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Key Points:
- A new fault zone named Fiumefreddo-Melito di Porto Salvo Fault Zone is discovered in the outer Messina Strait, Southern Italy
- A 60 m high escarpment at the seafloor characterizes this fault zone as the most prominent active feature in the outer Messina Strait
- Numerical modeling revealed that this fault zone can generate tsunami amplitudes exceeding 2 m by assuming a fault slip of 5 m

Supporting Information:
- Supporting Information S1

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Tsunamigenic potential of a newly discovered active fault zone in the outer Messina Strait, Southern Italy

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Abstract The 1908 Messina tsunami was the most catastrophic tsunami hitting the coastline of Southern Italy in the younger past. The source of this tsunami, however, is still heavily debated, and both rupture along a fault and a slope failure have been postulated as potential origin of the tsunami. Here we report a newly discovered active Fiumefreddo-Melito di Porto Salvo Fault Zone (F-MPS_FZ), which is located in the outer Messina Strait in a proposed landslide source area of the 1908 Messina tsunami. Tsunami modeling showed that this fault zone would produce devastating tsunamis by assuming slip amounts of ≥5 m. An assumed slip of up to 17 m could even generate a tsunami comparable to the 1908 Messina tsunami, but we do not consider the F-MPS_FZ as a source for the 1908 Messina tsunami because its E-W strike contradicts seismological observations of the 1908 Messina earthquake. Future researches on the F-MPS_FZ, however, may contribute to the tsunami risk assessment in the Messina Strait.

1. Introduction

The continental margins of Southern Italy are located along converging plate boundaries (Figure 1a), which are affected by intense seismicity and volcanic activities. Most of the coastal areas experienced severe earthquakes, landslides, and tsunamis in historical and/or modern times. There are three prominent examples since the 17th century: the Sicily earthquake of 11 January 1693 ($M_w = 7.4$; 60,000 casualties) [*Guidoboni et al.*, 2007], the Calabrian earthquake of 1783 ($M_w = 5.9$–7.0; 32,000–50,000 casualties) [*Jacques et al.*, 2002], and the Messina earthquake of 28 December 1908 ($M_w = 7.1$; 80,000 casualties) [*Platania*, 1909; *Baratta*, 1910]. All were followed by significant tsunamis [*Platania*, 1909; *Baratta*, 1910; *Jacques et al.*, 2002; *Guidoboni et al.*, 2007]. The 1693 Sicily earthquake struck parts of Southern Italy near Sicily, Calabria, and Malta [*Armigliato et al.*, 2007]. The epicenter of the earthquake was probably close to the coast, possibly offshore, although the exact position remains unknown [*Armigliato et al.*, 2007]. The 1783 Calabrian earthquake was a sequence of five strong earthquakes that hit Calabria in Southern Italy. The isoseismal areas were elongated NE-SW [*Somma*, 2004].

Numerous fault models were put forward as the seismogenic fault for the 1908 Messina event (Figure 1b). NW- or WNW-dipping faults were proposed based on macroseismic, tectonic, and morphological data [*Amoruso et al.*, 2002], while E-dipping faults were suggested based on leveling data, geodetic data, and the geological study of the state of deformation of a 125 ka marine terrace [*Valensise and Pantosti*, 1992]. Most authors suggested an NNW-SSE-trending normal fault in the Messina Strait as the seismogenic fault for the 1908 event [*Amoruso et al.*, 2002; *Tinti and Armigliato*, 2003; *Argnani et al.*, 2009a; *Favalli et al.*, 2009].

The 1908 Messina earthquake generated the worst tsunami that Italy experienced in historical times (~2000 casualties) [*Platania*, 1909; *Baratta*, 1910] and the most destructive tsunami in Europe since then, in terms of runup height (>10 m) [*Platania*, 1909] (Figure 1b) and the impacted area [*Soloviev et al.*, 2000]. It hit the entire coast of the Messina Strait (Figure 1b). The southern inner Messina Strait was hit by higher tsunami runup heights (5–10 m) than the northern part (1–3 m). The highest runup heights (up to 12 m) were reported south of Galati and Reggio Calabria (Figure 1b).

