are not applicable. Anyhow, an intensity XI scenario would imply that largest primary effects, including surface faulting, have occurred into the Messina Straits, with subsidence values possibly even higher than those measured along the coastlines by Loperfido (1909).

Local ESI values have been assessed for 66 localities (see Table 1; Fig. 21), where the characteristics of collected EEEs have been considered sufficiently diagnostic. Thus, each local intensity value is the result of an assessment that takes into account the characteristics and areal distribution of all EEEs referred to that locality (reported in Appendix), including also information about tectonic lowering/uplift by Loperfido (1909), where available. Moreover, the local ESI was attributed to 8 localities, described in Sect. 6.1, where the tsunami run-up was over 8 m (Figs. 11, 21, 22).

The maximum local ESI value, equal to XI, was recorded only at Lazzàro, due to the outstanding tsunami effects, together with several impressive ground effects (slope movements, ground subsidence, ground cracks, liquefactions, and hydrological anomalies).

Local ESIs equal to X have been estimated in 16 localities in Sicily as well as in Calabria, including Messina, Reggio Calabria, and Villa San Giovanni (Figs. 21, 22). These estimates are mostly based on local evidence of primary effects (tectonic lowering shown by levelling data of Loperfido 1909) and tsunami run-up (Fig. 11). Most of them fall along the Sicilian coast south of Messina, largely extending the area of intensity X ESI.

Other 13 localities, mostly in Calabria, recorded ESI values equal to IX, resulting from the characteristics and frequency of slope movements and other secondary effects. Furthermore, in the far field of the affected area, it was possible to assess local intensity values equal to VIII for 8 localities, to VII for 23 localities, and to VI for 13 localities.

The last column of Table 1 gives the corresponding MCS local intensities, based on the damage to inhabited centers (Guidoboni and Mariotti 2008). By comparison, local ESI and MCS local intensity values are fairly consistent as a whole (Fig. 23), with some divergences that point out the added value provided by the use of both ESI and MCS scales. In order to better point out the resulted mismatches, Fig. 24a plots the MCS and local ESI degrees versus distance from the epicenter, while Fig. 24B plots the differences between ESI and MCS versus distance from the epicenter. For distances up to ca. 120 km, the local ESI estimates are often lower than the corresponding MCS values. Further away, this never happens (Fig. 24b). The most common difference is 1°; only in 5 cases, the mismatch is ±3°. Actually, outstanding geological effects worth being remembered by non-specialists were rare away from the epicentral–mesoseismal area, unless where situations of highly unstable equilibrium already existed (e.g., the hydrological anomaly in Termini Imerese, near Palermo and the landslide in Naro, near Agrigento; respectively id 136, 137, 138, and 145 in Appendix), while damage to buildings and effects to humans were still diagnostic for MCS intensity evaluation. Lastly, the ESI estimates of X based on tsunami run-ups of at least 8 m (Figs. 11, 21, 22), especially along the Sicilian coast south of Messina, are up to 3° above those from other EEEs and the MCS ones, which are between VII and IX (see Table 1).

8 Discussion and conclusions

Misinterpretations and location uncertainties are unavoidable shortcomings of all historical investigations, even if focused on an event only one century old. In fact, the available

Table 1 Local ESI values for 66 localities in Calabria and Sicily where diagnostic descriptions are available (the ID effect column reports the id of the descriptions in Appendix)

