

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).

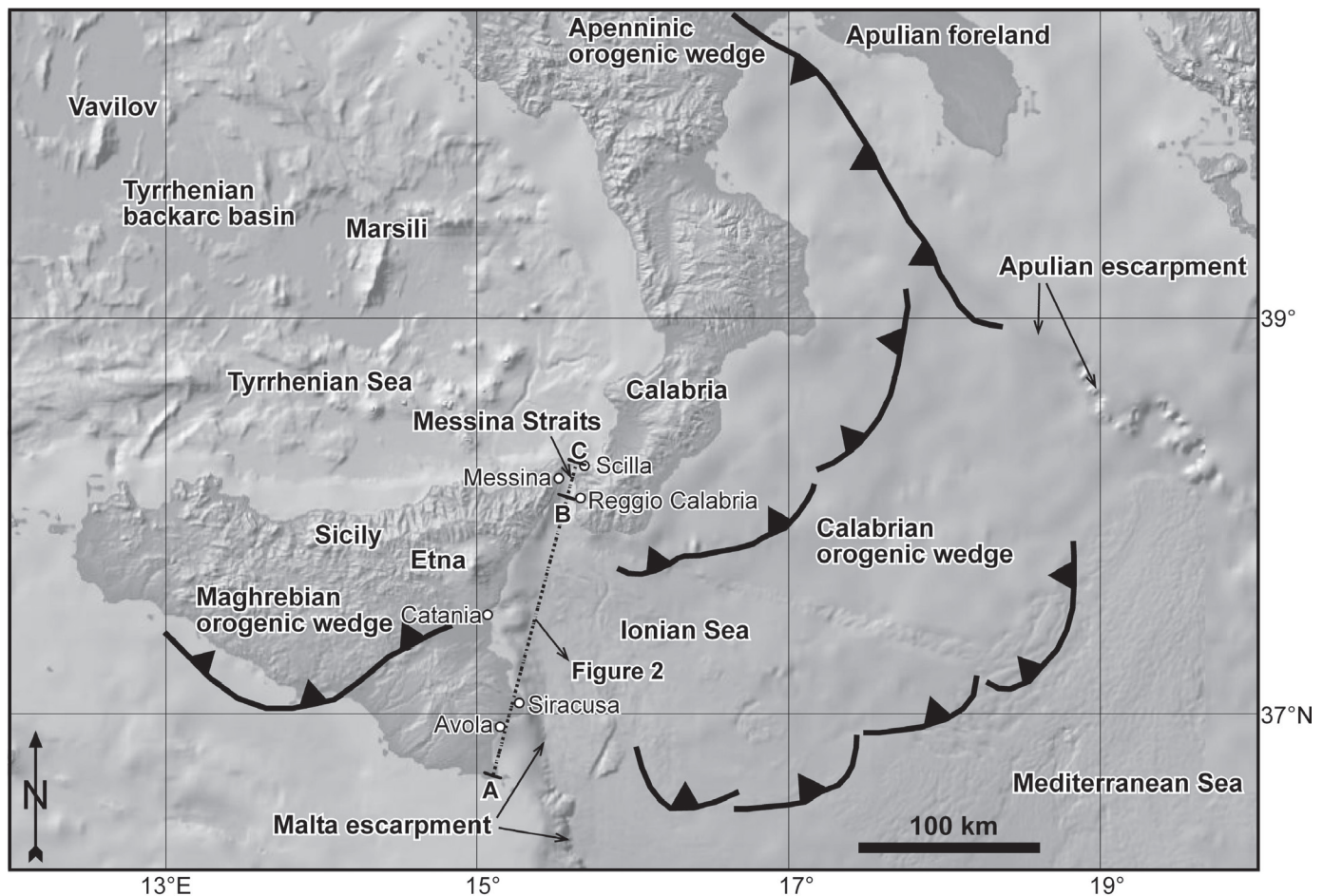
Eastern Sicily and southern Calabria front the Messina Straits in southern Italy and have been affected by recent and historical destructive earthquakes and tsunamis (Boschi *et al.* 2000; Tinti *et al.* 2004; Neri *et al.* 2006; Pareschi *et al.* 2006; Galli *et al.* 2008; Gerardi *et al.* 2008; Pantosti *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 K anođlu 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:

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

where ζ 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_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