As the tsunami was assumed to be triggered by the coseismic seafloor displacement during the 1908 Messina earthquake [*Tinti and Armigliato*, 2003], several tsunami modeling studies have been conducted based on

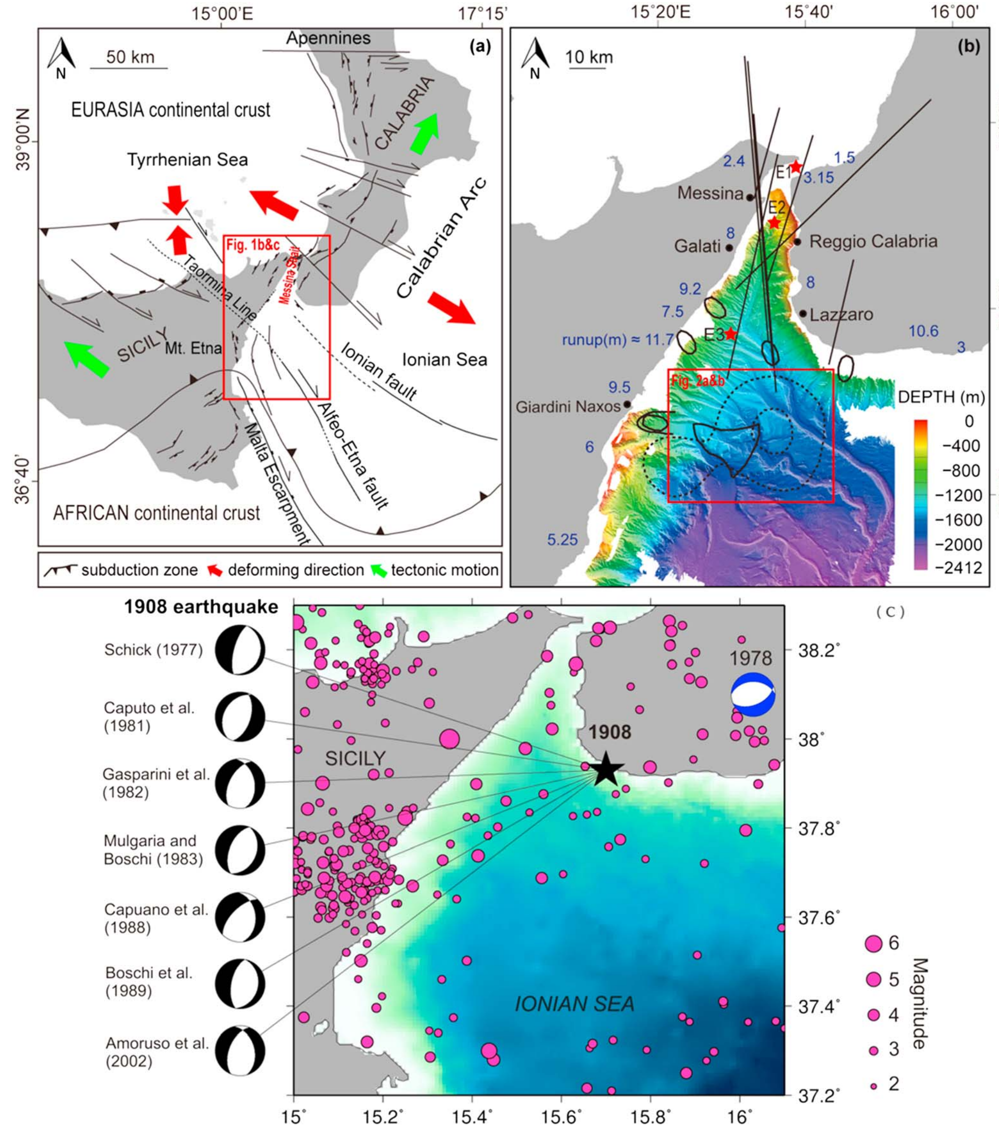

Figure 1. (a) Tectonic and structural elements of Southern Italy modified after *Pino et al.* [2000] and *Favalli et al.* [2009]. (b) Previously proposed source models of the 1908 Messina earthquake and tsunami. The black straight lines show the strike directions of suggested seismogenic faults. Fault orientations and sizes are adapted from *Schick et al.* [1977], *Mulargia and Boschi* [1983], *Bottari et al.* [1986], *Capuano et al.* [1988], *Boschi et al.* [1989], *De Natale and Pingue* [1991], *Valensise and Pantosti* [1992], and *Amoruso et al.* [2002]. The red stars, E1 [*Baratta*, 1910], E2 [*Baratta*, 1910; *Neri et al.*, 2004], and E3 [*Rovida et al.*, 2011], show the suggested locations of the epicenter of the 1908 Messina earthquake. The dashed lines show the most likely 1908 Messina tsunami generation area [*Billi et al.*, 2008]. The solid lines outline the landslide bodies proposed by *Billi et al.* [2008] and *Favalli et al.* [2009] but doubted by *Argnani et al.* [2009b] and *Gross et al.* [2014]. The numbers along the coasts indicate the observed runup heights in meters of the 1908 Messina tsunami [*Billi et al.*, 2008]. (c) Background seismicity of the region (pink circles) according to USGS catalog for the period of 1900–2016 (http://earthquake.usgs.gov/earthquakes/). The red box in Figure 1a marks the geographical area shown in Figures 1b, 1c, and S2, while the red box in Figure 1b shows the area discussed in this manuscript and shown in Figures 2a and 2b. The blue focal mechanism is from the Global Centroid-Moment-Tensor catalog (http://www.globalcmt.org/). The summary of available fault plane solutions for the 1908 Messina earthquake is shown by the black focal mechanism to the left of the map. The star is the epicenter of the 1908 event according to *Pino et al.* [2009].

