# Constraints to the Cause of Three Historical Tsunamis (1908, 1783, and 1693) in the Messina Straits Region, Sicily, Southern Italy

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## INTRODUCTION

Identifying the cause of past tsunamis is of paramount importance to mitigate the risk connected with future events, but recognizing a landslide-tsunami when the mass failure is entirely submarine is very challenging because of the paucity of detectable evidence (*e.g.*, Lynett *et al.* 1998; Tappin *et al.* 2001; Synolakis *et al.* 2002; Fritz *et al.* 2007). Efforts in this direction are, however, necessary because the arrival time of these tsunamis to the coast is commonly very short (*i.e.*, they usually originate along the margin of the continental shelf) and the related runup and inundation may be locally very large (Bardet *et al.* 2003; Okal *et al.* 2003; Scheffers and Kelletat 2003; Okal and Synolakis 2004; Tappin, Watts, and Grilli 2008; Fritz *et al.* 2007).

At present, the only effective way to mitigate the risk connected with landslide-tsunamis is to identify areas prone to these tsunamis. This task can be accomplished by marine surveys (*e.g.*, Tappin *et al.* 2001; Chiocci *et al.* 2008; Minisini and Trincardi 2009) or through the analysis of historical tsunamis where these events are adequately documented (*e.g.*, Okal *et al.* 2003, 2009; Marriner and Morhange 2007).

Eastern Sicily and southern Calabria front the Messina Straits in southern Italy and have been affected by recent and historical destructive earthquakes and tsunamis (Boschi *et al.* 2000; Tinti *et al.* 2004; Neri *et al.* 2006; Pareschi *et al.* 2006; Galli *et al.* 2008; Gerardi *et al.* 2008; Pantosti *et al.* 2008; De Martini *et al.* 2010). For several of these events, careful observations and data were collected (*e.g.*, Mercalli 1897, 1909; Omori 1909; Platania 1909; Baratta 1901, 1910), so that Sicily and Calabria are probably among the best regions worldwide where historical studies on earthquakes and tsunamis can be accomplished (*e.g.*, Boschi *et al.* 1995, 2000; Guidoboni and Traina 1996; Barbano and Rigano 2001; Tinti *et al.* 2004; Pino *et al.* 2009).

The aim of this paper is to contribute to the knowledge of tsunami hazard in the Messina Straits area (Figure 1) by constraining the cause (*i.e.*, seismic dislocation vs. mass failure) of three earthquake-related historical tsunamis (*i.e.*, the 1908, 1783, and 1693 tsunamis; Table 1). To do so, we review previously published datasets. We analyze, in particular, historical datasets of tsunami runup to discriminate between earthquake- and landslide-tsunamis according to the method of Okal and Synolakis (2004). We acknowledge that some of the presented results were previously published (Billi, Minelli *et al.* 2009), but here we use them to understand whether tsunamis are repeatedly excited by the same kind of source or whether multiple sources exist in the study region. We also aim to make progress in recent debates concerning the cause of the studied tsunamis (Table 1). Our results are important not only for knowledge of the local earthquake and tsunami hazard, but also for better comprehension of the causal relationship between earthquakes and tsunamis (*e.g.*, earthquake size and tsunami potential; Lomax and Michelini 2009) and for improvement of the historical tsunami database, against which numerical and physical models should be validated (Synolakis and Kânoğlu 2009). Moreover, as the causative faults of the studied earthquakes are still uncertain or unknown, identification of the tsunami sources will also be of help in searching for these faults. If, in fact, the tsunami sources are the coseismic dislocations of the seafloor, the causative faults must be located offshore or at least close to the sea, but if the tsunami sources are mass failures, then the earthquake causative faults can be searched for in both offshore and onshore areas. Clearly, this notion implies that in the first case (tsunami caused by coseismic dislocation) the numerical simulation of tsunami data can be used as constraint of the earthquake causative faults, whereas in the second case (tsunami caused by mass failure), this kind of data should be disregarded to constrain the earthquake source.

From a tectonic point of view, although the study area (Figure 1) is located along the active convergent margin between the African (Nubian) and Eurasian plates, GPS data, instrumentally recorded earthquakes, and the analysis of recent faults

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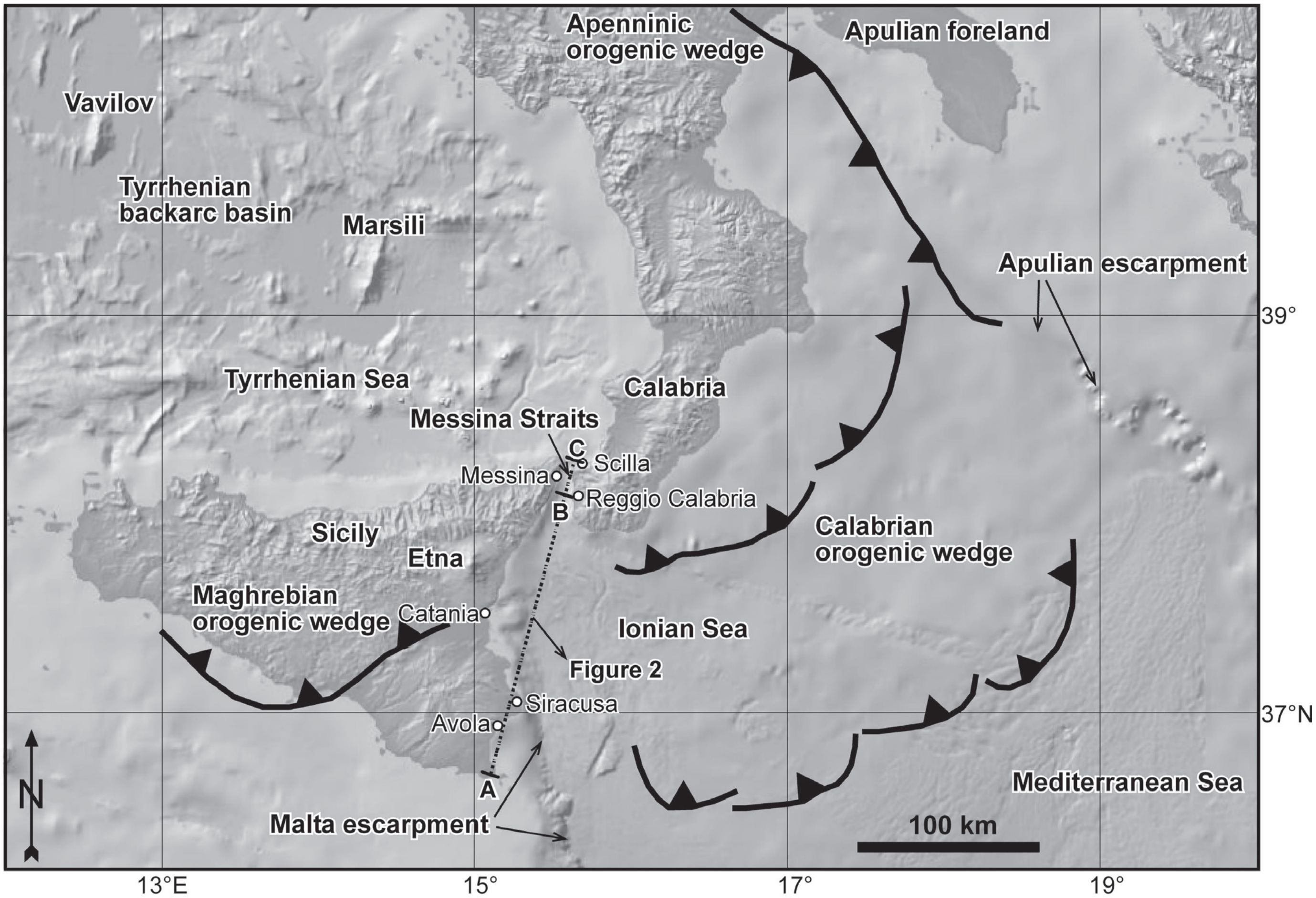


