Hints on active tectonics in the southern Messina Straits: preliminary results from the TAORMINA-2006 seismic cruise

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ABSTRACT The Straits of Messina and its surroundings are considered one of the most tectonically active areas of the Mediterranean; however, in spite of their hazard potential, modern geophysical data aimed at investigating the tectonic structures occurring in the marine areas are lacking. In order to bridge this gap, we carried out a multichannel seismic survey aimed at studying: i) the existence of the Taormina Fault, which many authors locate along the coast between Taormina and Messina; ii) the regional fault pattern in the area of the Messina 1908 earthquake; and iii) the instability offshore of Mt. Etna. Preliminary results show that the whole sector of the submarine slope located between Taormina and Messina has been tilted eastwards and that there is no Taormina Fault cutting the Quaternary sediments. On the other hand, the best-imaged active fault occurs on the Calabrian side of the Messina Straits. This NW-SE-trending fault is about 20 km long and dips westwards with a low-angle. Finally, a large submarine slide, longer than 10 km and thicker than 400 m, has been found offshore Mt. Etna.

1. Introduction

The aim of the TAORMINA-2006 cruise was to investigate the seismotectonics of the Messina Straits and surrounding regions. The Messina Straits area is tectonically active, as indicated by GPS velocities (D'Agostino and Selvaggi, 2004; Goes *et al*., 2004) and uplifted marine terraces (Antonioli *et al*., 2003; Catalano and De Guidi, 2003), and is characterized by the occurrence of the large 1908 Messina earthquake [M_W = 7.2: Pino *et al*. (2000); Gruppo di Lavoro CPTI (2004)]. However, in spite of its hazard potential, modern geophysical surveys purposely devised to investigate the neotectonic features are lacking. In order to bridge this gap, we carried out a multichannel seismic survey aimed at defining the structural pattern of the Messina Straits and surroundings (Fig. 1). Special attention has been dedicated to detecting the eventual occurrence of an active fault offshore Taormina which might represent a potentially large seismicity gap (Neri *et al*., 2006), and has not been directly documented, so far (Fig. 1).

2. Geological setting

The marine area stretching between northeastern Sicily and southern Calabria is home of