most common fault solutions [*Tinti and Armigliato*, 2003; *Favalli et al.*, 2009] (Figure 1b), but none of them meets all observations [*Gerardi et al.*, 2008]. Hence, *Billi et al.* [2008] and *Favalli et al.* [2009] postulated that the 1908 Messina tsunami may have been triggered by a submarine landslide caused by the earthquake. Such a landslide was reported to be located in the outer Messina Strait off Giardini Naxos and Lazzaro (Figure 1b). This scenario, however, was doubted by some authors [*Argnani et al.*, 2009b; *Gross et al.*, 2014]

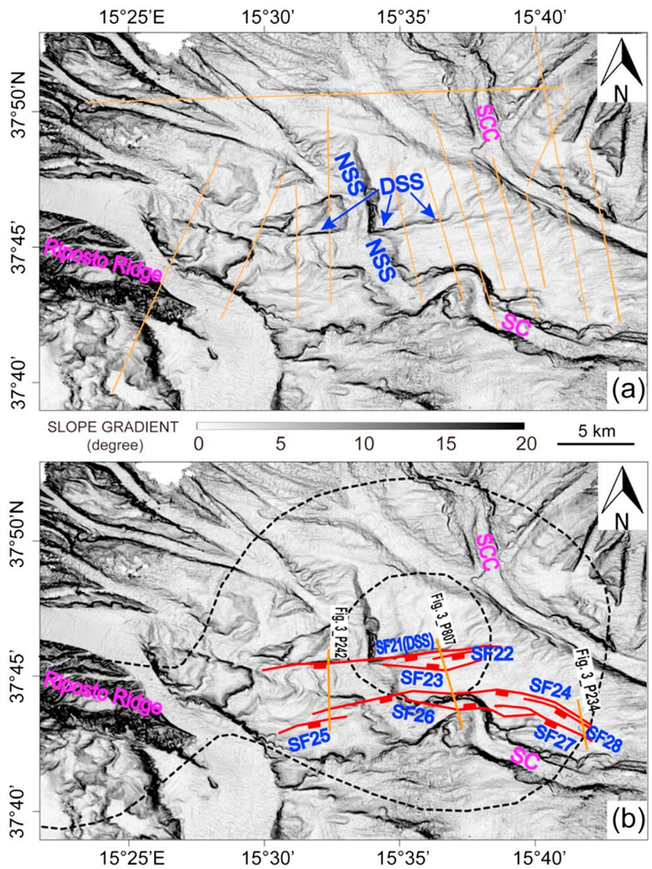

Figure 2. (a) Slope gradient map of the outer Messina Strait with location of 2-D seismic survey lines. Abbreviations: DSS, dominant scarp-like structure; NSS, N-S trending scarp-like structure; SCC, South Calabria Canyon [*Ridente et al.*, 2014]; SC, South Canyon. The orange solid lines show available 2-D seismic survey lines. (b) Fault pattern of the outer Messina Strait. The survey lines here correspond to the seismic profiles shown in Figure 3. The dashed lines circle out the source area proposed by *Billi et al.* [2008] for the 1908 Messina tsunami. See Figure 1b for location of the map.

as new high-resolution bathymetric and seismic data do not show indications for a recent submarine landslide in this area. Overall, from the published literature, it can be possibly inferred that tectonic-only or landside-only sources are unable to reproduce the available observations of this event; therefore, it is fair to speculate that a dual source mechanism (both earthquake and landslide) was involved [*David Tappin*, 2016, written communication].