▲ **Figure 1.** Schematic tectonic map of southern Italy (Minelli and Faccenna 2010). The three historical earthquakes studied in this paper occurred close to Messina and Reggio Calabria (1908), Scilla (1783), and Catania and Siracusa (1693) (Table 1). A, B, and C along the eastern coast of Sicily indicate the track of diagrams shown in Figure 2.

show that an extensional or transtensional tectonic regime affects and has recently affected eastern Sicily and southern Calabria (Ghisetti 1984; Valensise and Pantosti 1992; Monaco and Tortorici 2000; Neri *et al.* 2005; Billi *et al.* 2006; Pondrelli *et al.* 2006; D'Agostino *et al.* 2008; Mattia *et al.* 2009).

## METHOD, DATA, UNCERTAINTIES, AND RESULTS

We study the tsunami source by best-fitting the available datasets of observed tsunami runup with a previously published empirical function (*i.e.*, observed vs. expected runup distributions). This method is thoroughly explained in Okal and Synolakis (2004) and summarized as follows.

By numerical simulations validated against natural events, Okal and Synolakis (2004) recognized the following relationship as the function best-fitting both experimental and observed runup distributions:

$$\zeta(y) = \frac{b}{\left(\frac{y-c}{a}\right)^2 + 1}, \qquad (1)$$

where $\zeta$ is the runup along the linear distance $y$ that approximates the real coastline and $a$, $b$, and $c$ are optimized by best-fit and are, respectively, the lateral half-extent ($a$), maximum amplitude ($b$), and peak abscissa ($c$) of the runup distribution. Okal and Synolakis (2004) empirically demonstrated that when the ratio $I_2$ between $b$ and $a$ is greater than $10^{-4}$, the main cause of the tsunami is a landslide, whereas when $I_2$ is smaller than $10^{-4}$, the main cause of the tsunami is the seismic dislocation of the seafloor.

Below, we apply the above-explained method to the runup datasets of the 1908, 1783, and 1693 tsunamis in the Messina Straits region (Table 1). For the 1908 tsunami, we analyze the original dataset provided by Platania (1909), whereas for the 1783 and 1693 tsunamis, we analyze the datasets that were compiled by Gerardi *et al.* (2008) by considering several historical sources. In some cases, Gerardi *et al.* (2008) integrated the historical runup data with runup values obtained by inverting the historical inundation data (*i.e.*, observed inundation distances) into runup values through the formula of Hills and Mader (1997).

The analyzed runup data are characterized by the uncertainties typical of all historical reports (*e.g.*, Guidoboni and Ebel

**TABLE 1**
**Historical Earthquakes and Hypothetical Cause of the Related Tsunamis Studied in This Paper.**

| Yr | Mo | Day | Hypothetical Epicentral Area (Figure 1) | $I_0$ | $M_m$ | Tsunami Cause | Result from this Study |
|---|---|---|---|---|---|---|---|
| 1908 | 12 | 28 | Messina Straits (close to Reggio Calabria) | XI | 7.3 | landslide; debates on landslide size, site, etc.[a] | landslide-tsunami |
| 1783 | 2 | 6 | Southern Calabria (close to Scilla) | VIII–IX | 5.9 | possibly subaerial rockfall[b] | landslide-tsunami |
| 1693 | 1 | 11 | Southeastern Sicily (close to Siracusa) | X–XI | 7 | debated[c] | landslide-tsunami |

Key: $I_0$ = modified Mercalli epicentral intensity; $M_\mathrm{m}$ = macroseismic magnitude (Neri *et al.* 2006).

a. Compare Ryan and Heezen (1965), Piatanesi *et al.* (1999), Tinti *et al.* (1999), Tinti and Armigliato (2003), Billi *et al.* (2008), Billi, Funicello *et al.* (2009), Billi, Minelli *et al.* (2009), Gerardi *et al.* (2008), Piatanesi *et al.* (2008), Tappin, Watts, Grilli, Dubosq *et al.* (2008), Argnani *et al.* (2009), Favalli *et al.* (2009), and this work.
b. Compare Baratta (1901), Jacques *et al.* (2001), Bosman *et al.* (2006), Bozzano *et al.* (2006), Graziani *et al.* (2006), Gerardi *et al.* (2008), and this work.
c. Compare Piatanesi and Tinti (1998), Tinti *et al.* (2001), Gutscher *et al.* (2006), Armigliato *et al.* (2007), Gerardi *et al.* (2008), and this work.

2009) as discussed in previous papers (Billi *et al.* 2008; Billi, Minelli *et al.* 2009; Gerardi *et al.* 2008). Moreover, Equation 1 was validated against several natural tsunamis (Okal and Synolakis 2004), but this equation may not be suitable for all natural cases. In particular, Equation 1 was created to work in the case of straight coasts with no major bays, coves, or islands. The eastern coast of Sicily is as straight as other natural coasts where this criterion was previously applied with success (Okal and Synolakis 2004). Finally, the formula proposed by Hills and Mader (1997) to obtain tsunami runup data from the related inundation distances has still to be validated against modern tsunami events, for which runup and inundation (as well as the Manning's roughness coefficient of terrain) should be reliably measurable.

We plotted the runup data for the three studied tsunamis against distance and determined the best-fits of these data using Equation 1, which satisfactorily fits the runup spatial distributions as attested by the related values of the coefficient of determination $R^2$ (Figure 2). All best-fits are characterized by a significant amplitude ($b$) and a narrow lateral half-extent ($a$), so that their ratio ($I_2$) is greater than $10^{-4}$. These results suggest that the 1908, 1783, and 1693 tsunamis were chiefly excited by mass failures. Results in Figure 2 are similar to those obtained by Gerardi *et al.* (2008) for the 1783 tsunami (*i.e.*, landslide-tsunami), but different for the 1908 and 1693 tsunamis (*i.e.*, landslide-tsunamis instead of earthquake-tsunamis).

