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Source of the 1693 Catania earthquake and tsunami (southern Italy): New evidence from tsunami modeling of a locked subduction fault plane

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[1] The 1693 Catania earthquake, which caused 60000 deaths in eastern Sicily and generated a 5–10 m high tsunami, is investigated. GPS data indicate ESE-WNW convergence in the Calabrian arc at 4–5 mm/yr. New high-resolution seismic data image active compression at the toe of the accretionary wedge. The lack of instrumentally recorded thrust earthquakes suggests the presence of a locked subduction fault plane. Thermal modeling is applied to calculate the limits of the seismogenic zone. Tsunami modeling is performed to test the hypothesis that the 1693 earthquake occurred on the subduction fault plane (160 × 120 km in size) with 2 m of mean co-seismic slip. This source successfully reproduces historical observations with regard to polarity and predicts 1–3 m high amplitudes. It is likely that only the SW segment of the subduction fault plane ruptured in 1693 and 1169, implying a recurrence interval of roughly 500 years for similar events.

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1. Introduction

[2] Southern Italy has been struck repeatedly by very strong historical earthquakes (Mercalli intensity IX or greater), in 1169, 1542, 1624, 1693, 1783, 1905, 1908, often associated with destructive tsunami [Piatanesi and Tinti, 1998; Jacques *et al.*, 2001]. While several of these events, like the 1908 Messina, 1905 or 1783 Calabria earthquakes occurred along mapped, crustal, normal faults [Tinti and Piatanesi, 1996; Monaco and Tortorici, 2000; Jacques *et al.*, 2001] the source of some of the older events remains enigmatic. Since no strong (M6) earthquakes have occurred in the past 50 years, it is difficult to identify the main active faults. The 1693 event, with maximum intensities of X to XI, caused 60,000 casualties [Piatanesi and Tinti, 1998]. Because it generated an Ambraseys-Sieberg intensity V tsunami [Tinti *et al.*, 2004], and the isoseismals are open to the sea (Figure 1), it appears that the source region is offshore. Although its exact position remains unknown, it is of major importance for the assessment of seismic and tsunami risk in the region.

[3] Calabria is located above a 300 km wide, NW dipping subduction zone which is associated with an active volcanic arc, the Aeolian Islands (Figure 1) and a well defined Wadati-Benioff zone, with earthquakes descending to nearly 500 km depth (Figure 2). A continuous, high P-wave velocity anomaly (slab of cold dense lithosphere) is imaged by travel-time tomography down to 660 km depth, where the slab flattens and underlies the western Mediterranean below Sardinia [Lucente *et al.*, 1999; Wortel and Spakman, 2000]. It is widely accepted that Calabria has migrated SE to its current position due to a rapid roll-back of the Ionian-Tyrrhenian slab [Malinverno and Ryan, 1986; Gvirtzman and Nur, 1999; Faccenna *et al.*, 2001] and that the high heat flow and young oceanic lithosphere in the Tyrrhenian Sea are the result of the associated back-arc extension [Zito *et al.*, 2003].

[4] One major question, however, remains unanswered, “is the Calabria subduction zone still active”? The lack of seismicity along the subduction fault plane (with a characteristic shallow dipping thrust-type focal mechanism) implies one of three possibilities; 1) subduction has ceased, 2) subduction is active but aseismic, or 3) subduction is active and there is a large locked seismogenic zone. High-resolution seismic profiles image compressive deformation at the toe of the wedge [Hieke *et al.*, 2005] (Figure 3). The folding of the 10 m thick transparent layer identified as the 3500 BP Augias Turbidite [Cita *et al.*, 1984], indicates active shortening. Deep penetration multi-channel seismic profiles image SE vergent ramp thrusts, soling out to a regional NE dipping decollement [Cernobori *et al.*, 1996] and offer proof that compression at the toe is tectonic in origin and not gravitational. The recent discovery of a province of mud volcanoes, indicates active dewatering in the Calabrian prism [Ceramicola *et al.*, 2005]. If the third hypothesis is true, then Calabria may exhibit a similar behavior as the Nankai or Cascadia subduction zones, marked by long repeat times between great earthquakes on the order of hundreds of years [Hyndman and Wang, 1995; Oleskevich *et al.*, 1999]. The purpose of this paper is to test the hypothesis of a subduction fault plane source for the 1693 Catania earthquake, using tsunami modeling.

2. Fault Plane Geometry and Thermal Modeling

[5] The shallow (<20 km depth) geometry of the subduction fault plane is constrained by multi-channel seismic profiles, imaging a shallow NW dipping decollement (<2°), steepening somewhat (>5°) at greater depth [Cernobori *et al.*, 1996]. The deeper geometry is obtained from the distribution of earthquake hypocenters (Figure 2).

