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

Andrea Billi,1 Liliana Minelli,2,3 Barbara Orecchio,4,5 and Debora Presti2,5

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 Kellett 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 Morthange 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

1. Istituto di Geologia Ambientale e Geoingegneria, CNR, Rome, Italy
2. Dipartimento di Scienze Geologiche, Università Roma Tre, Rome, Italy
3. Dipartimento di Scienze della Terra, Università di Messina, Messina, Italy
4. Dipartimento di Fisica, Università della Calabria, Cosenza, Italy
5. Now at Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
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:

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

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...
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 ($I_b$) 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, $I_b$, between the measured maximum runup and the hypothetical coseismic slip (i.e., $I_b$ 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 Parisi 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%

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

Key: $I_b$ = 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, Duboq 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.
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 abovementioned 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 coastal 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.,
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 tsunami improve the statistics of Lomax and Michelini (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.

ACKNOWLEDGMENTS

This study was conceived and stimulated by Prof. Renato Funiciello during his last days of life. His love for historical studies and for the education of young scientists will be forever a model for us. We thank C. Faccenna and G. Neri for their encouragement, E. Okal for a thorough and constructive review, and L. Astiz and her staff for the editorial work.

REFERENCES


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 SS3A-1019.


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.

<table>
<thead>
<tr>
<th>Site and Year</th>
<th>Day and Month</th>
<th>Landslide</th>
<th>Main Constraints</th>
<th>Landslide Cause</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nusa Kambangan (Java) 2006</td>
<td>17 Jul.</td>
<td>submarine</td>
<td>NM, and RD</td>
<td>M7.8 EQ</td>
<td>Fritz et al. 2007</td>
</tr>
<tr>
<td>Stromboli (Italy) 2002</td>
<td>30 Dec.</td>
<td>subaerial and submarine</td>
<td>EA, MS, PM, PM, SS</td>
<td>volcanism</td>
<td>Tinti et al. 2005; Chiocci et al. 2008; Di Risio et al. 2009</td>
</tr>
<tr>
<td>Izmit (Turkey) 1999</td>
<td>17 Aug.</td>
<td>subaerial and submarine</td>
<td>EA, NM, and RD</td>
<td>M7.4 EQ</td>
<td>Tinti et al. 2006</td>
</tr>
<tr>
<td>Flores (Indonesia) 1992</td>
<td>12 Dec.</td>
<td>submarine</td>
<td>NM and RD</td>
<td>M7.5 EQ</td>
<td>Imamura et al. 1995; Watts et al. 2003</td>
</tr>
<tr>
<td>Nice (France) 1979</td>
<td>16 Oct.</td>
<td>subaerial and submarine</td>
<td>EA, MS, and NM</td>
<td>building operations</td>
<td>Assier-Rzadkiewicz et al. 2000; Ioulalalen et al. 2010</td>
</tr>
<tr>
<td>Hawaii 1975</td>
<td>29 Nov.</td>
<td>submarine</td>
<td>NM, RD, and TG</td>
<td>M7.2 EQ</td>
<td>Ma et al. 1999</td>
</tr>
<tr>
<td>Corinth Gulf (Greece) 1963</td>
<td>7 Feb.</td>
<td>submarine</td>
<td>NM, RD, and SS</td>
<td>gravity</td>
<td>Papadopoulos et al. 2007</td>
</tr>
<tr>
<td>Amorgos (Greece) 1956</td>
<td>9 Jul.</td>
<td>submarine</td>
<td>EA, NM, and RD</td>
<td>M7.8 EQ</td>
<td>Ambraseys 1960; Okal et al. 2009</td>
</tr>
<tr>
<td>Suva (Fiji) 1953</td>
<td>14 Sep.</td>
<td>submarine</td>
<td>EA, MS, NM, and RD</td>
<td>M6.7 EQ</td>
<td>Rahiman et al. 2007</td>
</tr>
<tr>
<td>Unimak (Alaska) 1946</td>
<td>1 Apr.</td>
<td>submarine</td>
<td>EA, NM, and RD</td>
<td>M7.4 EQ</td>
<td>Fryer et al. 2004; Okal and Synolakis 2004; López and Okal 2008; Okal and Hébert 2007</td>
</tr>
<tr>
<td>West of Luzon (China) 1934</td>
<td>14 Feb.</td>
<td>submarine</td>
<td>MS, NM, and SC</td>
<td>M7.9 EQ</td>
<td>Okal et al. forthcoming</td>
</tr>
<tr>
<td>Grand Banks (Canada) 1929</td>
<td>18 Nov.</td>
<td>submarine</td>
<td>NM, RD, and SC</td>
<td>M7.2 EQ</td>
<td>Heezen and Ewing 1952; Hasegawa and Kanamori 1987; Clague et al. 2003; Fine et al. 2005</td>
</tr>
<tr>
<td>Mona Passage (Puerto Rico) 1918</td>
<td>11 Oct.</td>
<td>submarine</td>
<td>AT, MS, NM, RD, and SC</td>
<td>M7.5 EQ</td>
<td>López-Venegas et al. 2008</td>
</tr>
<tr>
<td>Messina (Italy) 1908</td>
<td>28 Dec.</td>
<td>submarine</td>
<td>AT, EA, MS, RD, SC, and SS</td>
<td>M7.1 EQ</td>
<td>Billi et al. 2008; Billi, Funicello et al. 2009; Billi, Minelli et al. 2009; Favalli et al. 2009; Tinti and Armigliato 2003; this work</td>
</tr>
<tr>
<td>Southern Calabria (Italy) 1783</td>
<td>6 Feb.</td>
<td>submarine</td>
<td>EA, HS, and RD</td>
<td>M5.9 EQ</td>
<td>Gerardi et al. 2008; this work</td>
</tr>
<tr>
<td>Eastern Sicily (Italy) 1693</td>
<td>11 Jan.</td>
<td>submarine</td>
<td>HS and RD</td>
<td>M7 EQ</td>
<td>this work.</td>
</tr>
</tbody>
</table>

**Note:**
- **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


Istituto di Geologia Ambientale e Geoingegneria, CNR Area della Ricerca Roma 1 Via Salaria km 29,300 Monterotondo, 00015, Rome, Italy andrea.billi@cnr.it (A. B.)