Locality	ID effect	Leveling	Local intensity	
			ESI	MCS
Lazzaro	258, 259, 260, 261, 262, 263, 264, 265	YES	XI	X
Villla San Giovanni	216, 217, 218, 219, 220, 221, 222, 224	YES	X	X–XI
Reggio Calabria (harbor)	182, 183, 187, 188, 189	YES	X	X
Reggio Calabria	168, 169, 170, 171, 172, 173, 174, 175, 179, 180, 181, 184, 185, 186, 191,192, 193, 194, 195, 198	YES	X	X
Pellaro	240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 313, 348, 349, 350	YES	X	X
Faro	106, 114, 115, 116, 117	NO	X	XI
Ganzirri	106, 107, 108, 109, 110, 111, 112, 113	NO	X	IX
Messina harbor	4, 5, 9, 12, 14, 15, 17, 19, 37, 38, 40, 41, 42, 44, 45, 46, 47, 48, 49, 50, 51, 52, 54, 55, 56, 57, 58, 60	YES	X	XI
Messina Historical center	2, 3, 6, 7, 8, 10, 11, 13, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 59, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 85, 86, 89, 90, 91, 92, 93, 94, 95	YES	X	XI
Giardini Naxos	129	NO	X	VIII
Sant'Alessio		NO	X	
S. Teresa di Riva		NO	X	VII
Roccalumera		NO	X	VIII
Nizza di Sicilia—Ali'		NO	X	VIII
Scaletta Zanclea		NO	X	VIII
San Paolo		NO	X	IX
Galati Marina		NO	X	IX
Bagnara	200, 201, 202, 204, 208, 289	YES	IX	IX
Road Bagnara—Favazzina	286, 287, 290, 291, 292, 293, 294, 295, 296, 297	YES	IX	IX–X
Favazzina	285, 288, 298, 299, 301	YES	IX	X
Scilla	273, 274, 275, 276, 277, 278, 279, 280, 281, 284	YES	IX	IX
Calanna	233, 234, 235	NO	IX	X
Cannitello	238, 283	NO	IX	XI
Sambatello	232, 233, 234, 236, 237	NO	IX	X
Gallico	227, 229, 230, 231, 232	YES	IX	XI

Table 1 continued

Locality	ID effect	Leveling	Local intensity	
			ESI	MCS
Orti	209, 210, 211, 215	NO	IX	XI
Mosorrofa	268	NO	IX	XI
Cataforio	266, 267	NO	IX	XI
Messina hills	87, 94, 95, 97	NO	IX	X
Archi	227, 228	YES	IX	XI
Cerasi	328, 329	NO	IX	X–XI
Sinopoli	361	NO	VIII	VIII–IX
San Procopio	308, 309, 310	NO	VIII	X
San Roberto	311	NO	VIII	XI
Pavigliana	269, 270	NO	VIII	XI
Raddusa	133, 134	NO	VIII	VII
Santa Maria la scala	143	NO	VIII	VII
Road Reggio-Terreti	212, 213, 214	NO	VIII	X
Mileto	315, 316, 317	NO	VII	VIII
Between Mileto and Rosarno	318	NO	VII	VII–VIII
Terranova	347	NO	VII	VII–VIII
Palmi	302, 303	YES	VII	IX
Between Palmi and Bagnara	300, 301	YES	VII	VIII–IX
Pentedattilo	272	NO	VII	VIII
Rumboli	206, 207	YES	VII	VIII
Roccaforte del Greco	331, 332	NO	VII	IX
Casalnuovo d'Africo	325, 326	NO	VII	VIII
Staiti	345, 346	NO	VII	VII
Brancaleone Superiore	323	NO	VII	VII–VIII
Bruzzano	320, 321	NO	VII	VIII
Ferruzzano	322	NO	VII	VIII
Scaletta Superiore	131	NO	VII	VII
Ali' Superiore	154	NO	VII	VII–VIII
Pagliara	151	NO	VII	VII
Palermo Messina railway	124	NO	VII	
Mineo	139, 140	NO	VII	VII
Pietraperzia	146, 147	NO	VII	VI
Caltanissetta	148	NO	VII	VII
Sommatino	150	NO	VII	VI–VII
Ravanusa	132	NO	VII	VI–VII
Termini Imerese	136, 137, 138	NO	VII	IV
Anoja Superiore	271	NO	VI	VII–VIII
Mammola	339	NO	VI	VII
San Giovanni di Gerace	342	NO	VI	VII
Plati'	340	NO	VI	IX
Sant'Ilario dello Ionio	343	NO	VI	VIII
Sant'Agata	338	NO	VI	X–XI

