Title Page

The 1908 Messina Straits earthquake: Cornerstones and the need to step forward

Andrea Argnani* (1) and Nicola Alessandro Pino (2)

1 ISMAR-CNR, Via Gobetti 101, 40129 Bologna, Italy.

email: andrea.argnani@ismar.cnr.it

Orcid 0000-0003-0729-2782

2 Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, Via Diocleziano 328, 80134 Napoli, Italy.

email: alessandro.pino@ingv.it

Orcid 0000-0003-1092-7152

* corresponding author

The M 7.1 earthquake that on the 28th Decembre 1908 struck the cities of Messina and Reggio Calabria, facing each other across the Messina Straits, was one of the most destructive events of last century, and one of the deadliest earthquakes in human history, causing a huge death toll, estimated between 60,000 and over 100,000 (Bertolaso et al., 2008). None of the large earthquakes that occurred in Europe in the XX century, some of them with larger magnitude (Grünthal and Wahlström, 2012), resulted to be as deadly as the Messina earthquake, which sparked a wave of solidarity and grief throughout Italy and also worldwide, with the launch of international relief efforts.

The earthquake was soon followed by large tsunami waves that swept the coast of eastern Sicily, reaching as far south as the island of Malta, and caused about 2000 casualties (e.g., Schambach et al. 2020). The very early observations of Fusakichi Omori, that visited the devastated lands two months after the earthquake, suggested an offshore source for both the earthquake and tsunami (Omori, 1909; Valensise, 2019).

Over the years many scientists have tried to identify the fault that originated the 1908 Messina Straits earthquake. The analyses accomplished so far identified some important constraints for the causative fault, but no comprehensive source model has been presented yet and no general consensus has been reached.

Here, we briefly review some of the proposed interpretations of the 1908 Messina fault, commenting on their reliability, and suggest that looking for a different approach would be advisable.

Besides the scientific interest and the importance for hazard assessment, the understanding of the origin of the 1908 Messina Straits earthquake has also relevance for the project of a bridge crossing the strait, which always hovers. The bridge projects has its roots back in time, even before the 1908 earthquake, but since the 1970s this issue has been cyclically in political propaganda during the (far too many) election campaigns, in those occasions being considered a necessary infrastructure.

Seismology and Geodesy

The analysis of the seismological and geodetic data suffered from the limited (by modern standards) instrumental networks of the beginning of 20th century, and the subsequent record of seismicity has been characterized (luckily) only by moderate-small, sparse, earthquakes that brought little information on major fault planes. Nevertheless, the attempts to analyze the 1908 seismological and geodetic data have produced a considerable number of papers, from the late '80s to the beginning of 2000 (see Pino et al., 2009 for a review), which presented robust results at least for some specific characteristics of the rupture for the 1908 earthquake. Also, recent analyses of the contemporary seismicity and of the surface deformation data provide valuable information on the seismogenic layer, the crustal structure, and the stress field in the Straits area (Neri et al., 2021).

Source characteristics of the 1908 earthquake

The investigations of the historical data proposed different fault planes, derived from the inversion of either the first motion polarities or the levelling lines, or from both. Most of these models share an extensional focal mechanism, on a plane roughly oriented in the N-S direction (N345°-N15°), with similar low angle dip (30-40°) to the east (Fig. 1). The well-assessed evidence of northward rupture propagation, constrained from the analysis of the original waveforms (Pino et al., 2000) is fully consistent with the above indications and also confirms the location of the maximum strain energy release in the Straits area. It is worth noting that the location and the orientation of the fault plane, and the rupture propagation direction also appear to be consistent with the simulation of the felt intensity reports, through full wavefield synthetic seismograms (Convertito and Pino, 2014), which also indicates preference for a slightly rotated clockwise fault plane.

More recently, some authors presented alternative source geometries, characterized by significantly different location, geometry, or kinematics (e.g., Aloisi et al., 2013; Meschis et al., 2019; Barreca et al., 2021). However, the results of these studies rely on *ad hoc* hypotheses, derived from the levelling data alone, either neglecting the seismological data (e.g., first motion polarities) or not accounting for the well-assessed constraints derived from the seismological analyses, and some of them also have inconsistencies in the analysis (De Natale and Pino, 2014; Argnani, 2021; Pino et al., 2021). It is helpful to recall here that the geographical distribution of the first motion polarities is not wide enough to univocally determine the focal mechanism, however the net separation of compressions and dilations in the NE quadrant constrains the W-dipping plane to have azimuth roughly in the range N0°-30° and dip around 50° (e.g., Capuano et al., 1988).