[6] In order to determine the updip and downdip limits of the potentially seismogenic portion of the fault plane, 2-D numerical modeling of forearc thermal structure was per-

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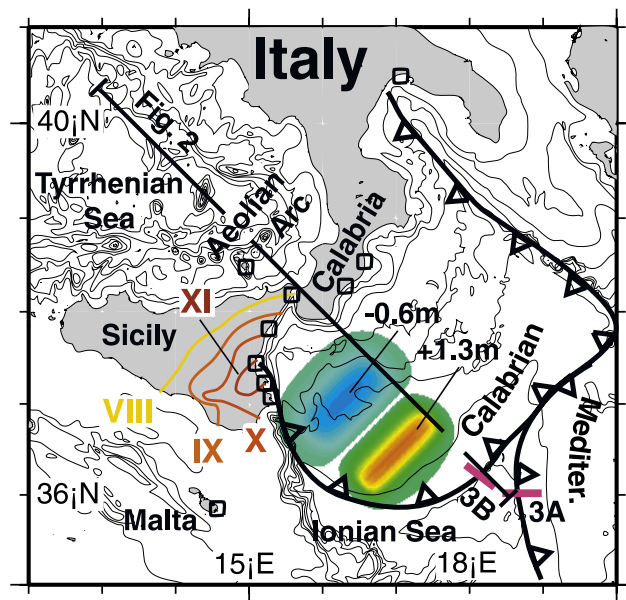


Figure 1. Location map, with proposed tsunami source. The initial vertical elastic displacement, ranging from +1.3 m to -0.6 m, was calculated for a rectangular fault plane with dimensions of 120×160 km and 2 m mean (but non-uniform) co-seismic slip. Also shown are bathymetric contours (500 m interval) from the Gebco 1 min grid [BODC, 2003], isoseismals (contours of equal shaking intensity) of the 1693 earthquake, position of virtual mareograph stations (squares - see text for geographic names), and the position of the thermal and seismic profiles (see Figures 2 and 3).

formed [Peacock and Wang, 1999; Gutscher and Peacock, 2003]. The updip limit is commonly considered to correspond to the 100–150°C isotherms and the downdip limit to the 350–450°C isotherms [Scholz, 1990; Oleskevich et al.,

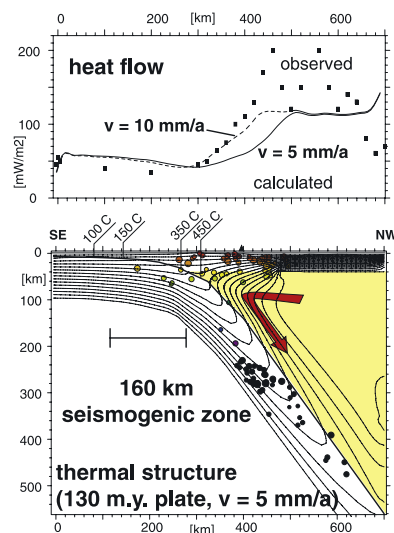


Figure 2. Thermal structure of the Calabrian arc, with the projected position of earthquakes from the relocated hypocenter catalog 1964–1995 [Engdahl et al., 1998]. The observed heat flow [Zito et al., 2003] is shown (squares) together with the calculated heat flow for two subduction velocities.

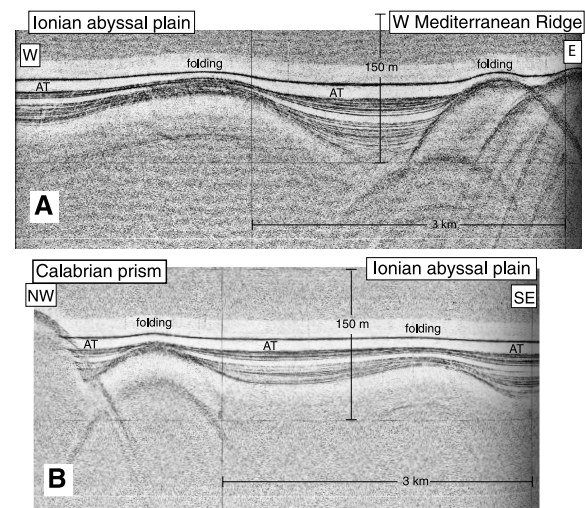


Figure 3. High-resolution (3.5 kHz) seismic profiles from the Ionian Sea. (a) across the toe of the Western Mediterranean Ridge, (b) across the toe of the Calabrian prism. Both profiles reveal active compressional deformation and syn-tectonic sedimentation. Folding affects the uppermost turbidite layers and even disturbs the sea-floor. The 10–15 m thick transparent layer labelled AT represents the Augias Turbidite deposited as a result of the Santorini collapse of 1500 BC [Cita et al., 1984; Hieke et al., 2005].