Table 1 continued

Locality	ID effect	Leveling	Local intensity	
			ESI	MCS
Casignana	334, 335	NO	VI	VIII
Pardesca	336	NO	VI	VIII
Maida Marina	312	NO	VI	VII
Girifalco	307	NO	VI	VII–VIII
Tricase	319	NO	VI	VII
Naro	145	NO	VI	IV
Cattolica Eraclea	149	NO	VI	VI

For some localities, the assessment has taken into account also the tectonic lowering/uplift provided by leveling (Loperfido 1909). Moreover, the local ESI X was attributed to 8 localities (reported in italics) where the tsunami run-up was at least 8 m (Fig. 11). The last column reports the corresponding MCS local intensity values from Guidoboni and Mariotti (2008)
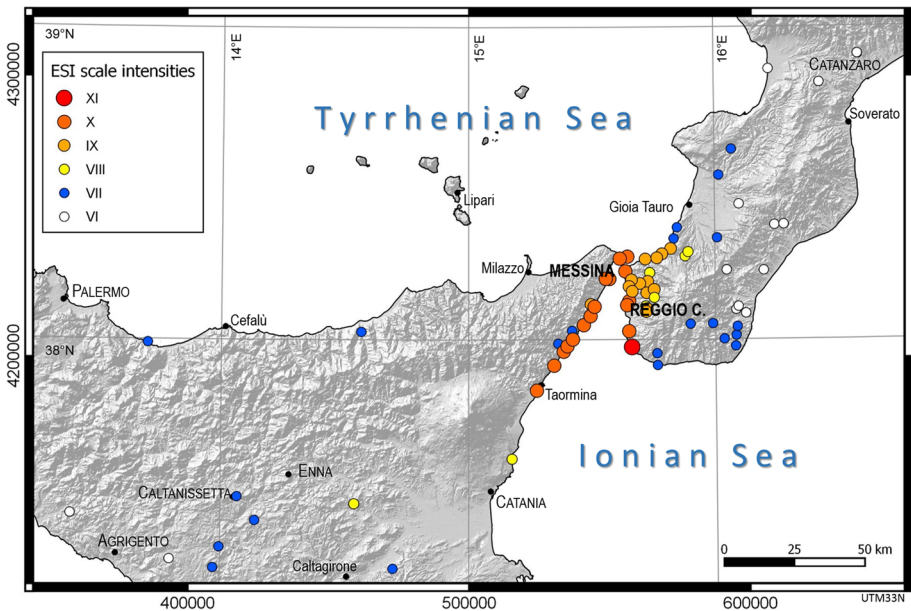
Fig. 21 Local ESI map. Local ESI values have been estimated for 74 localities in Sicily and Calabria (see Table 1)

descriptions are frequently generic and only rarely provide a scientific explanation of the phenomenon. Moreover, many effects had a complex genesis, deriving from the combined action of earthquake and tsunami waves. Despite all this, cross-references and experience gained in the field during recent earthquakes have helped interpret the testimonies in order to classify the reported effects of the 1908 earthquake under the most likely cause.