The re-examination of the first arrival times provided remarkably stable results for the epicentral location, indicating that the rupture started in the SE area of the Straits (Michelini et al., 2005), in agreement with both the location of the fault plane in the Straits area and its approximately NS orientation, and with the northward propagation of the rupture as well.

As for the fault extension, it seems to be confined along a 40-45 km lenght, as results for several models (Fig. 1). Some authors also derive dislocation outside the Straits area (e.g., Amoruso et al., 2002). In principle this cannot be excluded, but this result is inconsistent with the slip linear distribution derived from the seismograms' analysis (Pino et al., 2009).

Present seismicity and strain in the Straits area

During the last decades, in the Straits only minor earthquakes occurred, defining a cloud of scarce and sparse seismicity, characterized by M≤4.0 and depth in the range 5-15 km, with nearly all the M≥3.0 events occurring between 10 km and 15 km (e.g., Scarfì et al., 2009; Neri et al., 2021).

Tomographic images derived from the analysis of these events are not very well defined, generally evidencing the presence of a band of negative anomaly of the P-wave velocity, running along the Straits axis (e.g., Scarfì et al., 2009), while the available focal mechanisms – derived either from polarities (Scarfì et al., 2009) of the first arrivals or from waveform inversion (Neri et al., 2021) – are associated with ESE-WNW seismic strain direction. This latter evidence is fully consistent with the present crustal strain determined from GPS analysis, which display extension normal to the coast Sicilian side of the Straits with maximum rate of ~65 nanostrains/yr (Serpelloni et al., 2010).

Geology

In the geological approach it has been inferred that the 1908 Messina Straits earthquake, due to its great size, left a trace in the geological record, breaking a fault plan that can be imaged in the subsurface and which has possibly ruptured the seafloor. The Messina Strait is a relatively small area, that can fit within a 20 x 40 km box. The bathymetric data and multichannel reflection seismic profiles acquired in the last 20 years have reached a reasonable coverage, though deep seismic data are still lacking, mostly because of the difficulties of towing long streamers in such a narrow stretch of sea. These data allow a reasonable image of the seafloor morphology (e.g., Ridente et al., 2014; EMODnet, 2016) and of the sediments and rocks for a few km below it (e.g., Argnani et al., 2009; Argnani, 2011; Argnani 2021; Argnani, 2022; Barreca et al 2021). Nevertheless, these data have been often undervalued or forced to support preconceived interpretations.

Recent attempts to identify the surface rupture of the fault responsible for the 1908 Messina-Straits earthquake (Meschis et al., 2019; Barreca et al., 2021) have proved poory reliable (Pino et al., 2021; Argnani, 2022; Pino, 2022), in spite of echoes in the press. The high angle Messina-Taormina Fault (MTF; Fig. 1) has been proposed by Meschis et al (2019) on the basis of inversion of geodetic data as rupturing the seafloor for a length of ca. 60 km. This fault however is not visible in any of the seismic profiles crossing the Sicilian slope (Argnani et al., 2009; Barreca et al., 2021) and is not consistent with the first motion polarities observed at seismic stations, whatever crustal hypocentral depth is assumed (Capuano et al., 1988). The W-Fault, mostly running along the Messina channel, has been traced by Barreca et al (2021) using high resolution seismic profiles. The evidence for this fault, however, is not particularly convincing, with the data being over-interpreted (Argnani, 2022). The recent activity of this fault is doubtful, as its fault scarps are mostly erosional remains at seafloor, and elsewhere the fault is sealed by Late Pleistocene sediments (Argnani et al., 2009; Argnani 2011, 2022). This fault appears related to the fault system present onshore in Calabria, the age of which span from Late Pliocene to Middle Pleistocene (Selli, 1978; Ghisetti, 1992). These age constraints suggest that the 1908 Messina fault is active within a tectonic regime that has operated in the last 120 kyr. Besides that, the W-Fault has some critical seismological and geodetic issues, like the downward cutoff of seismicity, or the assumption that a long-term creep along the fault preceded the earthquake (Neri et al., 2021; Pino et al., 2021; Pino, 2022).