## DISCUSSION

The above-reported uncertainties imply that the runup distributions alone (Figure 2) cannot be considered definitive in classifying the 1908, 1783, and 1693 tsunamis as landslide-tsunamis. Our results are, however, important clues to suggest that the Messina Straits region, including eastern Sicily and southern Calabria, is prone to landslide-tsunamis.

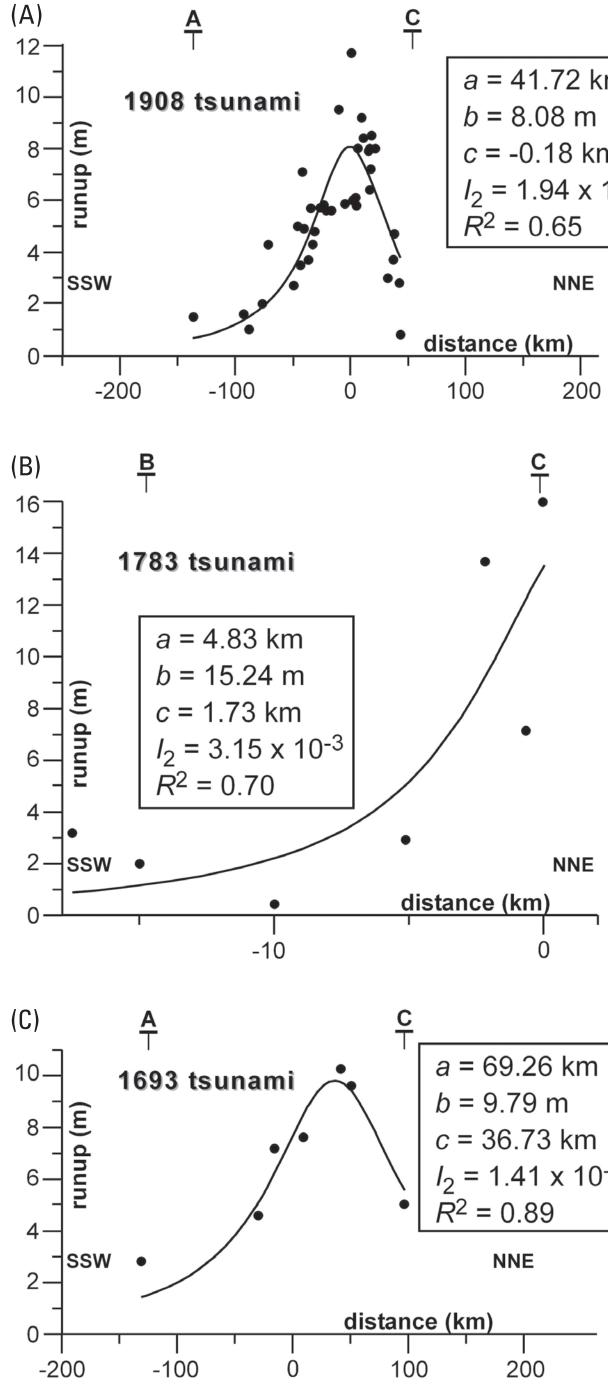
For the case of the 1908 tsunami, the landslide source hypothesis is supported by other evidence such as the interruption of submarine cables in the Ionian Sea (Ryan and Heezen 1965), the pattern of delay times between the arrivals of the earthquake and tsunami waves to the coasts (Billi *et al.* 2008), and the ratio, $I_1$, between the measured maximum runup and the hypothetical coseismic slip (*i.e.*, $I_1$ is between 2.7 and 6.0; Billi, Minelli *et al.* 2009). In particular, the interruption of submarine cables and evidence of submarine turbidity current provided by Ryan and Heezen (1965) are primary in demonstrating that there was a massive underwater slump in 1908, thus clearly breaking the landslide vs. seismic dislocation case and leaving open other reasonable debates such as those concerning the landslide size and location or the minor role possibly played by the seismic dislocation on the tsunami generation and runup (Table 1).

For the case of the 1783 tsunami, historical sources report that this tsunami was very likely generated by a huge earthquake-induced subaerial rockfall nucleated on the southwestern side of the Scilla beach, *i.e.*, the Monte Paci, which then collapsed into the Messina Straits (Tinti *et al.* 2004; Graziani *et al.* 2006). This information is consistent with the very short distance of runup decay (circa 10–15 km; Figure 2C) typical of landslide-tsunamis (*e.g.*, Okal and Synolakis 2004; Okal and Hébert 2007).

For the case of the 1693 tsunami, at present no further evidence exists in support of the landslide source as inferred from the runup distribution (Figure 2C).

The susceptibility to mass failures of the Messina Straits region is also largely demonstrated by several onshore studies (*e.g.*, Pantano *et al.* 2002 and Tertulliani and Cucci 2009, among others), three of which, at least, report on large sets of inland landslides triggered by the 1908, 1783, and 1693 earthquakes (Murphy 1995; Keefer 2002; Nicoletti and Parise 2002).

Although our results suggest that the studied tsunamis were generated by mass failures, we acknowledge that the method used does not allow us to detect the influence on the tsunami runup of possible coseismic seafloor dislocations. In the case of the 1908 tsunami, for instance, some recent studies based on numerical modeling (Piatanesi *et al.* 2008; Tappin, Watts, Grilli *et al.* 2008; Favalli *et al.* 2009) propose a contribution of the coseismic seafloor dislocation on the tsunami runup, but this contribution should be less than circa 20%



▲ **Figure 2.** Tsunami runup data (and related best-fits obtained applying Equation 1) plotted along a track parallel to the coast of eastern Sicily (Figure 1). Note that the vertical scale is the same for the three diagrams, whereas the horizontal scale is different for the diagram in (B). $a$, $b$, and $c$ are the parameters of Equation 1. $I_2$ is the $b$ to $a$ ratio. $R^2$ is the coefficient of correlation of the best-fits. A) Runup distribution for the 1908 tsunami. Data were collected by Platania (1909). B) Runup distribution for the 1783 tsunami. Data were compiled by Gerardi *et al.* (2008) after historical sources. C) Runup distribution for the 1693 tsunami. Data were compiled by Gerardi *et al.* (2008) after historical sources.

in terms of maximum observed runup (Piatanesi *et al.* 2008; Favalli *et al.* 2009).