Despite such limitations, the gained information remains of extreme value to interpret this event and outline the range and size of geological hazards to be expected from similar future events in the Straits area.
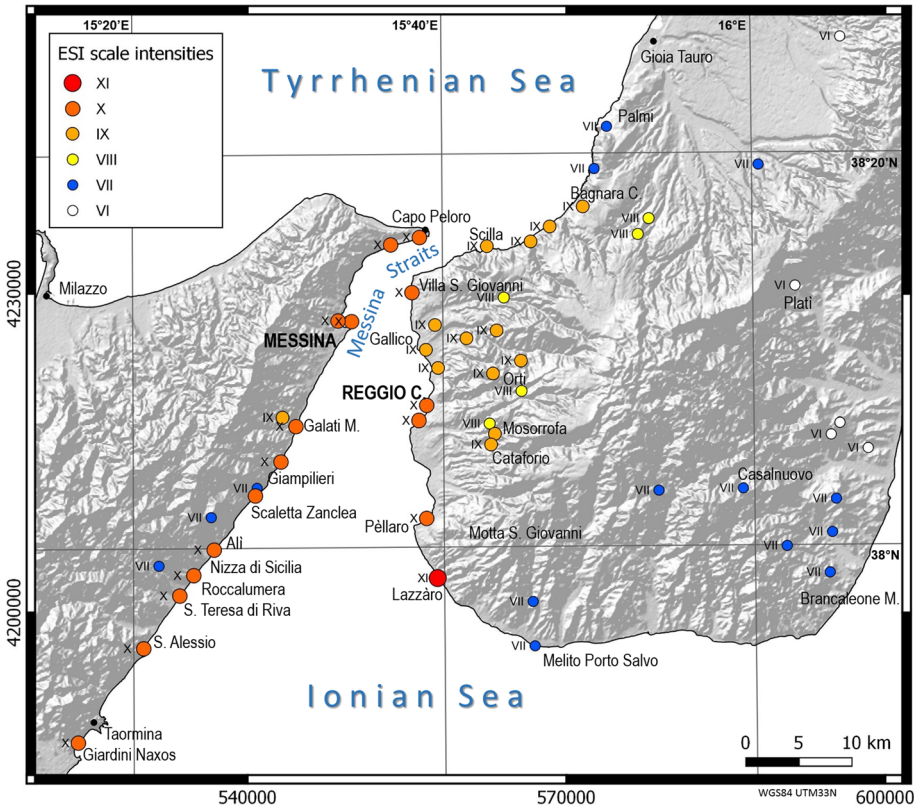
Fig. 22 Local ESIs: close-up of the Straits area. Along the Sicilian coast south of Messina and at Pèllaro and Reggio Calabria, ESIs X correspond to localities where the tsunami run-up was at least 8 m (see Fig. 11)

Evaluating the collected accounts as a whole, it readily stands out that the coseismic environmental effects are less than those observed for earthquakes of similar magnitude in that region, i.e., 1783 Calabrian and 1693 eastern Sicily earthquakes. The relatively small number of data and their spatial inhomogeneity can be at least in part explained by the location of the epicentral area, placed largely underwater in the Straits. Moreover, the region was certainly not surveyed with the same attention everywhere (as likely happened also after the two older events).

Actually, the strongly uneven distribution of effects (Fig. 3) suggests a substantial lack of information for more remote areas. Clearly, the attention of the contemporary reporters was more focused on the localities where the human emergencies were highest (the largest settlements in the epicentral areas) and on the most accessible areas, generally those along the coast. So, the knowledge of many coseismic geologic effects went certainly lost possibly including the evidence of fault rupture.