Given the constant interest for the 1908 earthquake and the uncertainties associated to the issue, other faults located in the surrounding of the Messina Strait have been proposed in the literature as responsible for this event, often on the basis of regional tectonic considerations, but without supporting documentation. One example is the Ionian Fault, which was originally traced along the western flank of the southern portion of the Messina channel (Fig. 1; Polonia et al., 2012), suggesting that "immediately south of the Messina Straits, a steep east-dipping fault is present at depth and satisfies the requirements of the causative fault for the 1908 earthquake." Later, on the basis of regional considerations, the same group of authors (Sgroi et al., 2021) changed their view and proposed a tectonic arrangement where right-lateral displacement along the Ionian Fault (now with a different trace; Fig. 1) causes extension in the Messina Strait as a kind of deformation at the northwestern tip of the fault (e.g., Kim and Sanderson, 2006). None of the two hypotheses satisfy the seismological and geological evidence. In the first case no fault has been imaged in the southern stretch of the Messina Straits (Argnani et al., 2009, Barreca et al., 2021) and the proposed fault ignore the northward rupture propagation inferred by seismology (Pino et al., 2000). The second one appears as an ad-hoc model, and the occurrence of a northwestern tip in the Ionian fault contrasts with the hypothesis, supported by the authors, that this fault is lithospheric and propagates from the hinterland into the Ionian foreland.

Seismic reflection data show that there is no large N-S fault cutting the Pleistocene sedimentary successions south of the epicenter of Schick (1977), and that in the northern part of the strait the faults imaged by seismic profiles are too short to account for a large earthquake (e.g., Argnani et al., 2009), leaving aside that these faults could be inactive. Although seismic reflection data do not offer an image of the fault plane responsible for the 1908 Messina Straits earthquake, they still provide useful constraints on this fault, which has to be blind and not rupturing the uppermost 2-3 km below the seafloor.

Outlook and Closing Remarks

The limited seismological and geodetic data for the 1908 Messina Straits earthquake allow to constrain a low-angle, ca. N-S-trending and E-dipping fault, with a maximum length of ca. 40-45 km, and a northward propagation of the rupture from a depth of 8-10 km (e.g., Pino et al.

2009). Shallow seismic profiles indicate an indirect dating of the origin of the 1908 Messina fault and allow to reject the occurrence of a fault plane rupturing the seafloor. Therefore, geological and seismological data both point to a blind fault. In this respect a re-examination of the morpho-bathymetry of the Messina Strait is advisable, with a closer inspection at the morphology of seabed looking for signs of the occurrence of an active, blind extensional fault.

The acquisition of a deep seismic profile, possibly amphibian, crossing the Messina Strait could be a way to image the plane of the blind fault, although the tectonic complexity of the Calabrian Arc may hinder the result. In the event a fault plane is imaged in the deep subsurface, with an upper tip likely deeper than 3-4 km, it can be verified whether some sort of deformation connected to the fault is observed in the shallow seismic profiles so far acquired. In this case it would be possible to transfer the information to the grid of seismic profiles, thus characterizing the geometry of the fault and better understanding its evolution. Should new and successful geophysical acquisitions be made in the near future, the seismogenic fault plane could also become a possible target for an ICDP drilling aimed at intercepting and monitoring an active fault.

In any case, we note that any new interpretation cannot be based on a partial analysis or on arbitrary assumptions, and that the proposed model must take into account all reliable constraints based on available data and observations.

Data and Resources

No data or additional sources were used in writing this article

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

Acknowledgments

The discussions made with many colleagues, on various occasions, contributed to shape the content of this contribution, even if the responsibility of what is written is only on the authors. The helpful suggestions provided by the anonymous reviewer have been appreciated.

References

Aloisi, M., V. Bruno, , F. Cannavo', L. Ferranti, M. Mattia, C. Monaco, and M. Palano (2013). Are the source models of the M 7.1 1908 Strait of Messina earthquake reliable? Insights from a novel inversion and a sensitivity analysis of leveling data, *Geophys. J. Int*. **192** (3), 1025–1041. https://doi.org/10.1093/gji/ggs062.

Amoruso, A., L. Crescentini, and R. Scarpa (2002). Source parameters of the 1908 Messina Straits, Italy, earthquake from geodetic and seismic data, *J. Geophys. Res*. **107**, 2080; doi:10.1029/2001JB000434.

Argnani, A. (2011). Marine geology in the region of the Messina Straits, and a puzzling pale of faults, earthquakes and tsunamis, in: *Marine Research at CNR*, Vol. DTA/**06–2011**, Roma, 845–855.

Argnani, A. (2021). Comment on “New simulations and understanding of the 1908 Messina tsunami for a dual seismic and deep submarine mass failure source” by L. Schambach, S.T. Grilli, D.R. Tappin, M.D. Gangemi, G. Barbaro [Marine Geology 421 (2020) 106093], *Mar. Geol.* **442** (2021), 106634.