Results from this study provide new insights into the location of the three earthquake-causative faults (*i.e.*, 1908, 1783, and 1693 earthquakes), which are still unknown or poorly constrained. The evidence that the three tsunamis were likely excited by mass failures extends the potential location of the causative faults also to inland regions. For instance, Bianca *et al.* (1999) as well as several other studies (Barbano and Rigano 2001; Sirovich and Pettenati 2001; Visini *et al.* 2009) ascribe the 1693 earthquake to an inland source. The causative fault system of the 1783 earthquake is commonly recognized as located in western Calabria (*i.e.*, onshore; Jacques *et al.* 2001; Galli and Bosi 2002), whereas the causative fault of the 1908 earthquake is still unknown, but most studies indicate the narrow section of the Messina Straits (*i.e.*, mostly offshore) as the probable location for this fault (Pino *et al.* 2009). The above-cited studies that propose onshore causative faults for the 1783 and 1693 earthquakes inherently support the landslide source hypothesis for the related tsunamis.

## BRIEF HISTORICAL PERSPECTIVE OF LANDSLIDE-TSUNAMIS

A brief historical perspective of rather well known landslide-tsunamis is here included to better understand the value of our results.

The NOAA (National Oceanic and Atmospheric Administration) world tsunami database (available online at `http://www.ngdc.noaa.gov/hazard/`) reports, at present (March 2010), 30 definite tsunamis caused by landslides and 48 definite tsunamis caused by earthquake and landslide, but for most events the runup documentation is poor. In fact, only for 13 tsunamis (Table 2) out of a total of 78 does the related runup documentation include more than five data with at least one datum greater than 2 m.

Table 3 reports a bibliographic survey of landslide-tsunamis recently studied by considering the runup distribution or other evidence. The comparison between the three studied landslide-tsunamis (Table 1) and those reported in Tables 2 and 3 shows the uniqueness of the events studied in this paper. No other instances exist, in fact, of a repetition of three destructive earthquake-related landslide-tsunamis within circa 200 years (from 1693 to 1908) along a coast segment of less than 200 km and with such a good documentation of tsunami runup and other evidence (Table 1).

## CONCLUSIONS

We conclude that, given the recurrence in the study area of strong earthquakes (Neri *et al.* 2006) and related mass failures (Ryan and Heezen 1965; Murphy 1995; Keefer 2002; Tertulliani and Cucci 2009), the Messina Straits area is at risk of earthquake-related landslide-tsunamis. This conclusion is corroborated by historical evidence presented in this paper and previously about the 1908, 1783, and 1693 tsunamis (*e.g.*,

TABLE 2
List of "definite tsunamis" sourced by landslide or by landslide and earthquake as reported (March 2010) in the NOAA database (available online at `http://www.ngdc.noaa.gov/hazard/`). Data are exclusively from the NOAA database. Reported events are only those defined as "definite tsunamis," for which the related runup documentation includes more than five data with at least one datum greater than 2 m.

| Site and Year | Day and Month | Tsunami Cause | Earthquake Magnitude | Present also in Table 3 |
|---|---|---|---|---|
| Izmit (Turkey) 1999 | 17 Aug. | landslide and earthquake | 7.6 | yes |
| Sissano (Papua New Guinea) 1998 | 17 Jul. | landslide and earthquake | 7.0 | yes |
| Hawaii 1975 | 29 Nov. | landslide and earthquake | 7.1 | yes |
| Prince William Sound (Alaska) 1964 | 28 Mar. | landslide and earthquake | 9.2 | yes |
| Lituya Bay (Alaska) 1958 | 10 Jul. | landslide and earthquake | 8.3 | yes |
| Suva (Fiji) 1953 | 14 Sep. | landslide and earthquake | 6.8 | yes |
| Tafjord (Norway) 1934 | 7 Apr. | landslide | no quakes | no |
| Grand Banks (Canada) 1929 | 18 Nov. | landslide and earthquake | 7.2 | yes |
| Honshu (Japan) 1927 | 7 Mar. | landslide and earthquake | 7.6 | no |
| Messina (Italy) 1908 | 28 Dec. | landslide and earthquake | 7.1 | yes |
| Banda (Indonesia) 1899 | 29 Sep. | landslide and earthquake | 7.8 | no |
| Yakutat (Alaska) 1899 | 10 Sep. | landslide and earthquake | 8.2 | no |
| Southern Calabria (Italy) 1783 | 6 Feb. | landslide and earthquake | 5.9 | yes |

Tinti *et al.* 2004; Graziani *et al.* 2006; Billi *et al.* 2008). Marine geological and geophysical surveys and an alert system should, therefore, be accomplished to better discern the susceptibility to landslide-tsunamis and attempt to mitigate the connected risk.

The successful application of the method by Okal and Synolakis (2004) to the runup dataset of the 1783 landslide-tsunami (see also Gerardi *et al.* 2008), whose cause was documented by eyewitness accounts as being a subaerial rockfall (Table 1), constitutes an important validation of this method for this type of tsunami.

If our results are correct, then the studied tsunamis improve the statistics of Lomax and Michelini (2009), according to whom destructive earthquake-tsunamis are unlikely for earthquakes with $\mathbf{M} \leq 7.5$ (see also Rosenau *et al.* 2010), but this conclusion is valid only if the sources of the studied earthquakes are located offshore.

The repetition of historical landslide-tsunamis addressed in this paper is unique worldwide. As such, the Messina Straits region may constitute a natural laboratory for studies on landslide-tsunamis and for those researchers needing well-documented instances of landslide-tsunamis as benchmarks of numerical and physical models or as suitable case histories to be simulated.

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## REFERENCES

Ambraseys, N. N. (1960). The seismic sea wave of July 9, 1956 in the Greek archipelago. *Journal of Geophysical Research* **65**, 1,257–1,265.

Argnani, A., F. L. Chiocci, S. Tinti, A. Bosman, M. V. Lodi, G. Pagnoni, and F. Zaniboni (2009). Comment on "On the cause of the 1908 Messina tsunami, southern Italy" by Andrea Billi *et al. Geophysical Research Letters* **36**, 13; doi:10.1029/2009GL037332, 2009.

Armigliato, A., S. Tinti, F. Zaniboni, G. Pagnoni, and A. Argnani (2007). New contributions to the debate on the cause of the January 11th, 1693 tsunami in eastern Sicily (Italy): Earthquake or offshore landslide source (or maybe both)? *Eos, Transactions of the American Geophysical Union* **88** (52), Fall Meeting Supplement, Abstract S53A-1019.

Assier-Rzadkiewicz, S., P. Heinrich, P.C. Sabatier, B. Savoye, and J. F. Bourillet (2000). Numerical modelling of a landslide-generated tsunami: The 1979 Nice event. *Pure and Applied Geophysics* **157**, 1,707–1,727.

Baratta, M. (1901). *I terremoti d'Italia*. Turin: Arnaldo Forni Editore, 950 pps.

Baratta, M. (1910). *La catastrofe sismica calabro-messinese (28 Dicembre 1908)*. Rome: Società Geografica Italiana, 426 pps.

Barbano, M. S., and R. Rigano (2001). Earthquake sources and seismic hazard in southeastern Sicily. *Annals of Geophysics—Italy* **44**, 723–738.