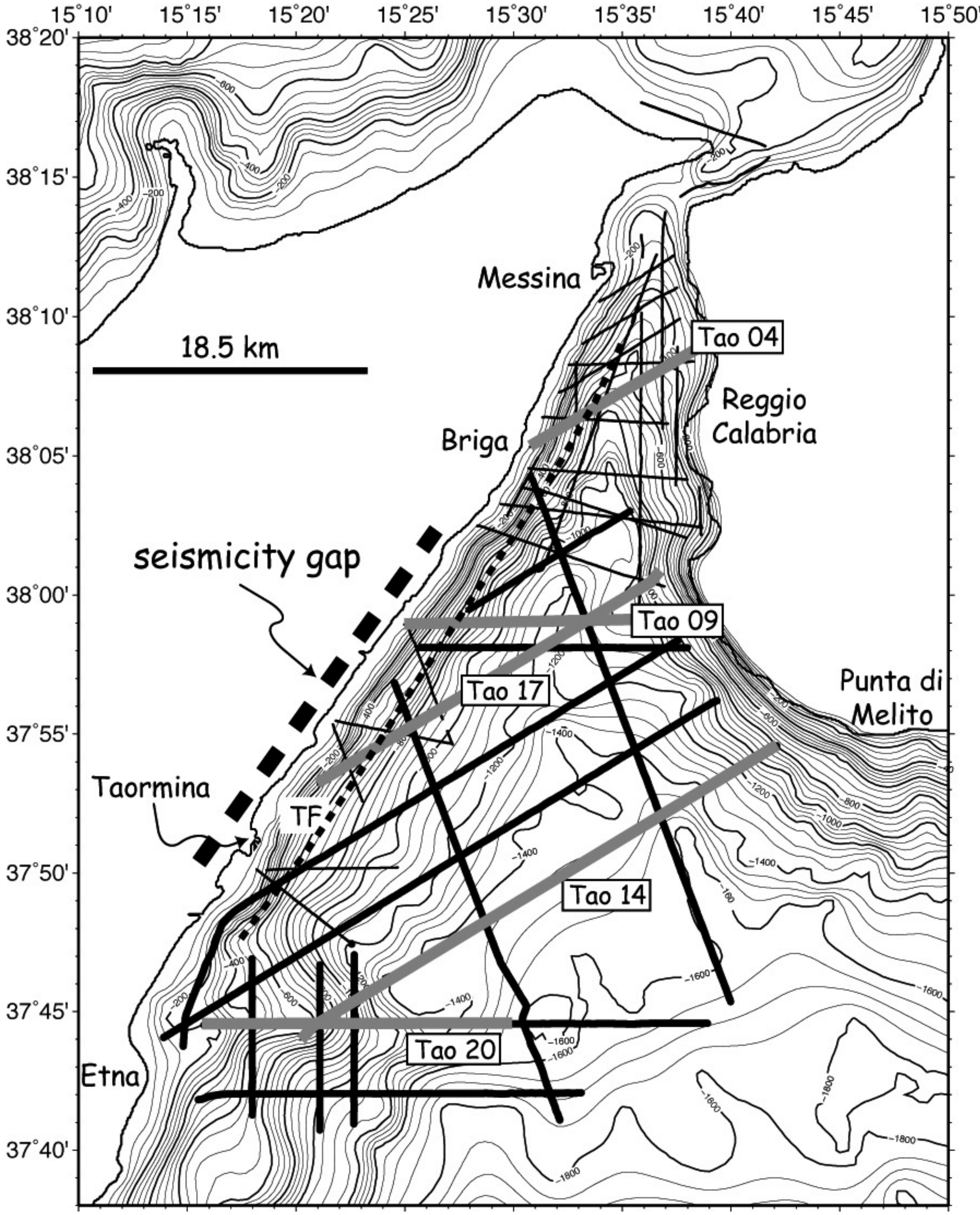

Fig. 1 - Map showing traces of seismic profiles in the study area. Bold black lines indicate the profiles acquired with the long streamer (see text for explanation), whereas profiles acquired with the short streamer are shown as thin black lines. The location of the seismicity gap (Neri *et al*., 2006) and of the inferred Taormina Fault (FT; Catalano and De Guidi, 2003) are also shown. The portions of seismic profiles shown in Figs. 2 to 6 are labelled and indicated with a thick gray line.

remarkably active neotectonics, often displaying hazardous seismicity (e.g., Gruppo di Lavoro CPTI, 2004) and high geodetic strain (D'Agostino and Selvaggi, 2004; Goes *et al*., 2004).

The 1908 Messina earthquake was one of the natural events that claimed the highest toll in human life in Italy's history. It is believed that over 80,000 people died in the cities of Messina and Reggio Calabria and the surrounding area, with buildings collapsing, fires and tsunamis (Baratta, 1910). In spite of such a devastating outcome, the fault responsible for the 1908 Messina earthquake is still unknown (see e.g., Galli *et al*., 2007). Inverse modelling of seismograms and geodetic levelling, and geological hints have produced a variety of results in terms of position, direction, length and dip of the fault [Fig. 2; see Amoruso *et al*. (2002) and references therein], and, moreover, the structural setting in which the Messina 1908 fault is active is still not clear, particularly when compared to onshore geology (Ghisetti, 1979, 1992; Monaco *et al.*, 1996; Galli and Bosi, 2002). It is worth noting that according to several authors (e.g., Valensise and Pantosti, 1992; Amoruso *et al*., 2002; Galli *et al*., 2007) the southern termination of the seismogenic fault should extend as far south as Capo Spartivento, the southern tip of Calabria.