1999]. The age of the subducting oceanic lithosphere is not well known, but the Ionian Sea is believed to be a remnant of the Tethys ocean and thus likely Jurassic in age [Faccenna et al., 2001]. An age of 130 Ma was taken. Available heat-flow data from the region show a typical forearc pattern, with low values of 50 mW/m² in the Ionian Sea and very high values reaching 150–200 mW/m² in the SE Tyrrhenian Sea, where very young oceanic lithosphere is present in the Marsili basin [Zito et al., 2003].

[7] Recent GPS measurements of the South Italian region confirm the overall NW motion of Africa with respect to Eurasia at a velocity of 5 mm/yr, as well as the SE motion of an intermediate Calabria block at 4–5 mm/yr (in a Nubia fixed reference frame), suggesting that subduction has not ceased [D'Agostino and Selvaggi, 2004]. We calculated the thermal structure of the Calabrian arc for subduction velocities of 0–20 mm/yr. Although 10 mm/yr provides the best fit to the observed heat-flow pattern (Figure 2), we retain the thermal structure for a velocity of 5 mm/yr as observed by GPS. The thermally predicted downdip width of the seismogenic zone is 160 km, spanning 120 km to 280 km from the deformation front.

3. Fault Parameters

[8] Very high intensities (X and XI) and a strong tsunami were reported in eastern Sicily in 1693. However, no available historical records indicate widespread damage in Calabria, or Central Italy. Thus, it seems unlikely that the entire 300 km long subduction fault plane ruptured, as this would have produced a magnitude $M_w = 8.3$ felt over a greater distance. This is calculated, for a mean co-seismic slip of 2 m, from the relationship $M_0 = \mu SD$, where rigidity $\mu = 3 \times 10^{10}$ Pa, the rupture area $S = 300 \text{ km} \times 160 \text{ km} = 48000 \text{ km}^2$, and the slip

$D = 2$ m. This yields $M_0 = 2.88 \times 10^{21}$ Nm and then using $M_w = 2/3 \log M_0 - 6.03$, the resulting magnitude is $M_w = 8.28$. Therefore, we consider only a 120 km long segment, which yields a smaller magnitude of $M_w = 8.0$. The fault plane dips 5° to the NW, extending from 5 km depth (shallowest) to 20 km depth (deepest).

[9] The mean co-seismic slip of 2 m is obtained by considering the recurrence interval and the subduction velocity (4 mm/yr). In 1169 a strong earthquake with similar intensities (X and XI) struck eastern Sicily, producing almost exactly the same isoseismal pattern [Barbano *et al.*, 1984]. If the two earthquakes occurred along the same fault, then a recurrence time of about 500 years is implied.

4. Tsunami Modeling

[10] The fault parameters above were used to perform tsunami wave form modeling of a shallow NW dipping subduction source. The initial displacement of the seafloor, considered to be similar to the initial displacement of the water surface, is calculated using the elastic half-space approach [Okada, 1985]. The vertical seafloor displacement (for a pure thrust mechanism) is shown in map view and ranges from 1.3 m uplift to the SE, to 0.6 m subsidence to the NW (Figure 1). To account for non-uniform slip within the fault plane [Geist and Dmowska, 1999], we used the smooth closure condition [Freund and Barnett, 1976] applying a skewness parameter of 0.3 and a discretization of 8 km. For the tsunami wave propagation, finite difference software SWAN Code [Mader, 2004] was applied, using a shallow water non-linear wave model and a cell size of 0.025 degrees. The Gebco 1 min bathymetric grid was used [British Oceanographic Data Centre (BODC), 2003].

[11] Synthetic mareograms were calculated for ten stations in the southern Italy region (Figure 4). These stations were selected for the most part on the availability of historical records.

[12] They are situated along the eastern coast of Sicily (from S to N: Syracuse, Augusta, Catania, Taormina and Messina), one in the Aeolian islands (Vulcano), one on Malta, two on the SE coast of Calabria and one in the Gulf of Taranto.

[13] Synthetic mareograms provide information on wave phase, amplitude and arrival time of the tsunami wave (Figure 4). One of the most crucial observations concerning the 1693 tsunami was a strong withdrawal of the sea at all port towns of the eastern coast of Sicily which was so sudden and violent that many ships were damaged [Piatanesi and Tinti, 1998].