Bardet, J. P., C. E. Synolakis, H. L. Davies, F. Imamura, and E. A. Okal (2003). Landslide tsunamis: Recent findings and research directions. *Pure and Applied Geophysics* **160**, 1,793–1,809.

Bianca, M., C. Monaco, L. Tortorici, and L. Cernobori (1999). Quaternary normal faulting in southeastern Sicily (Italy): A seismic source for the 1693 large earthquake. *Geophysical Journal International* **139**, 370–394.

Billi, A., G. Barberi, C. Faccenna, G. Neri, F. Pepe, and A. Sulli (2006). Tectonics and seismicity of the Tindari fault system, southern Italy: Crustal deformations at the transition between ongoing contractional and extensional domains located above the edge of a subducting slab. *Tectonics* **25**, TC2006; doi:10.1029/2004TC001763.

Billi, A., R. Funiciello, L. Minelli, C. Faccenna, G. Neri, B. Orecchio, and D. Presti (2008). On the cause of the 1908 Messina tsu-

**TABLE 3**
**Survey of some recent and historical, rather well-known landslide-tsunamis recently documented in the geophysical literature. The cause of most listed tsunamis is still debated and, in several cases, is likely composite (*i.e.*, landslide and earthquake; *e.g.*, Turkey 1999, Alaska 1964, Greece 1956, Fiji 1953, and Alaska 1946). Compare this table with Table 2.**

| Site and Year | Day and Month | Landslide | Main Constraints | Landslide Cause | References |
|---|---|---|---|---|---|
| Nusa Kambangan (Java) 2006 | 17 Jul. | submarine | NM, and RD | M7.8 EQ | Fritz *et al.* 2007 |
| Stromboli (Italy) 2002 | 30 Dec. | subaerial and submarine | EA, MS, PM, and SS | volcanism | Tinti *et al.* 2005; Chiocci *et al.* 2008; Di Risio *et al.* 2009 |
| Izmit (Turkey) 1999 | 17 Aug. | subaerial and submarine | EA, NM, and RD | M7.4 EQ | Tinti *et al.* 2006 |
| Sissano (Papua New Guinea) 1998 | 17 Jul. | submarine | HR, MS, and RD | M7.1 EQ | Okal and Synolakis 2001, 2004; Tappin *et al.* 2001; Synolakis *et al.* 2002 |
| Skagway (Alaska) 1994 | 3 Nov. | subaerial | EA, RD, and TG | low tide | Kulikov *et al.* 1996; Synolakis *et al.* 2000 |
| Flores (Indonesia) 1992 | 12 Dec. | submarine | NM and RD | M7.5 EQ | Imamura *et al.* 1995; Watts *et al.* 2003 |
| Nice (France) 1979 | 16 Oct. | subaerial and submarine | EA, MS, and NM | building operations | Assier-Rzadkiewicz *et al.* 2000; Ioualalen *et al.* 2010 |
| Hawaii 1975 | 29 Nov. | submarine | NM, RD, and TG | M7.2 EQ | Ma *et al.* 1999 |
| Prince William Sound (Alaska) 1964 | 28 Mar. | subaerial and submarine | EA, MS, NM, RD, and SS | M9.2 EQ | Plafker *et al.* 1969; Haeussler *et al.* 2007; Sulemaini *et al.* 2009 |
| Corinth Gulf (Greece) 1963 | 7 Feb. | submarine | NM, RD, and SS | gravity | Papadopoulos *et al.* 2007 |
| Lituya Bay (Alaska) 1958 | 10 Jul. | subaerial | EA, PM, RD, and SS | M8.3 EQ | Fritz *et al.* 2009; Weiss *et al.* 2009 |
| Amorgos (Greece) 1956 | 9 Jul. | submarine | EA, NM, and RD | M7.8 EQ | Ambraseys 1960; Okal *et al.* 2009 |
| Suva (Fiji) 1953 | 14 Sep. | submarine | EA, MS, NM, and RD | M6.7 EQ | Rahiman *et al.* 2007 |
| Unimak (Alaska) 1946 | 1 Apr. | submarine | EA, NM, and RD | M7.4 EQ | Fryer *et al.* 2004; Okal and Synolakis 2004; López and Okal 2006; Okal and Hébert 2007 |
| West of Luzon (China) 1934 | 14 Feb. | submarine | MS, NM, and SC | M7.9 EQ | Okal *et al.* forthcoming |
| Grand Banks (Canada) 1929 | 18 Nov. | submarine | NM, RD, and SC | M7.2 EQ | Heezen and Ewing 1952; Hasegawa and Kanamori 1987; Clague *et al.* 2003; Fine *et al.* 2005 ; |
| Mona Passage (Puerto Rico) 1918 | 11 Oct. | submarine | AT, MS, NM, RD, and SC | M7.5 EQ | López-Venegas *et al.* 2008 |
| Messina (Italy) 1908 | 28 Dec. | submarine | AT, EA, MS, RD, SC, and SS | M7.1 EQ | Billi *et al.* 2008; Billi, Funicello *et al.* 2009; Billi, Minelli *et al.* 2009; Favalli *et al.* 2009; Tinti and Armigliato 2003; this work |
| Southern Calabria (Italy) 1783 | 6 Feb. | submarine | EA, HS, and RD | M5.9 EQ | Gerardi *et al.* 2008; this work |
| Eastern Sicily (Italy) 1693 | 11 Jan. | submarine | HS and RD | M7 EQ | this work. |

AT = tsunami arrival times; EA = eyewitness accounts; EQ = earthquake; HR = hydroacustic record; HS = historical sources; M = magnitude; MS = marine survey; NM = numerical modeling; PD = physical modeling; RD = runup distribution; SC = interruption of submarine cables; SS = surface survey; TG = tide gauge record.

nami, southern Italy. *Geophysical Research Letters* **35**, 6; doi:10.1029/2008GL033251.

Billi, A., R. Funiciello, L. Minelli, C. Faccenna, G. Neri, B. Orecchio, and D. Presti (2009). Reply to comment by Andrea Argnani *et al.* on "On the cause of the 1908 Messina tsunami, southern Italy." *Geophysical Research Letters* **36**, 13; doi:10.1029/2009GL037499.

Billi, A., L. Minelli, B. Orecchio and D. Presti (2009). Runup distribution for the 1908 Messina tsunami in Italy: Observed data versus expected curves. *Bulletin of the Seismological Society of America* **99**, 3,502–3,509.

Boschi, E., E. Guidoboni, and D. Mariotti (1995). Seismic effects of the strongest historical earthquakes in the Syracuse area. *Annals of Geophysics* **38**, 223–253.

Boschi, E., E. Guidoboni, G. Ferrari, P. Gasperini, D. Mariotti, and G. Valensise (2000). Catalogue of strong Italian earthquakes from 461 B.C. to 1997. *Annals of Geophysics* **43**, 609–868.