A spectacular flight of emergent marine terraces occurs along the coast of Sicily from Taormina to Briga (Fig. 1) with the terrace surfaces that converge both southwards and northwards along the coastline and that present a slight, regional southward tilt (Catalano and De Guidi, 2003). The occurrence of a large and active extensional fault, running offshore, has been inferred on the basis of coastal geomorphology (Stewart *et al*., 1997; Rust and Kershaw, 2000; Antonioli *et al*., 2003; Catalano and De Guidi, 2003). Works on these terraces has shown that the uplift has occurred since 125 ka, with rates as high as 1.07 mm/yr (Catalano and De Guidi, 2003); a remarkable increase in uplift rates, with values close to 2 mm/yr, occurred in the Holocene, as indicated by marine notches (Antonioli *et al*., 2006) . The flexural uplift on the fault footwall of the offshore fault named Taormina Fault is thought to be responsible for the remakable uplift of the Late Pleistocene marine terraces.

Previous structural studies (e.g., Ghisetti, 1979, 1992) have shown the occurrence of a system of faults that runs along the Sicilian coast; the faults of this system, however, do not have a large throw and their position does not explain the uplift of marine terraces. In addition, it seems that the most active faults during the Pleistocene are those located on the Calabrian side of the Messina Straits (Ghisetti, 1992).

According to some investigators (e.g., Monaco and Tortorici, 2000; Jacques *et al*., 2001) the fault system of southern Calabria can be linked to the fault system of eastern Sicily (e.g., Bianca *et al*., 1999; Argnani *et al*., 2002; Argnani and Bonazzi, 2005) through the Taormina Fault (Fig. 1). Large and destructive earthquakes can be associated to fault activity along eastern Sicily and to southern Calabrian faults, during this century and the previous ones (Gruppo di Lavoro CPTI, 2004). However, historical data (Boschi *et al*., 1995; Gruppo di lavoro CPTI, 2004) and recent instrumental records (Chiarabba *et al*., 2005) indicate a lack of seismicity along the belt corresponding to the inferred Taormina Fault (Neri *et al*., 2006). The assumption that the hypothesized Taormina Fault is actually part of a single rift system, connecting Calabria to eastern Sicily, implies that it represents one of the most dangerous seismic gaps in Italy, a potential site for large future earthquakes (Stewart *et al*., 1997). Alternatively, the lack of seismicity observed between Taormina and Messina might indicate the absence of active tectonic structures. Actually, the Taormina fault has not been directly documented, but only inferred on