So far, mainly because of the unclear tectonics in the Messina Strait and the uncertain mechanisms of the 1908 event, no general agreement has been achieved on the source of this event. *Billi et al.* [2008] suggested a new possible location within the outer Messina Strait as a source area, which is consistent with the travel times reported in the chronicles for the 1908 Messina tsunami [*Platania*, 1909; *Baratta*, 1910]. To improve the understanding of the newly proposed tsunami source area, we launched the R/V *Meteor Cruise M86/2* in this area and discovered a prominent fault zone based on new high-resolution hydroacoustic and 2-D seismic data presented in this study. The objectives of this study are therefore to (a) describe this newly discovered fault zone, (b) to assess its tsunamigenic potential based on numerical tsunami modeling, and (c) to evaluate any possible compatibility as a source for the 1908 Messina tsunami.

2. Data Sets and Methods

High-resolution 2-D reflection seismic (Figure 2a) and multibeam echosounder data were acquired during R/V *Meteor Cruise M86/2* off Southern Italy from 27 December 2011 to 17 January 2012. Additional high-resolution bathymetric data, collected in the frame of the MaGIC project (Marine Geohazards along the Italian Coasts [*Chiocci and Ridente*, 2011]), were assessed for this study as well.

High-resolution 2-D reflection seismic data were collected by using a 162.5 m long, 104-channel digital Geometrics GeoEel streamer. The seismic signal was generated by means of a 1.7 L GI gun, operated in harmonic mode with a shot interval of 4 s. With this configuration, a sub-bottom penetration of up to 1 s two-way travel time was achieved in the area [*Gross et al.*, 2016]. The processing steps included geometry setup, binning, band-pass filtering (low truncation frequency/low cut frequency/high cut frequency/high truncation frequency: 10/20/600/1000 Hz), normal moveout (NMO) correction, stacking, and time migration. The lateral bin size was set to 2 m. A constant sound velocity of 1500 m/s was applied during NMO corrections and data migration because the short length of the streamer does not allow a reliable velocity analysis.

Tsunami modeling was performed by the nonlinear shallow water code TUNAMI-N2, developed at Tohoku University, Japan [*Goto et al.*, 1997]. TUNAMI-N2, which solves governing equations of water motions by using the leapfrog scheme of finite differences on a Cartesian coordinate system, has been validated by using experimental and field data [*Synolakis and Bernard*, 2006] and has been applied to several worldwide tsunamigenic zones [*Yalçiner et al.*, 2004; *Heidarzadeh et al.*, 2009; *Suppasri et al.*, 2011]. We applied a 30 arc sec bathymetric grid, which was generated by us based on the available multibeam data. Simulations were conducted by using a time step of 2 s and for a total simulation time of 12 h to account for possible reflected waves as the region is geographically narrow and several reflections are expected. Coseismic seafloor deformation was calculated by using the analytical formula by *Okada* [1985], which solves the dislocation problem on a half space. Fault parameters used for coseismic seafloor calculations are strike, dip, rake angles, top depth of the fault, length and width of the fault, and the slip amount (see Table S1 in the supporting information). Parts of these parameters were taken from the seismic data (e.g., fault length, strike, and dip); several runs were conducted for parameters that could not be determined by the seismic data (e.g., slip amount). The observed runup heights and arrival times of the 1908 Messina tsunami were taken as references to test the simulated results. Parameters K and k were applied to examine how much our simulated data fit to the observed data, according to the following equations [*Aida*, 1977]:

$$\log K = \frac{1}{N}\sum_{i=1}^{N} \log\left(\frac{\mathrm{Obs}_i}{\mathrm{Sim}_i}\right) \quad (1)$$

$$\log \mathrm{k} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\left(\log\frac{\mathrm{Obs}_i}{\mathrm{Sim}_i}\right)^2 - (\log K)^2\right]} \quad (2)$$

in which N is the total number of data and Obs_i and Sim_i are the observed and simulated values, respectively. If the observed and simulated values are the same, then K will be 1. If K is less than 1, then the simulations overestimate the observations and vice versa. Earthquake scaling laws of *Wells and Coppersmith* [1994] were used to make connections between rupture length and maximum slip values as below:

$$\log D = -1.98 + 1.51 \log L \quad (3)$$

in which D is maximum slip in m and L is rupture length in km. Earthquake moment magnitude (M_w) was estimated by using the equation of *Kanamori* [1977]:

$$M_w = \frac{2}{3}(-16.1 + \log M_0) \quad (4)$$

in which M_0 is seismic moment in Nm which is the product of rupture length (L), rupture width (W), slip (D), and Earth rigidity (μ, assumed to be 3×10^{10} Nm^{-2}).