Indeed, crustal events of magnitude 7 are expected to be associated with surface faulting, commonly tens of kilometers long and with offsets ranging from several tens of centimeters up to a few meters (e.g., Wells and Coppersmith 1994), but any unequivocal description of such ground displacement is missing for the 1908 earthquake (Caciagli
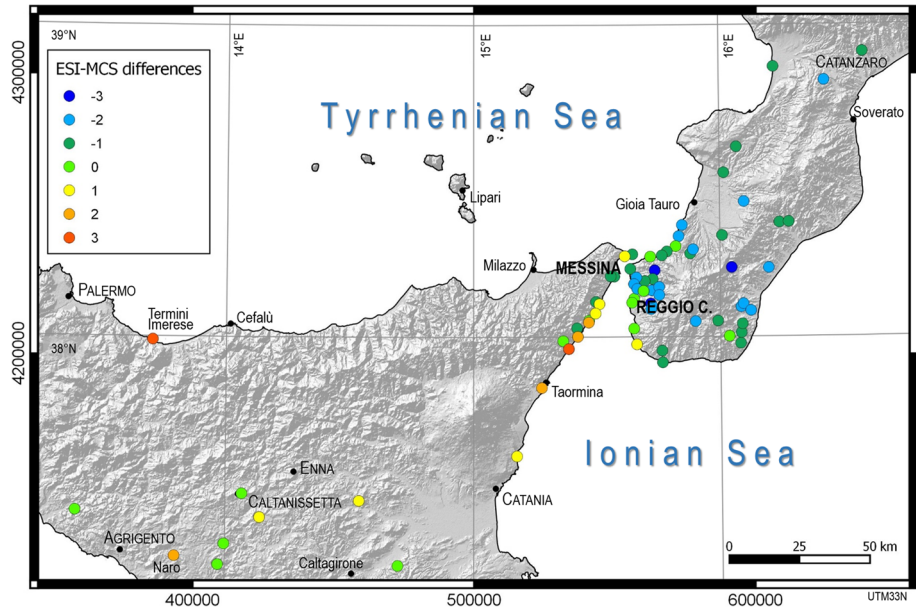
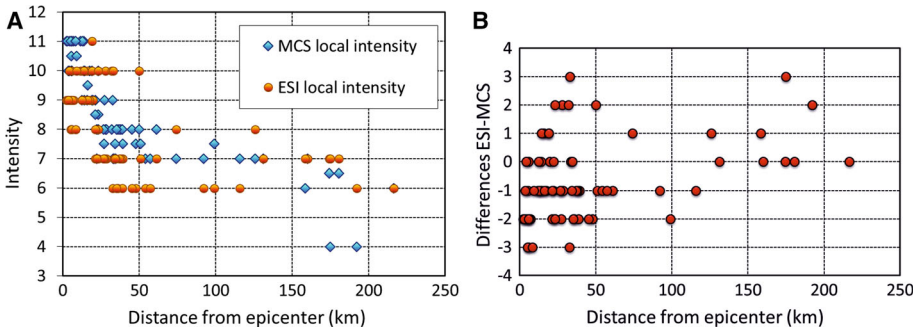**Fig. 23** ESI–MCS intensity difference for 72 localities in Sicily and Calabria

Fig. 24 Plots of ESI and MCS local intensity degrees (**A**) and ESI–MCS differences (**B**) versus distance of common measurement locality from macroseismic epicenter

2008; Comerci et al. 2008a, b). Despite several effects, e.g., ground cracks and ground lowering, were close to mapped tectonic structures and possibly suggestive of reactivation, for example along the Armo and Reggio Calabria faults near Reggio (Figs. 4, 5, 6), none of them can be unequivocally attributed to surface faulting and, in particular, to the seismogenic fault. Moreover, the frequent overlap of several factors (e.g., shaking, tsunami, and local instabilities) makes it difficult now to determine the root cause of many effects. Alternatively, surface faulting associated with the seismogenic rupture could have occurred underwater in the Straits, likely contributing to the devastating tsunami effects (e.g., Gerardi et al. 2008, and references therein), but no direct prove of it does exist as well.

Knowledge on surface faulting of engineers and geologists, especially in Europe, was still immature at that time, just beginning to realize then that sudden displacement along a

fault produces earthquakes (Yeats et al. 1997). The question whether earthquakes produce faults or faults cause earthquakes was definitely answered only after the 1906 San Francisco earthquake (Bryant 2013) and was generally assimilated in Italy much later (at the time of the 1908 earthquake, many scientists still believed to the volcanic origin of earthquakes or even to underground gas explosions!).

Nevertheless, some surveyors used the term "fault" to describe the observed effects: Taramelli (id 20 and 189) ascribes to "underground faults" the damage in the Messina and Reggio Calabria harbors, while Oddone (id 367) reports the presence almost everywhere along the Straits coast of "threatening faults" and throws up to 80 cm, without, unfortunately, more precise localization.

In principle, a verification of the tectonic nature of some displacement effects might be possible today by means of paleoseismological studies, but suitable trench sites have not been identified yet. Slip along secondary capable faults triggered by the still elusive main seismogenic fault was very probable, being typically observed for moderate-to-strong earthquakes. For example, the coastline retreat occurred in many places of the Straits could have been a combination of the secondary reactivation of tectonic lineaments and seaward slip/lateral expansion, triggered by the shaking, of unconsolidated recent sediments. Regarding the Reggio Calabria coast, Baratta (1910) reports "The coastline close to Reggio has been unquestionably lowered: violent tidal-seismic phenomena occurred on December 28 have accelerated the slow lowering process affecting the beach, as highlighted by Carbone-Grio, Cortese and Di Stefano's observations." According to these accounts, "the buildings on the beach are gradually drowning and the beach line tends to retreat more or less intensively" (id 370).