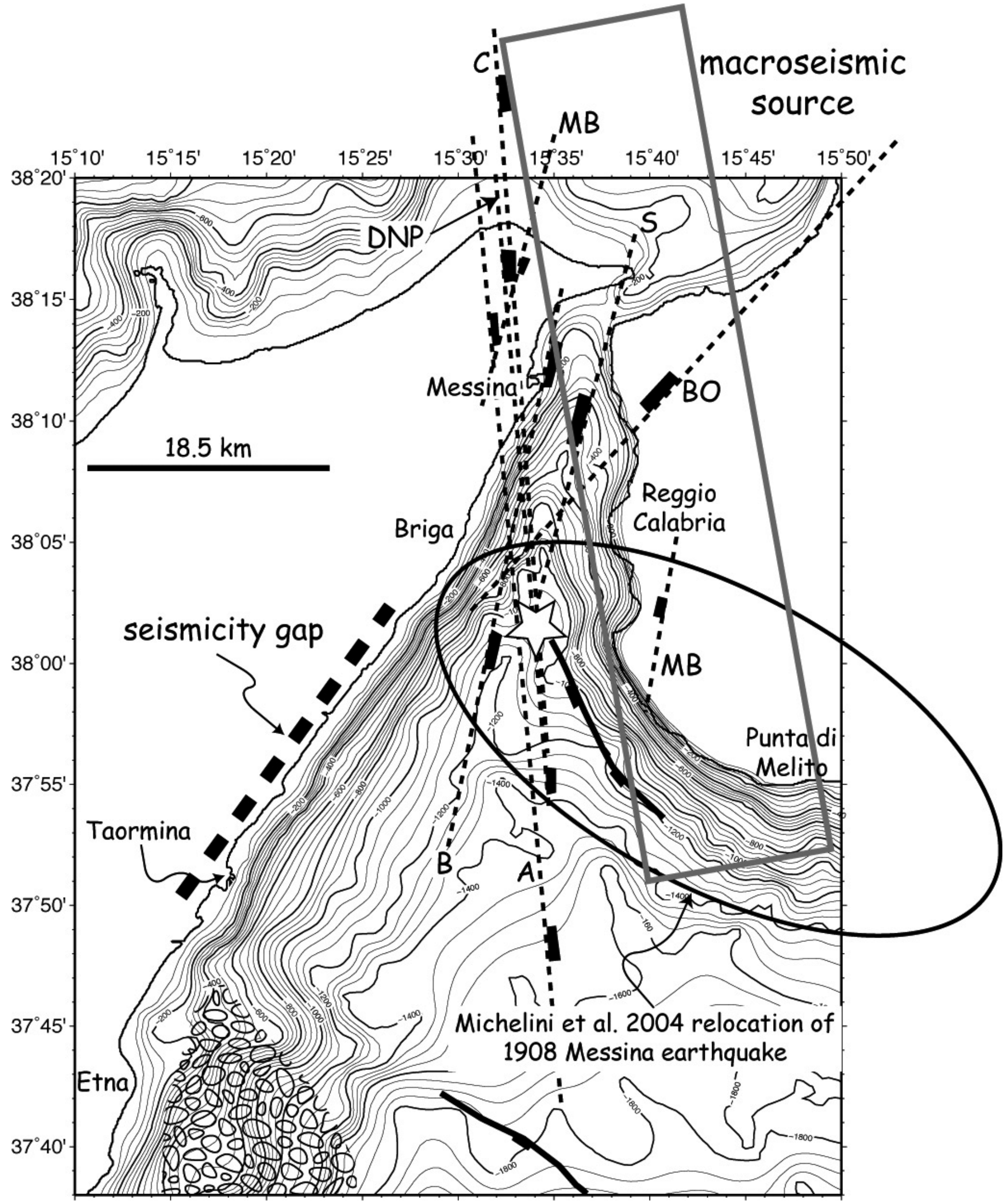

Fig. 2 - Map showing the location of the fault identified offhsore southern Calabria through the Taormina-2007 seismic survey. The star indicates the epicentre of the Messina 1908 earthquake according to Schick (1977), whereas the dashed lines show suggested fault planes for the same event, from various authors [S: Schick (1977), MB: Mulargia and Boschi (1983), BO: Bottari *et al*. (1986), C: Capuano *et al*. (1988), B: Boschi *et al*. (1989), DNP: De Natale and Pingue (1991), A: Amoruso *et al*. (2002)]. The relocation of Michelini *et al*. (2004) and the macroseismic location (Gasperini *et al*., 1999; DISS Working Group, 2006) for the Messina 1908 earhquake are also indicated. The seismicity gap is located after Neri *et al*. (2006). The gravel pattern next to Mt. Etna, indicating a chaotic seismic facies, and the adjacent fault are from Argnani and Bonazzi (2005).

the basis of the regularity of the range front and on uplifted coastal terraces, and the very sparse seismic data in the proximity of the fault (1970's ISMAR-Bologna property single-channel Sparker profiles) did not show any evidence of fault occurrence.

Finally, it is worth taking into account the fact that the whole of the Calabrian Arc, including the Peloritani Mountains of Sicily, has been regionally uplifted, with rates as high as 1-2 mm/yr in the last 800 ka (Westaway, 1993; Bordoni and Valensise, 1998; Cucci and Cinti, 1998). Uplift rates, however, can vary substantially along the Calabrian Arc, and as far as the uplifted marine terraces of NE Sicily are concerned, this makes it difficult to separate the regional contribution from an eventual fault footwall uplift.

In order to assess the potential seismic hazard of the Messina Straits region and its marine surroundings, it seems of key importance to obtain a reliable map of the active tectonic structures based on marine geophysical surveys. The TAORMINA 2006 survey was aimed at acquiring a grid of purposely planned seismic profiles that should help to outline the active tectonics of the Messina Straits and its marine surroundings.