5. Discussion

[14] Previous source models for the 1693 earthquake tested primarily NE-SW trending normal faults on-land in eastern Sicily, as well as NNW-SSE trending steeply dipping normal faults offshore along the Malta escarpment [Piatanesi and Tinti, 1998; Bianca *et al.*, 1999; Tinti *et al.*, 2001]. None of the on-land faults tested succeeds in reproducing the observed initial withdrawal of the sea at all eastern Sicily port towns, and these must therefore be rejected as potential sources [Piatanesi and Tinti, 1998]. Along the Malta escarpment south of Syracuse, marine seismic profiles reveal no evidence of Quaternary deformation [Argnani and Bonazzi, 2005].

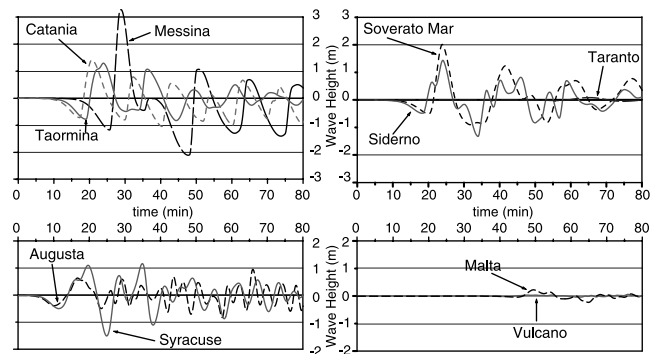


Figure 4. Synthetic mareograms calculated for the ten virtual tide gauge stations in the SE Italy region.

But the main drawback of all of these proposed sources is that unreasonably large slip values (6–8 m) are required [Piatanesi and Tinti, 1998; Tinti *et al.*, 2001] to generate an earthquake of magnitude 7–7.5, with respect to the length of the fault, violating established earthquake scaling laws [Wells and Coppersmith, 1994]. The large surface area of the subduction fault generates a very strong earthquake M8.0 for only 2 m of co-seismic slip and is consistent with relative plate velocities (4–5 mm/yr) and the available evidence on the recurrence interval (500 yrs). For the non-uniform slip model tested, the maximum slip is 4 m and thus requires portions of the fault to have accumulated a significant slip deficit during the previous seismic cycle.

[15] The subduction fault plane generates a tsunami with an initial withdrawal of the sea for all stations in eastern Sicily. Wave heights obtained, range from 1–1.3 m for the east coast of Sicily, with the highest amplitude (3.3 m) in Messina. Although this may appear small with respect to the 5–10 m high wave reported, these simulations do not reproduce the amplification effects from the run-up, which may increase wave heights by a factor of 2 to 5. For instance, following the 26 December 2004 M9.3 earthquake, the tsunami amplitudes observed at tidal gauge stations in SE India (Vishakapatnam, and Tuticorin) were only 1.4 m (<http://www.nio.org/jsp/tsunami.jsp>). Likewise in Colombo (Sri Lanka) and NW Sumatra (Sibolga, Belawan) recorded wave heights were 2.1 m and 0.5 m, respectively [Merrifield *et al.*, 2005]. Yet eye-witness accounts and the physical damage in these areas indicate wave heights ranging from 5–10 m.

[16] Calculated amplitudes for more distant stations (Vulcano, Malta or Taranto) are small (0.1–0.25 m). But depending on the amplification through run-up, this wave may have been noticeable. Travel-times are shortest for the east Sicily coast. The initial withdrawal would have occurred most rapidly in Syracuse and Augusta (10 min), and 15–20 min after the earthquake for Catania, and Taormina (Figure 4). The ensuing positive wave would have flooded the ports 5–10 min later. Unfortunately, no historical observations are available with regard to travel time and thus this key piece of information cannot be used to support or disprove a particular source model.

6. Conclusion

[17] High-resolution seismic images from the toe of the Calabrian accretionary wedge as well as recent GPS data

indicate ongoing ESE-WNW convergence in the Calabrian arc at rates of roughly 4–5 mm/yr. The lack of instrumentally recorded thrust earthquakes supports the hypothesis of a locked subduction fault plane. For the periodicity of 500 years suggested by historical records, a mean co-seismic slip of about 2 m can be expected. Tsunami modeling of a subduction fault plane (160 × 120 km in size) successfully reproduces the available historical observations with regard to polarity and predicts 1–3 m amplitudes. If this hypothesis is true, then it is likely that only the SW segment of the subduction plane ruptured in 1693 and 1169. It is unknown when the remainder of the subduction fault plane may have ruptured, yet this knowledge is crucial for estimating the seismic and tsunami hazard in the Southern Italian region.

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