Argnani, A. (2022). Comment on the paper by Barreca et al.: "The Strait of Messina: Seismotectonics and the source of the 1908 earthquake" (Earth-Science Reviews 218, 2021, 103685), *Earth-Sci. Rev.*, **226**, 103961

Argnani, A., G. Brancolini, C. Bonazzi, M. Rovere, F. Accaino, F. Zgur, and E. Lodolo, (2009). The result of the Taormina 2006 seismic survey: possible implications for active tectonics in the Messina Straits, *Tectonophysics* **476**, 159–169.

Barreca, G., F. Gross, L. Scarfì, M. Aloisi, C. Monaco, and S. Krastel (2021). The Strait of Messina: Seismotectonics and the source of the 1908 earthquake, *Earth-Sci. Rev*. **218**, 103685 https://doi.org/10.1016/j.earscirev.2021.103685.

Bertolaso, G., Boschi, E., Guidoboni, E. and G. Valensise (Eds.) (2008). *Il terremoto e il maremoto del 28 dicembre 1908. Analisi sismologica, impatto, prospettive*, SGA, Bologna, 814 pp (in Italian).

Boschi, E., D. Pantosti, and G. Valensise (1989). Modello di sorgente per il terremoto di Messina del 1908, *Atti VIII Convegno GNGTS*, 246, p. 258.

Capuano, P., G. De Natale, P. Gasparini, F. Pingue, and R. Scarpa (1988). A model for the 1908 Messina Straits (Italy) earthquake by inversion of levelling data, *Bull. Seismol. Soc. Am*., **78**, 1930–1947.

Convertito, V. and N.A. Pino (2014). Discriminating among distinct source models of the 1908 Messina Straits earthquake by modelling intensity data through full wavefield seismograms, *Geophys. J. Int.* **198**, 164-173.

De Natale, G. and N.A. Pino, (2014). Comment on 'are the source models of the M 7.1 1908 Messina Straits earthquake reliable? Insights from a novel inversion and sensitivity analysis of levelling data' by M. Aloisi, V. Bruno, F. Cannavò, L. Ferranti, M. Mattia, C. Monaco and M. Palano, *Geophys. J. Int.* **197**, 1399–1402. https://doi.org/10.1093/gji/ggu063.

EMODnet Bathymetry Consortium (2016). EMODnet Digital Bathymetry (DTM). The European Marine Observation and Data Network, https://doi.org/10.12770/ c7b53704-999d-4721-b1a3-04ec60c87238.

Farr, T.G. and 17 others (2007). The shuttle radar topography mission, *Rev. Geophys*. **45** https://doi.org/10.1029/2005RG000183. RG2004.

Ghisetti, F. (1992). Fault parameters in the Messina Strait (southern Italy) and relations with the seismogenic source, *Tectonophysics* **210**, 117–133.

Grünthal, G. and R. Wahlström (2012). The European-Mediterranean earthquake catalogue (EMEC) for the last millennium, *Journal of Seismology* **16**, 535-570.

Kim, Y-S. and D. Sanders (2006). Structural similarity and variety at the tips in a wide range of strike–slip faults: a review, *Terra Nova*, **18**, 330–344.

Meschis, M., G.P. Roberts, Z.K. Mildon, J. Robertson, A.M. Michetti, and J.F. Walker (2019). Slip on a mapped normal fault for the 28th December 1908 Messina earthquake (Mw 7.1) in Italy, *Sci. Rep*. **9** (1), 6481.

Michelini, A., A. Lomax, A. Nardi, A. Rossi, B. Palombo, and A. Bono (2005). A modern re-examination of the location of the 1905 Calabria and the 1908 Messina Straits earthquake, *Geophysical Research Abstracts* 7, EGU05-A-07909.

Neri, G., B. Orecchio, D. Presti, S. Scolaro, and C. Totaro (2021). Recent seismicity in the area of the major, 1908 Messina Straits earthquake, South Italy, *Front. Earth Sci*. **9**, 667501. https://doi.org/10.3389/feart.2021.667501.

Omori, F. (1909). Preliminary report on the Messina-Reggio earthquake of Dec. 28 1908, *Bull. Imp. Earthquake Invest. Comm***. 3** (2), 37–46.