An interesting side issue that has been addressed during the TAORMINA-2006 survey concerns the gravitational instability of the eastern flank of Mt. Etna. The basal portion of the eastern side of Mt. Etna is located at sea, and intercepts the Malta Escarpment where the steep topographic gradient might affect the stability of the volcanic edifice (Borgia *et al*., 1992, 2000), McGuire, 1996). Within this assumption radial contraction should be observed also at the submarine base of the volcano (Borgia *et al*., 2000). The role of gravity on the evolution of Mt. Etna, however, is disputed by other authors (Lanzafame and Bousquet, 1997) on the basis of field data, but so far no clear offshore data has been presented to support or to reject the hypothesis of volcanic spreading. Moreover, a large sector collapse, known as Valle del Bove occurs on the eastern side of Mt. Etna, and is thought to be responsible for the deposition of the Chiancone unit, a mainly conglomeratic deposit whose attributed age is about 8,000 yr BP (Calvari and Groppelli, 1996). The occurrence of chaotic seismic facies was reported during a previous seismic survey carried out within the Gruppo Nazionale Difesa Terremoti projects (Argnani and Bonazzi, 2005), and the emplacement of a large submarine slide complex related to the Valle del Bove collapse has been recently suggested on the basis of a multichannel seismic survey offshore Mt. Etna (Pareschi *et al*., 2006b); an event that has possibly generate a huge tsunami, sweeping the whole of the eastern Mediterranean (Pareschi *et al*., 2006a).

3. Cruise activity

3.1. Navigation and positioning

The system RESON PDS2000 was used for navigation on board R/V Urania, with positioning obtained from DGPS FUGRO SEASTAR and motion sensors VT-TSS MAHRS.

3.2. Chirp sonar

Sub-Bottom Profiles data were acquired by a 16 transducer hull-mounted DATASONICS CHIRP-II profiler, with operating frequencies ranging between 2-7 kHz, in order to investigate the near bottom sediments.

3.3. Seismic survey

3.3.1. Acquisition

The MCS survey, carried out from August 25 to September 7, 2006, onboard the R/V Urania of the National Council of Researches (CNR), has led to the acquisition of ca. 700 km of seismic profiles (Fig. 1). Following the initial operations to install and connect the instruments, activity onboard was carried out with 24 hour shift work, with 4 hours of work followed by 8 hours of rest for each operator

The seismic survey was carried out with two different systems, according to operating conditions, mostly the closeness to the coast, encountered during the survey:

a) 48-channel Teledyne seismic streamer with 600 m of active section and 12.5 m group interval. The streamer was kept at an operation depth of ca. 10 m. Shot interval was 18.75 m to get a 16-fold coverage. A seismograph StrataVisor (Geometrics) was used for acquisition, with 1 ms sampling and 5 s of record length.

b) 24-channel Teledyne seismic streamer with 120 m of active section and 5 m group interval. The streamer was kept at an operation depth of ca. 1 m. Shot interval varied between 12.5 and 20 m to give a coverage from 3 to 4.8. A seismograph DAQ Link II (Seismic Source) was used for acquisition, with 1 to 2 ms sampling and 3 to 4 s record length.

In both cases the energy source was a G.I. Gun Sodera in Harmonic mode (105 + 105 ci), fed by a 3500 l electrically-driven compressor Bauer, and operating with a pressure of 140 bars. The Sure Shot system (Real Time Micro Systems) was used to control the shots. The depth of the energy source ranged at 8 m.

3.3.2. Processing

Preliminary near trace profiles were obtained on board using the processing software packages VISTA (GEDCO) and SeismicUnix (Colorado School of Mines).

Subsequently, seismic data recoreded with the long streamer and StrataVisor seismograph were processed using a standard sequence (Yilmaz, 1987) up to time migration, using the software Disco/Focus by Paradigm. The main processing steps are:

i) resampling every 2 ms of the original record,
ii) spherical divergence gain to recover signal amplitude,
iii) editing and CDP sorting,
iv) velocity analysis every 200 CDP,
v) normal Move Out correction,
vi) stack,
vii) muting to remove noise in the water column, and
viii) Finite-Difference Time Migration.