3. Results

3.1. The Fiumefreddo-Melito di Porto Salvo Fault Zone

Figures 2 and 3 show the pattern of the newly discovered fault zone, the Fiumefreddo-Melito di Porto Salvo Fault Zone (F-MPS_FZ) in the outer Messina Strait. Apart from the remarkable canyons observable at the seafloor, the most eye-catching feature is a "dominant scarp-like structure" (DSS; Figure 2a). It is located in the center of the outer Messina Strait in the landslide source area proposed by *Billi et al.* [2008] for the 1908 Messina tsunami. The DSS strikes E-W, terminating west of the South Calabria Canyon (SCC) [*Ridente et al.*, 2014] and cutting across the South Canyon (SC) with its western segment (Figure 2a). The DSS is ~13 km long and on average ~60 m high.

Seismic profiles P234, P807, and P242, crossing the F-MPS_FZ (Figures 2b and 3), are shown as representative sections covering all the major surface faults that offset the seafloor and abundant minor faults. In general, the subsurface of the outer Messina Strait shows a well-stratified sedimentary succession (Figure 3). All profiles show patterns of major and minor faults (Figure 3). Major faults could be traced between profiles, while minor faults were identified only on a single profile. The major faults SF21-28 (Figures 2b and 3) form the E-W-striking F-MPS_FZ (Figure 2b). This fault zone is ~20 km long in the E-W direction and ~15 km wide in the N-S direction. Most of the faults in this fault zone are dipping toward the south (Figure 3) with apparent dip angles of ~60°. The seismic sections clearly show dominant normal components for all faults.