The levelling data of Loperfido (1909) are certainly a noteworthy instrument to depict the regional tectonic deformation induced by the earthquake, even if the reliability of some benchmark measurements might be questionable. Unluckily, the Sicilian coast was not covered by a former grid of benchmarks similar to the Calabrian one, strongly limiting the modelling possibilities. In fact, as pointed out by Aloisi et al. 2013, there is not a single best solution for the modelling of the geodetic deformation pattern. In contrast to other solutions (e.g., Capuano et al. 1988; Boschi et al. 1989; De Natale and Pingue 1991; Amoruso et al. 2002; Valensise et al. 2008), they suggest a steep normal fault-dipping northwest, corresponding at least partially with the Armo fault, as the best possibility, also based on the geological evidence of recent activity along this fault trend. However, a west-dipping fault is ruled out by Cannelli et al. 2013, based on the modelling of the post-seismic deformation shown by the tide gauge in the Messina harbor from 1896 until 1923. The latter authors would admit only east-dipping faults, despite being unable to choose one among the several proposed modelled faults. Finally, in two recent papers, De Natale and Pino (2014), based on seismological and geodetic data, and Convertito and Pino (2014), based on the intensity data, propose that a low-angle, east-dipping fault is the most likely source of the earthquake.

In our perspective, a fault slip in Messina is possibly suggested by the general, quite homogeneous, subsidence of its coastal area, east of the well-evident morphological step bounded by the Messina Lineament (Fig. 8). The homogeneity of the elevation drop reported by many different sources is locally altered by significant secondary phenomena of compaction/liquefaction of the Holocene deposits (Bottari et al. 2010). According to Franchi (1909), cemented conglomerate (possibly *panchina* cemented beach sand deposits) makes part of the southern edge of the "sickle," in particular under the Don Blasco Bastion (Fig. 25; for location, see Fig. 8). Loose sediments prone to liquefaction dominate the inner part of the harbor under the Citadel and the Saintest Saviour fortress (Fig. 8), according to Bottari et al. 2010.

Fig. 25 Don Blasco Bastion resting on *panchina* type deposits uncovered by the tsunami waves (Franchi 1909). See Fig. 8 for location

The suggested normal displacement along the hypothetical east-dipping NNE-striking Messina Lineament would not necessarily imply that this is the seismogenic structure responsible of the earthquake. However, such a reactivation, as well as the larger diffusion of geological effects and damage on the Calabrian side (with the exclusion of the Messina coast side), would be more suggestive of an east-dipping seismogenic structure (see discussion in Pino et al. 2009). The Reggio Calabria and Armo primary faults, which belong to the same fault system that caused the February 5, 1783, Intensity XI MCS, Calabrian earthquake (Galli and Bosi 2002), may have experienced some triggered movement too, suggested by land subsidence and alignments of cracks, but no undisputable proof of it was found in the analyzed documents.

An epicentral intensity XI characterizes the 1908 event, applying both the MCS (Guidoboni and Mariotti 2008; Locati et al. 2011) and the ESI (Michetti et al. 2007) scales.

According to the distribution of ESIs X and XI (Fig. 22), the 1908 epicenter and seismogenic structure should be located in the Messina Straits, likely trending between N–S and NNE–SSW. Despite a large portion of the mesoseismal area falls at sea, the areal distribution of the 1908 triggered landslide scales well (see also Esposito et al. 2013) with the areal distribution of landslides seen in other seismic events along the Apennines (e.g., 1980, 1997, and 2009) and can be used as a diagnostic tool for ESI assessment.