Similar processing sequences have been applied to the seismic data acquired with the short streamer that have been processed up to the stack using the software packages VISTA (GEDCO) and SeismicUnix (Colorado School of Mines).

3.4. Multibeam survey

The Multibeam survey was carried out during seismic acquisition, and independently in

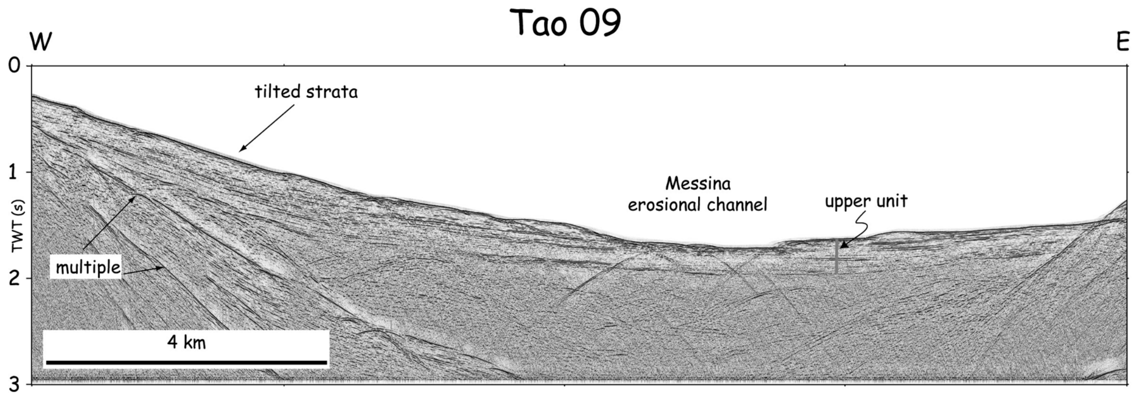

Fig. 3 - Seismic profile TAO 09 (stack) across the central part of the supposed Taormina fault. Note the 0.4 –0.5 s (TWT) thick package of almost parallel strata dipping to the east on the slope and flattening further to the east (upper unit). Some minor onlaps occur at the very base of the package on the western slope. Profile acquired with the short streamer. See Fig. 2 for location.

selected areas, using the system RESON SeaBat 8160, installed on board R/V Urania. It is characterized by 126 beams, spaced at 1.2 degrees with a coverage of 150 degrees, and has an operation frequency of 50 kHz. Multibeam data were preleminarily processed on board using the free software package MB System, in order to reduce noise and bad echoes.

4. Preliminary results

The processing of seismic data is still ongoing and, therefore, a thorough interpretation of the whole data set is not available. Although the data collected still require additional work, particularly in the Messina Straits, some preliminary results have relevance on the seismotectonics of the study area.

In a simplified approach, two major seismic stratigraphic units can be indentified over the whole survey (e.g., Fig. 3). An upper unit is characterized by a package of reflections, more or less continuous and with variable amplitude. Its upper boundary is the sea floor, which is often an erosional surface, the lower boundary being a somewhat irregular surface where basal reflections onlap on the western part. The unit presents internal unconformities which could be further subdivided; the basal reflections show very low amplitude and little contrast in places, outlining a basal package with almost transparent seismic facies, which could be attributed to the Trubi Formation (e.g., Barone *et al.*, 1982; Argnani and Bonazzi, 2005). Although the Trubi Formation typically belongs to the early Pliocene (Sprovieri, 1974), in the central Mediterranean marine region, the typical Trubi marly sediments can cover the whole of the Pliocene. Therefore, the upper unit is interpreted as covering the Pliocene- Quaternary time span, and likely most of the sediments belong to the Quaternary.