Bosman, A., F. Bozzano, F. L. Chiocci, and P. Mazzanti (2006). The 1783 Scilla tsunami: Evidences of a submarine landslide as a possible (con?)cause. *Geophysical Research Abstracts* **8**, 10,558.

Bozzano, F., F. L. Chiocci, P. Mazzanti, A. Bosman, D. Casalbore, R. Giuliani, S. Martino, A. Prestininzi, and G. Scarascia Mugnozza (2006). Subaerial and submarine characterization of the landslide responsible for the 1783 Scilla tsunami. *Geophysical Research Abstracts* **8**, 10,422.

Chiocci, F. L., C. Romagnoli, P. Tommasi, and A. Bosman (2008). The Stromboli 2002 tsunamigenic submarine slide: Characteristics and possible failure mechanisms. *Journal of Geophysical Research* **113**, B10; doi:10.1029/2007JB005172.

Clague, J. J., A. Munro, and T. S. Murty (2003). Tsunami hazard and risk in Canada. *Natural Hazards* **28**, 433–461.

D'Agostino, N., A. Avallone, D. Cheloni, E. D'Anastasio, S. Mantenuto, and G. Selvaggi (2008). Active tectonics of the Adriatic region from GPS and earthquake slip vectors. *Journal of Geophysical Research* **113**, B12413; doi:10.1029/2008JB005860.

De Martini, P. M., M. S. Barbano, A. Smedile, F. Gerardi, D. Pantosti, P. Del Carlo, and C. Pirrotta (2010). A unique 4,000 yrs long geological record of multiple tsunami inundations in the Augusta Bay (eastern Sicily, Italy). *Marine Geology* **276**, 42–57.

Di Risio, M., P. De Girolamo, G. Bellotti, A. Panizzo, F. Aristodemo, M. G. Molfetta, and A.,F. Petrillo (2009). Landslide-generated tsunamis runup at the coast of a conical island: New physical model experiments. *Journal of Geophysical Research* **114**, C01009; doi:10.1029/2008JC004858.

Favalli, M., E. Boschi, F. Mazzarini, and M. T. Pareschi (2009). Seismic and landslide source of the 1908 Straits of Messina tsunami (Sicily, Italy). *Geophysical Research Letters* **36**, L16304; doi:10.1029/2009GL039135.

Fine, I. V., A. B. Rabinovich, B. D. Bornhold, R. E. Thomson, and E. A. Kulikov (2005). The Grand Banks landslide-generated tsunami of November 18, 1929: Preliminary analysis and numerical modeling. *Marine Geology* **215**, 45–57.

Fritz, H. M., W. Kongko, A. Moore, B. McAdoo, J. Goff, C. Harbitz, B. Uslu, N. Kalligeris, D. Suteja, K. Kalsum, V. Titov, A. Gusman, H. Latief, E. Santoso, S. Sujoko, D. Djulkarnaen, H. Sunendar, and C. E. Synolakis (2007). Extreme runup from the 17 July 2006 Java tsunami. *Geophysical Research Letters* **34**, L12602; doi:10.1029/2007GL029404.

Fritz, H. M., F. Mohammed, and J. Yoo (2009). Lituya Bay landslide impact generated mega-tsunami 50th anniversary. *Pure and Applied Geophysics* **166**, 153–175.

Fryer, G. J., P. Watts, and L. F. Pratson (2004). Source of the great tsunami of 1 April 1946: A landslide in the upper Aleutian forearc. *Marine Geology* **203**, 201–218.

Galli, P., and V. Bosi (2002). Paleoseismology along the Cittanova fault: Implications for seismotectonics and earthquake recurrence in Calabria (southern Italy). *Journal of Geophysical Research* **107**, 2,044; doi:10.1029/2001JB000234.

Galli, P., F. Galadini, and D. Pantosti (2008). Twenty years of paleoseismology in Italy. *Earth-Science Reviews* **88**, 89–117.

Gerardi, F., M. S. Barbano, P. M. De Martini, and D. Pantosti (2008). Discrimination of tsunami sources (earthquake versus landslide) on the basis of historical data in eastern Sicily and southern Calabria. *Bulletin of the Seismological Society of America* **98**, 2,795–2,805.

Ghisetti, F. (1984). Recent deformations and the seismogenic source in the Messina Strait (southern Italy). *Tectonophysics* **109**, 191–208.

Graziani, L., A. Maramai, and S. Tinti (2006). A revision of the 1783–1784 Calabrian (southern Italy) tsunamis. *Natural Hazards and Earth System Sciences* **6**, 1,053–1,060.

Guidoboni, E., and J. E. Ebel (2009). *Earthquakes and Tsunamis in the Past: A Guide to Techniques in Historical Seismology*. Cambridge: Cambridge University Press.

Guidoboni, E., and G. Traina (1996). Earthquakes in medieval Sicily: A historical review. *Annals of Geophysics* **39**, 1,201–1,225.

Gutscher, M. A., J. Roger, M. A. Baptista, J. M. Mirando, and S. Tinti (2006). Source of the 1693 Catania earthquake and tsunami (southern Italy): New evidence from tsunami modelling of a locked subduction fault plane. *Geophysical Research Letters* **33**, L08309; doi:10.1029/2005GL025442.

Hasegawa, H. S., and H. Kanamori (1987). Source mechanisms of the magnitude 7.2 Grand Banks earthquake of November 1929: Double couple or submarine landslide? *Bulletin of the Seismological Society of America* **77**, 1,984–2,004.

Haeussler, P., H. Lee, H. Ryan, K. Labay, R. Kayen, M. Hampton, and E. Suleimani (2007). Submarine slope failures near Seward, Alaska, during the **M** 9.2 1964 earthquake. In *Submarine Mass Movements and Their Consequences*, ed. V. Lykousis, D. Sakellariou, and J. Locat, 269–278. Springer: available at `http://www.springerlink.com/content/l4688246tn86284m/`

Heezen, B. C., and M. Ewing (1952). Turbidity currents and submarine slumps and the 1929 Grand Banks, Newfoundland earthquake. *American Journal of Science* **250**, 849–873.

Hills, J. G., and C. L. Mader (1997). Tsunami produced by the impact of small asteroids. *Annals of the New York Academy of Science* **822**, 381–394.

Imamura, F., E. Gica, T. Takahashi, and N. Shuto (1995). Numerical simulation of the 1992 Flores Tsunami: Interpretation of tsunami phenomena in the north-eastern Flores Island and damage at Babi Island. *Pure and Applied Geophysics* **144**, 555–568.

Ioualalen, M., S. Mignon, and O. Sardoux (2010). Landslide tsunami vulnerability in the Ligurian Sea: Case study of the 1979 October 16 Nice international airport submarine landslide and of identified geological mass failures. *Geophysical Journal International* **181**, 724–740.