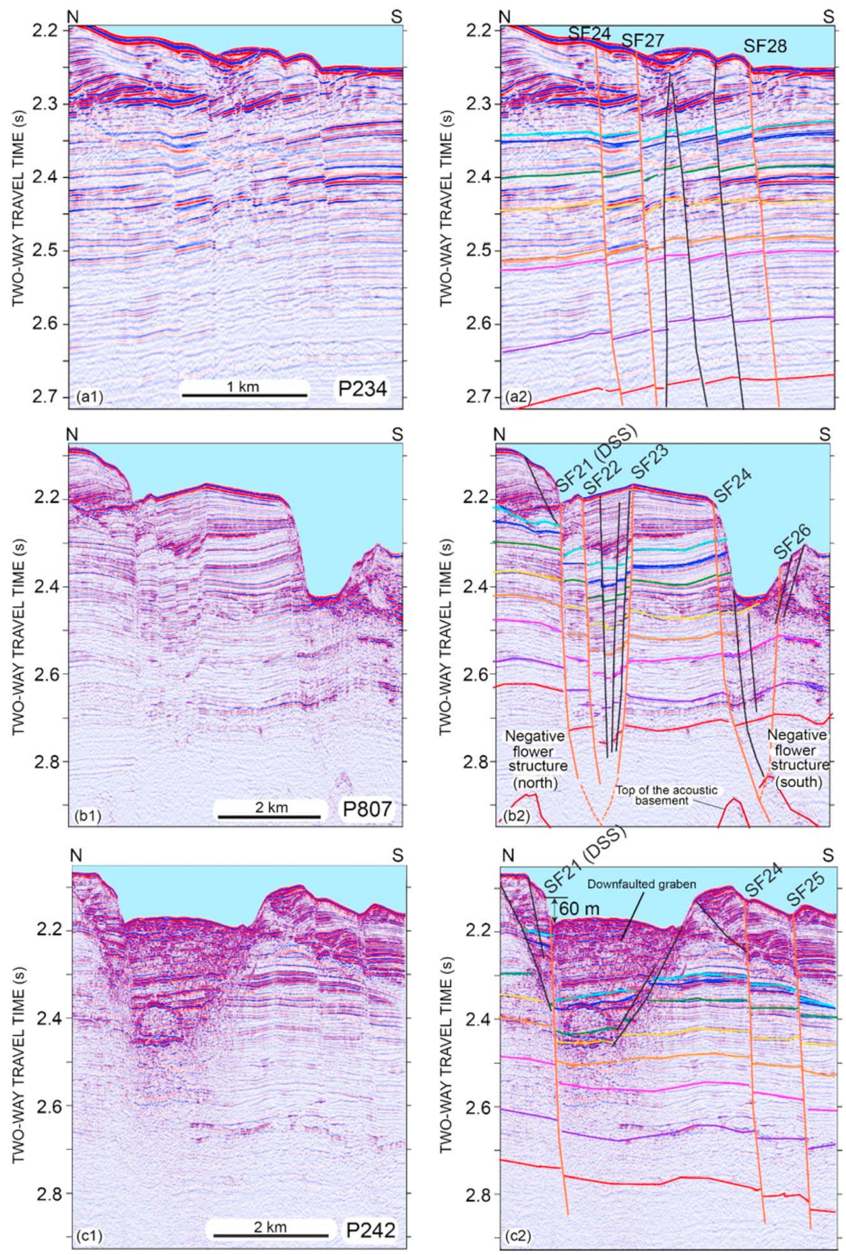

Figure 3. (left) Uninterpreted and (right) interpreted seismic sections across the F-MPS_FZ. See Figure 2b for the location of seismic profiles. The orange subvertical lines mark major faults; the dashed lines indicate uncertain sections of the faults. Minor faults are marked in black. The solid colored horizontal lines show picked horizons.

Two well-developed negative flower structures have been recognized on the seismic profile P807 (Figure 3). They are located in the core region of the tsunamigenic landslide source area proposed by *Billi et al.* [2008] (Figure 2b). The horizontal width across the negative flower structure is 1–2 km. SF21 and SF24 are master faults of the northern and the southern negative flower structures, respectively. All major faults in the F-MPS_FZ are outcropping at the seafloor (Figure 3), indicating that this fault zone is currently active. Current activity is supported by the results of fault activity reconstructions (Figure S1 in the supporting information). The F-MPS_FZ has been active during its development, especially during the ongoing phase of transtension. SF21 is the primary fault and the most important contributor to the F-MPS_FZ. However, we could not give recurrence intervals or periods of highest fault activities because no age control is available for any of the picked reflectors. Hence, we cannot link the reconstructed fault history to the overall tectonic evolution of the Messina region. The DSS is exactly the surface expression of SF21 (Figures 2b and 3b2 and 3c2).

SF21 shows larger vertical offset (>60 m) than other faults (<20 m). It is a south dipping fault with a ~60° apparent dip angle. Fault parameters are summarized in Table S1.

3.2. Numerical Modeling of Tsunami

We modeled possible tsunamis from the F-MPS_FZ and compared the simulated coastal wave heights and arrival times with those observed during the 1908 Messina tsunami. Four different tsunami scenarios have been modeled, using the following fault parameters: strike: 83°, dip: 58°, rake: −90° (=270°), length: 20 km (consistent with the length of the total length of the new fault zone), width: 15 km, the depth of the top of the fault: 1.5 km, and various slip amounts: 1, 5, 10, and 17 m. The first scenario with slip of 1 m is a realistic scenario because the expected slip from a fault with the length of 20 km is ~1 m according to the scaling relationships of *Wells and Coppersmith* [1994] (see equation (3)). The other three scenarios with slip values of 5, 10, and 17 m are hypothetical scenarios. By using the seismic moment magnitude equation of *Kanamori* [1977] (equation (4)), these four scenarios are equivalent to earthquakes with moment magnitudes (M_w) of 6.6, 7.1, 7.3, and 7.4. For all scenarios, the strike, dip, rake angles, length, width, and top depth were the same; only the slip amounts were changed. Among these parameters, the dip and the top depth of the fault were taken from seismic data (Figure 3 and Table S1). The strike angle, length, and the width of the fault zone were estimated by combining bathymetric and seismic data (Figures 2b and 3 and Table S1). Normal fault (rake = −90°) mechanisms were considered for all scenarios as the seismic data (Figure 3) suggest dominant normal faulting mechanisms in recent times.

Figure 4 presents the results of tsunami simulations, which are compared with both coastal runup heights (Figures 4a–4d) and arrival times (Figure 4e) reported after the 1908 Messina tsunami. Figures 4a–4d show that a fault with a slip of <5 m would not cause a significant tsunami. According to Figures 4d and 4e, a fault with a slip of 17 m is able to fairly reproduce the runup heights and arrival times of a tsunami comparable to those observed during the 1908 Messina tsunami.

4. Discussion

The E-W trending F-MPS_FZ is cutting across the dominant NW-SE regional structures in the outer Messina Strait (Figure S2). We speculate that the F-MPS_FZ has a left-lateral strike-slip component. *A* ~ N115°E extension [*D'Agostino and Selvaggi*, 2004; *Catalano et al.*, 2008] (Figure 1a) and a clockwise rotation (Figure S3) of the Messina Strait would likely result in a left-lateral F-MPS_FZ. The dislocation of the NSS cutting across the DSS (Figure 2a) suggests a left-lateral F-MPS_FZ as well, but we need to point out that we cannot exclude erosional processes, as this area is shaped by a complex pattern of canyons.