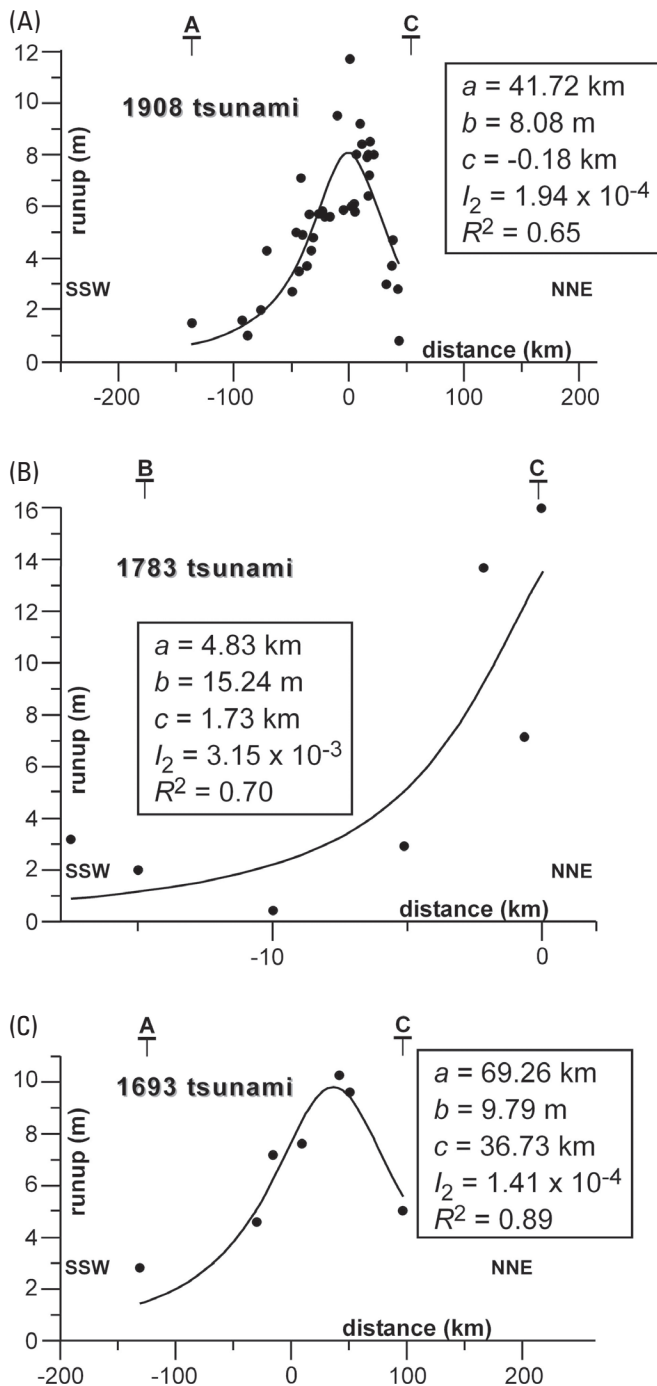
earthquake and tsunami waves to the coasts (Billi *et al.* 2008), and the ratio, I_1 , between the measured maximum runup and the hypothetical coseismic slip (*i.e.*, I_1 is between 2.7 and 6.0; Billi, Minelli *et al.* 2009). In particular, the interruption of submarine cables and evidence of submarine 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 Micheline (2009), according to whom destructive earthquake-tsunamis are unlikely for earthquakes with $M \leq 7.5$ (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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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 <i>et al.</i> 2007
Stromboli (Italy) 2002	30 Dec.	subaerial and submarine	EA, MS, PM, and SS	volcanism	Tinti <i>et al.</i> 2005; Chiocci <i>et al.</i> 2008; Di Risio <i>et al.</i> 2009
Izmit (Turkey) 1999	17 Aug.	subaerial and submarine	EA, NM, and RD	M7.4 EQ	Tinti <i>et al.</i> 2006
Sissano (Papua New Guinea) 1998	17 Jul.	submarine	HR, MS, and RD	M7.1 EQ	Okal and Synolakis 2001, 2004; Tappin <i>et al.</i> 2001; Synolakis <i>et al.</i> 2002
Skagway (Alaska) 1994	3 Nov.	subaerial	EA, RD, and TG	low tide	Kulikov <i>et al.</i> 1996; Synolakis <i>et al.</i> 2000
Flores (Indonesia) 1992	12 Dec.	submarine	NM and RD	M7.5 EQ	Imamura <i>et al.</i> 1995; Watts <i>et al.</i> 2003
Nice (France) 1979	16 Oct.	subaerial and submarine	EA, MS, and NM	building operations	Assier-Rzadkiewicz <i>et al.</i> 2000; Ioualalen <i>et al.</i> 2010
Hawaii 1975	29 Nov.	submarine	NM, RD, and TG	M7.2 EQ	Ma <i>et al.</i> 1999
Prince William Sound (Alaska) 1964	28 Mar.	subaerial and submarine	EA, MS, NM, RD, and SS	M9.2 EQ	Plafker <i>et al.</i> 1969; Haeussler <i>et al.</i> 2007; Sulemaini <i>et al.</i> 2009
Corinth Gulf (Greece) 1963	7 Feb.	submarine	NM, RD, and SS	gravity	Papadopoulos <i>et al.</i> 2007
Lituya Bay (Alaska) 1958	10 Jul.	subaerial	EA, PM, RD, and SS	M8.3 EQ	Fritz <i>et al.</i> 2009; Weiss <i>et al.</i> 2009
Amorgos (Greece) 1956	9 Jul.	submarine	EA, NM, and RD	M7.8 EQ	Ambraseys 1960; Okal <i>et al.</i> 2009
Suva (Fiji) 1953	14 Sep.	submarine	EA, MS, NM, and RD	M6.7 EQ	Rahiman <i>et al.</i> 2007
Unimak (Alaska) 1946	1 Apr.	submarine	EA, NM, and RD	M7.4 EQ	Fryer <i>et al.</i> 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 <i>et al.</i> forthcoming
Grand Banks (Canada) 1929	18 Nov.	submarine	NM, RD, and SC	M7.2 EQ	Heezen and Ewing 1952; Hasegawa and Kanamori 1987; Clague <i>et al.</i> 2003; Fine <i>et al.</i> 2005;
Mona Passage (Puerto Rico) 1918	11 Oct.	submarine	AT, MS, NM, RD, and SC	M7.5 EQ	López-Venegas <i>et al.</i> 2008
Messina (Italy) 1908	28 Dec.	submarine	AT, EA, MS, RD, SC, and SS	M7.1 EQ	Billi <i>et al.</i> 2008; Billi, Funicello <i>et al.</i> 2009; Billi, Minelli <i>et al.</i> 2009; Favalli <i>et al.</i> 2009; Tinti and Armigliato 2003; this work
Southern Calabria (Italy) 1783	6 Feb.	submarine	EA, HS, and RD	M5.9 EQ	Gerardi <i>et al.</i> 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 = hydroacoustic 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.

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