The MCS local intensities (Guidoboni and Mariotti 2008; Locati et al. 2011) are often larger than the corresponding ESI values, especially in the near-field area, on the intensity interval IX–XI (Fig. 24). This occurs largely because the ESI scale is tuned on the MM and MSK scales, which generally provide smaller intensity assessments than the MCS, one degree up to intensity IX MCS and even 2° from intensity X to XII MCS (e.g., Reiter 1991). Moreover, the earthquake severity portrayed by the MCS intensities in the highest degrees might be influenced by the modest quality of buildings and the weakness introduced by the recent earthquakes of 1894, 1905, and 1907 (e.g., Blaserna 1909; Mercalli 1909; Baratta 1910). An example of the consequences of bad-quality construction and restoration was the killing of hundreds of soldiers under the collapse of the nearly 20-year-old Mezzacapo barracks of Reggio Calabria, which were built with fluvial pebbles and

almost without cement (Mercalli 1909). Furthermore, already Blaserna (1909) stressed that the largest damage in Messina and Reggio Calabria affected masonry buildings two or more story high and that the building standards were often disregarded after the 1860 (annexation of the Reign of the Two Sicilies to the new born Italian State), following the disconcerting statement *"Libera costruzione in libero paese"* (free constructions in free country).

Therefore, the ESI assessment in the near field might be more reliable as an estimator of the earthquake size, as it is independent from damage to buildings, being only based on the effects on natural environment.

A particular case is that of the large negative differences in MCS, up to 3°, with the ESI estimates based on tsunami run-ups. Likely, the devastating effects of the tsunami waves have been purposely excluded from the MCS assessment.

Away from the epicentral–mesoseismal area, in historical accounts, EEEs are reported only where outstanding effects took place, whereas macroseismic effects are widely reported and still highly diagnostic for intensity assessment. Thus, the merge of the macroseismic and ESI datasets would provide the most complete picture of the whole event. In a conservative perspective, when the estimates differ in a locality, seismic hazard assessment should consider the maximum value between them.

Although it has been outside the scope of this paper to discuss the seismic risk of the Straits area, still, it must be remarked that the impact of a 1908-like event would be even more devastating now, given the poorly concerned broad urban and infrastructural development ongoing since then. Today, the city of Messina has approximately 250,000 inhabitants (100,000 more than in 1908) residing in about 35,000 buildings. The distribution of different levels of damage to the building stock within Messina and subsequent economic and social losses related to an earthquake scenario with similar characteristics to the 1908 event have been estimated by the University of Messina, EUCENTRE, INGV, and ETH (Teramo et al. 2008a, 2008b). According to them, 52 % of the surveyed buildings would be damaged and the victims could be tens of thousands, only because the ground shaking, thus not considering the geological effects. The cost of reparation alone would amount to billions of euro.

The information illustrated in our study, related to the ground coseismic environmental effects, add more items to be considered in order to define a complete seismic hazard scenario. Primary and secondary effects (tectonic subsidence, slope failures, fractures, and liquefaction) will greatly contribute to the seismic damage, e.g., by direct impact on power plants and buildings or interrupting crucial lifelines, and must be taken in consideration both for the preparedness of existing structures (and infrastructures) and for the planning of future works (e.g., the bridge over the Straits). The subsidence alone, which reached at least 70 cm as testified by the measurements of Loperfido, may give an idea of the impact along the coast, not considering that a tsunami similar to that of 1908 would expose the Straits to devastating effects, in terms of damage to population, infrastructures, and industrial plants. The industrial areas and port facilities of Milazzo, Messina, and Reggio Calabria could have also a dramatic impact on the environment. Moreover, in 1908, the dozens of landslides affected areas often not inhabited; today, the same lands are densely occupied by human structures and buildings.

Thus, the detailed knowledge of past EEEs offers now a unique tool to (1) carry out appropriate surveys targeted to test the susceptibility of the territory to the same phenomena (surface faulting/fractures, subsidence, landslides, liquefaction, inundation, etc.); (2) improve preparedness to face the land changes that a strong seismic event commonly causes.

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