Jacques, E., C. Monaco, P. Tapponier, L. Tortorici, and T. Winter (2001). Faulting and earthquake triggering during the 1783 Calabria seismic sequence. *Geophysical Journal International* **147**, 499–516.

Keefer, D. K. (2002). Investigating landslides caused by earthquakes—A historical review. *Surveys in Geophysics* **23**, 473–510.

Kulikov, E. A., A. B. Rabinovich, R. E. Thomson, and B. D. Bornhold (1996). The landslide tsunami of November 3, 1994, Skagway Harbor, Alaska. *Journal of Geophysical Research* **101**, 6,609–6,615.

Lomax, A., and A. Michelini (2009). M-wpd: A duration-amplitude procedure for rapid determination of earthquake magnitude and tsunamigenic potential from *P* waveforms. *Geophysical Journal International* **176**, 200–214.

López, A. M., and E. A. Okal (2006). A seismological reassessment of the source of the 1946 Aleutian "tsunami" earthquake. *Geophysical Journal International* **165**, 835–849.

López-Venegas, A. M., U. S. ten Brink, and E. L. Geist (2007). Submarine landslide as the source for the October 11, 1918 Mona Passage tsunami: Observations and modelling. *Marine Geology* **254**, 35–46.

Lynett, P. J., J. C. Borrero, P. L. F. Liu, and C. E. Synolakis (1998). Field survey and numerical simulations: A review of the 1998 Papua New Guinea tsunami. *Pure and Applied Geophysics* **160**, 2,119–2,146.

Ma, K.-F., H. Kanamori, and K. Satake (1999). Mechanism of the 1975 Kalapana, Hawaii, earthquake inferred from tsunami data. *Journal of Geophysical Research* **104**, 13,153–13,167.

Marriner, N., and C. Morhange (2007). Geoscience of ancient Mediterranean harbours. *Earth-Science Reviews* **80**, 137–194.

Mattia, M., M. Palano, V. Bruno, and F. Cannavò (2009). Crustal motion along the Calabro-Peloritano arc as imaged by twelve years of measurements on a dense GPS network. *Tectonophysics* **476**, 528–537.

Mercalli, G. (1897). I terremoti della Calabria meridionale e del messinese. *Memorie della Società Italiana delle Scienze* **11**, 117–266.

Mercalli, G. (1909). Contributo allo studio del terremoto calabro-messinese del 28 dicembre 1908. *Atti del Regio Istituto di Incoraggiamento di Napoli* **7**, 249–292.

Minelli, L., and C. Faccenna (2010). Evolution of the Calabrian accretionary wedge (Central Mediterranean). *Tectonics* **29**, TC4004; doi:10.1029/2009TC002562.

Minisini, D., and F. Trincardi (2009). Frequent failure of the continental slope: The Gela Basin (Sicily Channel). *Journal of Geophysical Research* **114**, F03014; doi:10.1029/2008JF001037.

Monaco, C., and L. Tortorici (2000). Active faulting in the Calabrian arc and eastern Sicily. *Journal of Geodynamics* **29**, 407–424.

Murphy, W. (1995). The geomorphological controls on seismically triggered landslides during the 1908 Straits of Messina earthquake, southern Italy. *Quarterly Journal of Engineering Geology and Hydrogeology* **28**, 61–74.

Neri, G., G. Barberi, G. Oliva, and B. Orecchio (2005). Spatial variations of seismogenic stress orientations in Sicily, south Italy. *Physics of the Earth and Planetary Interiors* **148**, 175–191.

Neri, G., B. Oliva, B. Orecchio, and D. Presti (2006). A possible seismic gap within a highly seismogenic belt crossing Calabria and eastern Sicily, Italy. *Bulletin of the Seismological Society of America* **96**, 1,321–1,331.

Nicoletti, P. G. (2005). Inconsistent patterns of historical seismicity and earthquake-triggered landsliding in southeastern Sicily: An alarm bell? *Geomorphology* **65**, 257–278.

Nicoletti, P. G., and M. Parise (2002). Seven landslide dams of old seismic origin in southeastern Sicily (Italy). *Geomorphology* **46**, 203-222.

Okal, E. A., and H. Hébert (2007). Far-field simulation of the 1946 Aleutian tsunami. *Geophysical Journal International* **169**, 1,229–1,238.

Okal, E. A., G. Plafker, C. E. Synolakis, and J. C. Borrero (2003). Near-field survey of the 1946 Aleutian tsunami on Unimak and Sanak Islands. *Bulletin of the Seismological Society of America* **93**, 1,226–1,234.

Okal, E. A., and C. E. Synolakis (2001). Comment on "Origin of the 17 July 1998 Papua New Guinea tsunami: Earthquake or landslide?" by E. L. Geist. *Seismological Research Letters* **72**, 363–366.

Okal, E. A., and C. E. Synolakis (2004). Source discriminants for near-field tsunamis. *Geophysical Journal International* **158**, 899–912.

Okal, E. A., C. E. Synolakis, and N. Kalligeris (forthcoming). Tsunami simulations for regional sources in the South China and adjoining seas. *Pure and Applied Geophysics*.

Okal, E. A, C. E. Synolakis, B. Uslu, N. Kalligeris, and E. Voukouvalas (2009). The 1956 earthquake and tsunami in Amorgos, Greece. *Geophysical Journal International* **178**, 1,533–1,554.

Omori, F. (1909). Preliminary report on the Messina-Reggio earthquake of December 28, 1908. *Bulletin of Imperial Earthquake Investigation Committee* **3**, 37–46 (in Japanese).

Pantano, F. G., P. G. Nicoletti, and M. Parise (2002). Historical and geological evidence for seismic origin of newly recognized landslides in southeastern Sicily, and its significance in terms of hazard. *Environmental Management* **29**, 116–131.

Pantosti, D., M. S. Barbano, A. Smedile, P. M. De Martini, and G. Tigano (2008). Geological evidence of paleotsunamis at Torre degli Inglesi (northeast Sicily). *Geophysical Research Letters* **35**, L05311; doi:10.1029/2007GL032935.

Papadopoulos, G. A., L. I. Lobkovsky, R. K. Mazova, I. A. Garagash, V. Karastathis, L. Y. Kataeva, and V. G. Kaz'min (2007). Numerical modeling of sediment mass sliding and tsunami generation: The case of February 7, 1963, in Corinth Gulf, Greece. *Marine Geodesy* **30**, 315–331.

Pareschi, M. T., E. Boschi, F. Mazzarini, and M. Favalli (2006). Large submarine landslides offshore Mt. Etna. *Geophysical Research Letters* **33**, L13302; doi:10.1029/2006GL026064.

Piatanesi, A., S. Lorito, and F. Romano (2008). Il grande maremoto del 1908: Analisi e modellazione. *In Il Terremoto e il Maremoto del 28 Dicembre 1908*, ed. G. Bertolaso, E. Boschi, E. Guidoboni, and G. Valensise, 183–196. Rome: Dipartimento della Protezione Civile e Istituto Nazionale di Geofisica e Vulcanologia.