The lower unit presents a dominantly chaotic seismic facies, with only small patches with continous and sometimes parallel reflections. The upper boundary is typically given by an irregular surface, whereas the lower boundary is not imaged on seismic profiles. Such a unit is

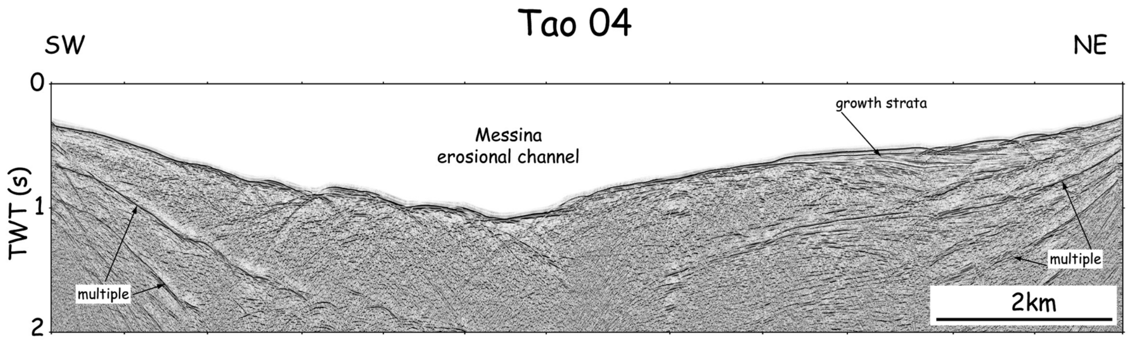

Fig. 4 - Seismic profile TAO 04 (stack) crossing the Messina Straits. Major sea-floor erosion and ensuing hard bottom contribute to deterioring the quality of the seismic signal. Evidence of growth strata on a west-dipping fault, possibly not currently active, can be seen on the Calabrian side (NE). Profile acquired with the short streamer. Location in Fig. 2.

interpreted as representing the terranes of the Calabrian Arc accretionary complex, composed of more or less disrupted sediments and units of pre-Pliocene age (e.g., Argnani and Bonazzi, 2005).

According to our preliminary interpretation of the seismic profiles, the most relevant results may be summarized in the following.

The Taormina Fault

As mentioned before, the Taormina Fault is supposed to trend NNE-SSW along the coast of Sicily, between Taormina and Briga (Fig. 1). However, a part from uplifted marine terraces, the fault has not been directly documented, and its occurrence remains hypothetical. Our data do not image a fault running parallel to the coast; on the other hand, the slope between the villages of Taormina and Briga is characterized by a package of sediments originally deposited sub-horizontally and now tilted eastwards (Upper Unit; Fig. 3). A basal onlap of variable extent, minor in places, more pronounced in others, characterizes the lower part of this unit, suggesting the occurrence of a pre-existing mild slope to the west. The same relationship observed on Fig. 3 can be extended to the other seismic profiles all along the segment of coastline where the Taormina Fault is supposed to be located (Fig. 1). This evidence and the record of onshore uplift obtained from coastal geology, suggest that the whole sector straddling the coastline has been tilted seawards; in fact, a slight seaward tilting has been reported from the oldest (125 ka) terraces (Catalano and De Guidi, 2003). Possibly, this tilting did not occur at a constant rate, as indicated by the study of the uplifted marine terraces (De Guidi *et al*., 2003).

This result has two major implications. On the one hand, the absence of the Taormina Fault weakens the model of a single rift belt that extends from Calabria to eastern Sicily, that is from the upper to the lower plate of the Calabrian subduction system (e.g. Monaco and Tortorici, 2000). In fact, this fault represents a basic element in joining the Calabrian and Sicilian branches of the rift system. On the other hand, the lack of seismicity observed in NE Sicily (Neri *et al*., 2006) should be simply interpreted as due to a lack of faults rather than representing a long, and potentially hazardous, loading period along an active fault.