The apparent displacements (half of them >10 m; Table S1 and Figure 3) of the faults in the F-MPS_FZ seem to be large enough for generating destructive tsunamis. The largest uncertainty is how many earthquakes had contributed to the slips of faults. We tested a large range of slips between 1 and 17 m to understand the effect of different slip values on tsunami generation. In each case, the slip is assumed to occur in one event. Parameters *K* and *k* were applied to examine the goodness of match between observations and simulations under each case. The parameter *K* for Figures 4d and 4e are 1.1 and 0.86 for the runup heights and arrival times, respectively, which are closer to 1 when compared with the *K* values of other scenarios, indicating that Figure 4d would generate a tsunami similar to the 1908 Messina tsunami. One of the main difficulties of tectonic source models proposed in the past for the 1908 Messina tsunami was the lack of match between observations and simulations along the coast of Sicily (coast A in Figures 4a–4d) [*Piatanesi et al.*, 1999]. Our scenario gives acceptable results along the coast of Sicily (coast A in Figure 4d).

In our three hypothetical scenarios, the slip amount is ranging from 5 to 17 m (Figures 4b–4d). According to empirical relationships between fault length and slip [*Wells and Coppersmith*, 1994], the maximum predicated slip from a fault with length of 20 km is ~1 m. However, large fault offsets of up to 60 m (Table S1) are indicated by the seismic profiles, although it is unlikely that such large slips occurred during one or a few events, but the seismic profiles (Figures 3a2, 3b2, and 3c2) may suggest that the F-MPS_FZ is susceptible to large slips. This may justify applications of slip values of up to 17 m for fault parameters in our three hypothetical tsunami simulations (Figures 4c and 4d). While tectonic forces from the 20 km long F-MPS_FZ are unlikely to produce large slips of up to 17 m, regional tectonic forces associated with the subduction zone to the south of the F-MPS_FZ (Figure 1a) could provide adequate tectonic forces for large slips during certain tectonic