Piatanesi, A., and S. Tinti (1998). A revision of the 1693 eastern Sicily earthquake and tsunami. *Journal of Geophysical Research* **103**, 2,749–2,758.

Piatanesi, A., S. Tinti, and E. Bortolucci (1999). Finite-element simulations of the 28 December 1908 Messina Straits (southern Italy) tsunami. *Physics and Chemistry of the Earth* **24**, 145–150.

Pino, N., 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. *Seismological Research Letters* **80**, 243–259.

Plafker, G., R. Kachadoorian, E. Eckel, and L. Mayo (1969). *Effects of the Earthquake of March 27, 1964 on Various Communities*. USGS Professional Paper 542-G, 50 pps.

Platania, G. (1909). Il maremoto dello stretto di Messina del 28 Dicembre 1908. *Bollettino della Società Sismologica Italiana* **13**, 369–458.

Pondrelli, S., S. Salimbeni, G. Ekström, A. Morelli, P. Gasperini, and G. Vannucci (2006). The Italian CMT dataset from 1977 to the present. *Physics of the Earth and Planetary Interiors* **159**, 286–303.

Rahiman, T. I. H., J. R. Pettinga, and P. Watts (2007). The source mechanism and numerical modelling of the 1953 Suva tsunami, Fiji. *Marine Geology*, 237, 55-70.

Rosenau, M., R. Nerlich, S. Brune, and O. Oncken (2010). Experimental insights into the scaling and variability of local tsunamis triggered by giant subduction megathrust earthquakes. *Journal of Geophysical Research* **115**, B09314, doi:10.1029/2009JB007100.

Ryan, W. B. F., and B. C. Heezen (1965). Ionian Sea submarine canyons and the 1908 Messina turbidity current. *Geological Society of America Bulletin* **76**, 915–932.

Scheffers, A., and D. Kelletat (2003). Sedimentologic and geomorphologic tsunami imprints worldwide—a review. *Earth-Science Reviews* **63**, 83–92.

Sirovich, L., and F. Pettenati (2001). Test of source-parameter of the intensities of a 54,000-death shock of the seventeenth century in southeast Sicily. *Bulletin of the Seismological Society of America* **91**, 792–811.

Sulemaini, E., R. Hansen, and P. J. Haeussler (2009). Numerical study of tsunami generated by multiple submarine slope failures in Resurrection Bay, Alaska, during the *Mw* 9.2 1964 earthquake. *Pure and Applied Geophysics* **166**, 131–152.

Synolakis, C. E., J. P. Bardet, J. Borrero, H. Davies, E. Okal, E. Silver, J. Sweet, and D. Tappin (2002). The slump origin of the 1998 Papua New Guinea tsunami. *Proceedings of the Royal Society of London, Series A,* **458**, 763–789.

Synolakis, C. E., J. C. Borrero, G. Plafker, A. Yalçiner, G. Greene, and P. Watts (2000). Modeling the 1994 Skagway, Alaska tsunami. *Eos, Transactions of the American Geophysical Union* **81**, F748 (abstract).

Synolakis, C. E., and U. Kânoğlu (2009). Tsunami modelling. In *Tsunamis*, ed. E. N. Bernard and A. R. Robinson, 237–294. Cambridge, MA: Harvard University Press.

Tappin, D. R., P. Watts, G. M. McMurtry, Y. Lafoy, and T. Matsumoto (2001). The Sissano, Papua New Guinea tsunami of July 1998—offshore evidence on the source mechanism. *Marine Geol*ogy **175**, 1–23.

Tappin, D. R., P. Watts, and S. T. Grilli (2008). The Papua New Guinea tsunami of 17 July 1998: Anatomy of a catastrophic event. *Natural Hazards and Earth System Sciences* **8**, 243–266.

Tappin, D. R., P. Watts, S. T. Grilli, S. Dubosq, A. Billi, N. Pophet, and M. P. Marani (2008). The 1908 Messina tsunami. Some comments on the source: Earthquake, submarine landslide or a combination of both? *Eos, Transactions of the American Geophysical Union* **89** (53), Fall Meeting Supplement, Abstract S41D-07.

Tertulliani, A., and L. Cucci (2009). Clues to the identification of a seismogenic source from environmental effects: The case of the 1905 Calabria (southern Italy) earthquake. *Natural Hazards and Earth System Sciences* **9**, 1,787–1,803.

Tinti, S., and A. Armigliato (2003). The use of scenarios to evaluate the tsunami impact in southern Italy. *Marine Geology* **199**, 221–243.

Tinti, S., A. Armigliato, and E. Bortolucci (2001). Contribution of tsunami data analysis to constrain the seismic source: The case of the 1693 eastern Sicily earthquake. *Journal of Seismology* **5,** 41–61.

Tinti, S., A. Armigliato, E. Bortolucci, and A. Piatanesi (1999). Identification of the source fault of the 1908 Messina earthquake through tsunami modelling. Is it a possible task? *Physics and Chemistry of the Earth* **24**, 417–421.

Tinti, S., A. Armigliato, A. Manucci, G. Pagnoni, F. Zaniboni, A.C. Yalçiner and Y. Altinok (2006). The gene rating mechanisms of the August 17, 1999 İzmit bay (Turkey) tsunami: Regional (tectonic) and local (mass instabilities) causes. *Marine Geology* **225**, 311–330.

Tinti, S., A. Manucci, G. Pagnoni, A. Armigliato, and F. Zaniboni (2005). The 30 December 2002 landslide-induced tsunamis in Stromboli: Sequence of events reconstructed from the eyewitness accounts. *Natural Hazards and Earth System Sciences* **5**, 763–775.

Tinti, S., A. Maramai, and L. Graziani (2004). The new catalogue of Italian tsunamis. *Natural Hazards* **33**, 439–465.

Valensise, L., and D. Pantosti (1992). A 125 kyr-long geological record of seismic source repeatability: The Messina Straits (southern Italy) and the 1908 earthquake ($Ms$ = 7½). *Terra Nova* **4**, 472–483.

Visini, F., R. De Nardis, M. S. Barbano, and G. Lavecchia (2009). Testing the seismogenic sources of the January 11th 1693 Sicilian earthquake (Io X/XI): Insights from macroseismic field simulations. *Italian Journal of Geosciences* **128**, 147–156.

Watts, P., S. T. Grilli, J. T. Kirby, G. J. Fryer, and D. R. Tappin (2003). Landslide tsunami case studies using a Boussinesq model and a fully nonlinear tsunami generation model. *Natural Hazards and Earth System Sciences* **3**, 391–402.

Weiss, R., H. M. Fritz, and K. Wünnemann (2009). Hybrid modeling of the mega-tsunami runup in Lituya Bay after half a century. *Geophysical Research Letters* **36**, L09602; doi:10.1029/2009GL037814.

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