Pino N.A. (2022). Brief communication: The crucial assessment of possible significant vertical movements preceding the 28 December 1908, Mw = 7.1, Messina Straits earthquake, *Nat. Hazards Earth Syst. Sci*., 22, 3787–3792, 2022

Pino, N.A., D. Giardini, and E. Boschi (2000). The December 28, 1908, Messina Straits, southern Italy, earthquake: Waveform modeling of regional seismograms, *J. Geophys. Res*. **105**, 25,473-25,492.

Pino, N.A., A. Piatanesi, G. Valensise, and E. Boschi (2009). The 28 December 1908 Messina Straits earthquake (Mw 7.1): a great earthquake throughout a century of seismology, *Seismol. Res. Lett.* **80** (2), 243–259.

Pino, N.A., M. Palano, and G. Ventura (2021). Comment on the paper by Barreca et al.: “The Strait of Messina: Seismotectonics and the source of the 1908 earthquake” (Earth- Science Reviews 218, 2021, 103685), *Earth-Sci. Rev*., **223** (2021) 103865

Polonia, A., L. Torelli, L. Gasperini, and P. Mussoni (2012). Active faults and historical earthquakes in the Ionian Sea, *Natural Hazards and Earth System Sciences* **12**, 2311–2328. http://dx.doi.org/10.5194/nhess-12-2311-2012.

Ridente, D., E. Martorelli, A. Bosman, and F.L. Chiocci (2014). High-resolution morphobathymetric imaging of the Messina Straits (Southern Italy). New insights on the 1908 earthquake and tsunami, *Geomorphology* **208**, 149–159. https://doi.org/ 10.1016/j.geomorph.2013.11.021.

Scarfì, L., H. Langer, and A. Scaltrito (2009). Seismicity, seismotectonics and crustal velocity structure of the Messina Strait (Italy), *Phys. Earth Planet. Int.* **177**, 65-78.

Schambach, L., S.T. Grilli , D.R. Tappin, M.D. Gangemi, and G. Barbaro (2020). New simulations and understanding of the 1908 Messina tsunami for a dual seismic and deep submarine mass failure source, *Mar. Geol*. **421**, 106093.

Schick, R. (1977). Eine seismotektonische Bearbeitung des Erdbebens von Messina im Jahre 1908, *Geol. Jahrb*. **11**, 3–74.

Selli, R. (1978). Geologia e sismotettonica dello Stretto di Messina, *Atti Accademia Nazionale dei Lincei* **43**, 119–154 (in Italian).

Serpelloni, E., R. Bürgmann, M. Anzidei, P. Baldi, B. Mastrolembo, and E. Boschi (2010). Strain accumulation across the Messina Straits and kinematics of Sicily and Calabria from GPS data and dislocation modeling, *Earth Planet. Sci. Lett*. **298** (3–4), 347–360.

Sgroi, T., A. Polonia, G. Barberi, A. Billi, and L. Gasperini (2021). New seismological data from the Calabrian arc reveal arc-orthogonal extension across the subduction zone, *Sci. Rep*. (2021), **11**–473. https://doi.org/10.1038/s41598-020-79719-8.

Valensise, G. (2019). Fusakichi Omori and Italy: excerpts from the Visits of a Japanese Seismologist in the Belpaese, *Hist. Sci.* **28**–3, 258–277.

Andrea Argnani

ISMAR-CNR, Via Gobetti 101, 40129 Bologna, Italy, Orcid 0000-0003-0729-2782

andrea.argnani@ismar.cnr.it

Nicola Alessandro Pino

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, Via Diocleziano 328, 80134 Napoli, Italy, Orcid 0000-0003-1092-7152

alessandro.pino@ingv.it

List of Figure captions

Figure 1. Morpho-bathymetry of the Messina Strait region with superimposed the trace of the faults inferred by Meschis et al. (MTF) and Barreca et al (W-Fault). The Ionian Fault-Messina Strait Fault system (MSF) of Polonia et al. (2012) and the Ionian fault (IF) of Sgroi et al. (2021) are also shown; for this latter fault the greenish and purple fields represent areas subject to extension and compression, respectively. The area of strongest shaking produced by the 1908 earthquake is outlined by a dotted blue line. The black box is the surface projection of the model fault proposed by Boschi et al. (1989). The small yellow star indicates the epicentral location of Schick (1977). The white star locates the epicenter proposed by Michelini et al. (2005), and the white arrow indicates the rupture directivity (Pino et al., 2000). The thick white bars show the geodetic strain (Serpelloni et al., 2010). ME= Messina and RC= Reggio Calabria Bathymetric data have been obtained from EMODnet (2016) and topography is from Shuttle Radar Topography Mission (Farr et al., 2007).

Figure 1 colour