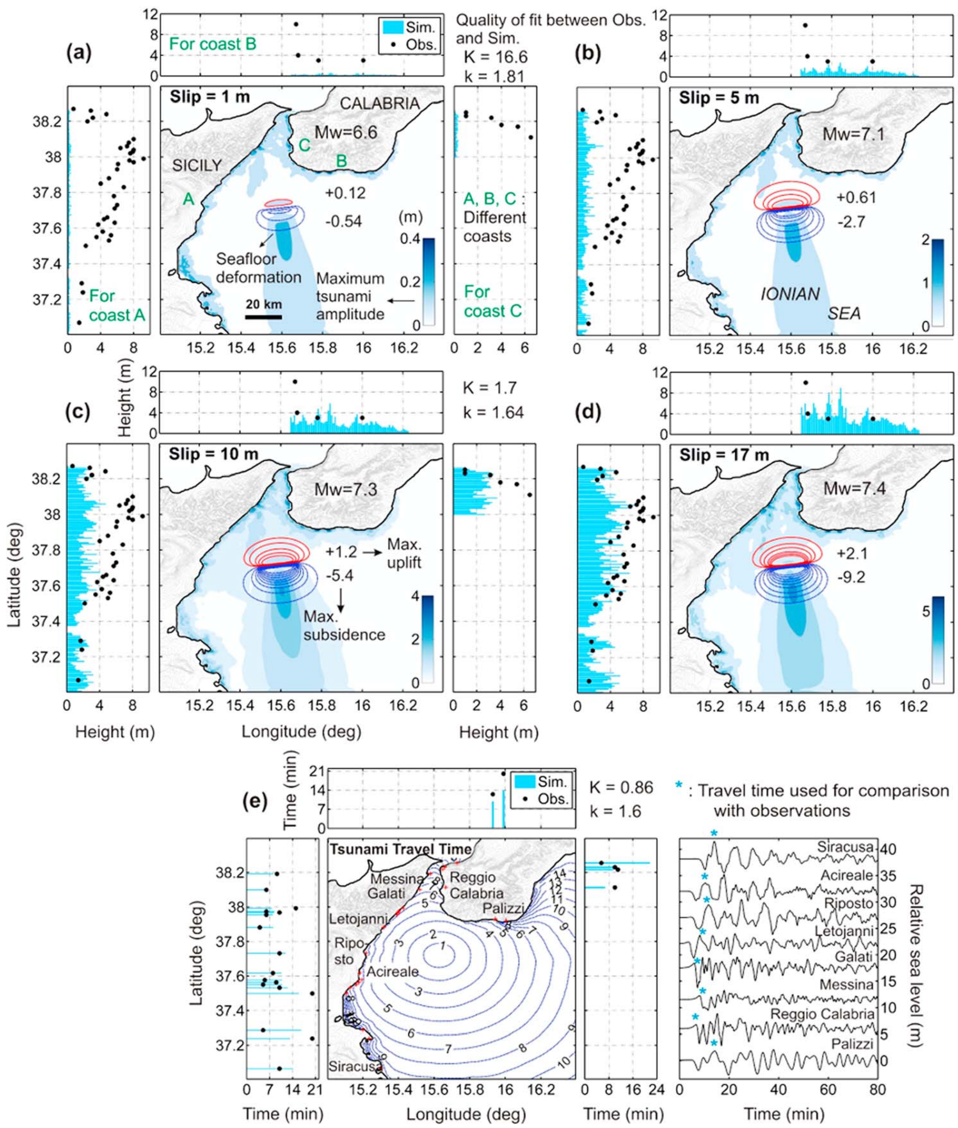

Figure 4. (a–d) Results of tsunami simulations of four scenarios with slip amounts of 1, 5, 10, and 17 m and comparisons with observed wave heights during the 1908 Messina tsunami. The red and blue contours represent the seafloor uplift and subsidence due to the tectonic source, respectively. The color maps show the distribution of maximum tsunami amplitudes for each source scenario. (e) Tsunami travel times in minutes for Figure 4d. The contours are in minutes and show the arrivals of first tsunami waves. The side plots compare the observed arrival times with the first noticeable peak (with amplitude > 0.5 m) in simulations. (right column) Some of the simulated waveforms. The parameters K and k in each panel show the quality of fit between observations and simulations according to equations (1) and (2). M_w is moment magnitude of the earthquake.

circumstances [*Hiroshi Sato*, 2015, Personal communications]. In addition, it is possible that the lengths of the identified faults are shorter than those of the actual faults because of the limitations in our seismic and bathymetric study and also due to other complexities related to surface and depth appearance of the fault systems. Despite the fact that our tsunami models match fairly well with the observed data of the 1908 Messina tsunami and that the location corresponds well with the landslide source area suggested by *Billi et al.* [2008], we doubt that the F-MPS_FZ was the source of the 1908 Messina tsunami because the strike of the fault zone contradicts all seismological observations, suggesting an N-S-striking fault in the inner Messina Strait [*Amoruso et al.*, 2002; *Tinti and Armigliato*, 2003; *Argnani et al.*, 2009a]. However, we consider the F-MPS_FZ as a potential source of submarine hazards because it is the most obvious tectonic feature in the entire Messina Strait with an escarpment height at the seafloor of up to 60 m. The tsunami modeling suggests that a slip rate of ~1 m would not trigger a significant tsunami, but a slip rate of ~5 m would result in local runup heights of more than 2 m. An even higher slip increases the estimated tsunami height significantly. In addition, there are a number of major events that occurred in the area indicating a real hazard and risk, such as the 1693 Sicily earthquake and tsunami. Therefore, there may be hazards here that were previously unperceived. The newly discovered F-MPS_FZ adds a new source candidate for tsunamis in the Messina Strait in Southern Italy.

5. Conclusions

Tsunamis are a major threat to the coastlines of Southern Italy as demonstrated by the devastating tsunami following the 1908 Messina earthquake. There is still no conclusive explanation for the source of this tsunami. Common fault solutions of the earthquake have difficulty to explain the observed runup heights and arrival times. A landslide source for the tsunami has been suggested, but no obvious young landslide scarps are present in the area in the reconstructed source area of the tsunami according to our newly acquired seismic and bathymetric data.

In this research, we presented a newly discovered active E-W striking fault zone: the Fiumefreddo-Melito di Porto Salvo Fault Zone. A prominent 60 m high escarpment at the seafloor characterizes this fault zone, making it the most prominent morphologically visible fault zone in the outer Messina Strait. This fault zone is capable of generating a tsunami comparable to the 1908 Messina tsunami by assuming a slip of 17 m on this fault, although such a scenario looks unlikely. In addition, the strike direction of this fault zone does not fit the seismological data. Smaller slip rates (~5 m) would still generate significant tsunami runup heights of more than 2 m. Hence, we consider this fault zone as a potential submarine hazard source for the Messina Strait and surrounding areas, although it is highly unlikely that it triggered the 1908 tsunami.

Acknowledgments
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