The fault of the 1908 Messina earthquake

The direction, length and dip of the fault responsible for the Messina 1908 earthquake are

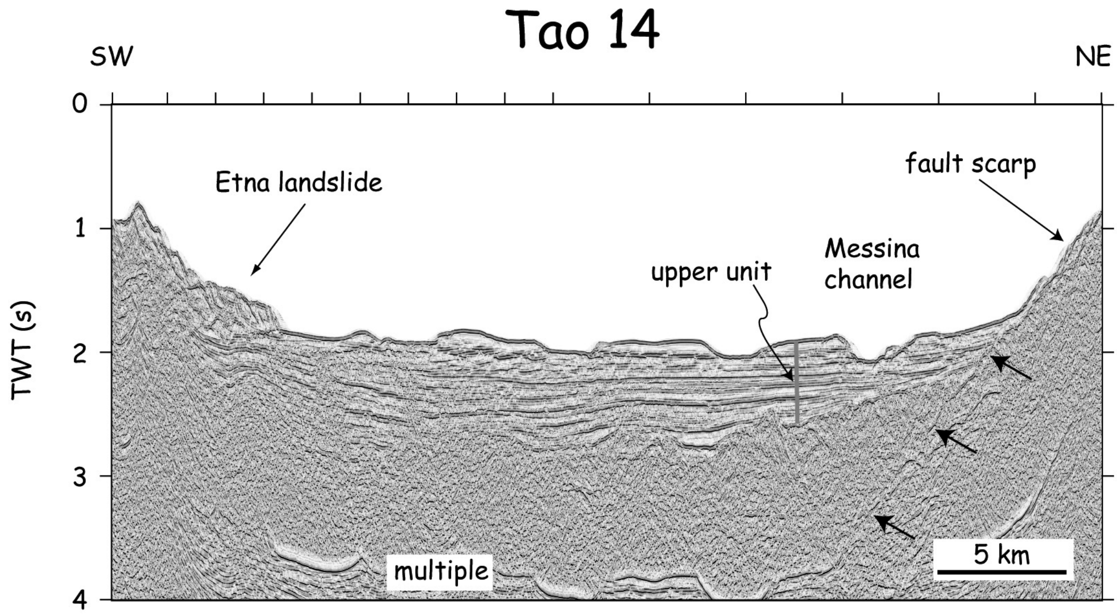

Fig. 5 - Seismic profile TAO 14 (migrated). Note the absence of faulting and the undisrupted Quaternary strata across most of the profile, whereas a fault scarp occurs on the Calabrian side (NE), with arrows indicating the fault plane. On the SW side the profile reaches the Etna submarine slide (see text). Profile acquired with the long streamer. See Fig. 2 for location.

poorly constrained, and vary substantially among diffent authors. Moreover, the structural setting in which the Messina 1908 fault is active is still not clear, also when compared to onshore geology. Within the Messina Straits s.s. the faults imaged by our survey occur on the Calabrian side (e.g., Fig. 4) where they are possibly connected to the fault system reported onshore near Reggio Calabria (Ghisetti, 1992), but they have no obvious relationship with the 1908 Messina earthquake and their current activity is not yet proven.

Some interesting results have been shown by the profiles approaching SW Calabria, where a 20 km-long west-dipping fault is cutting the sea floor (Figs. 5, 6). This fault trends NW-SE and represents the longest lineament observed within the northern Messina Straits (Fig. 2) as the faults inferred as responsible for the 1908 earthquake (see Fig. 2) do not show up on seismic data. The lack of evident extensional faults within the narrower part of the Messina Straits [see also Monaco *et al*. (1996) which show line drawings of seismic profiles that lack major extensional faults] might support the interpretation of a seismogenic fault located to the south of this area or, alternatively, of a blind fault located within the northern Messina Straits. The idea that the 1908 fault might be located along the coasts of southern Calabria has been recently proposed also by Galli *et al*. (2007), on the basis of the geometry and activity of the southern Calabrian faults and of the arrival times of the 1908 tsunami along the Sicilian and Calabrian coasts (see also Tinti, 2007). The most recent macroseismic locations also suggest a NNW-SSE trending seismogenic fault located on the Calabrian side (Fig. 2; Gasperini *et al*., 1999; Michelini *et al*., 2004; DISS Working Group, 2006). However, a west-dipping Calabrian fault contrasts with the results from the most recent studies on the 1908 Messina earthquake that envisage an east-dipping, fairly low-

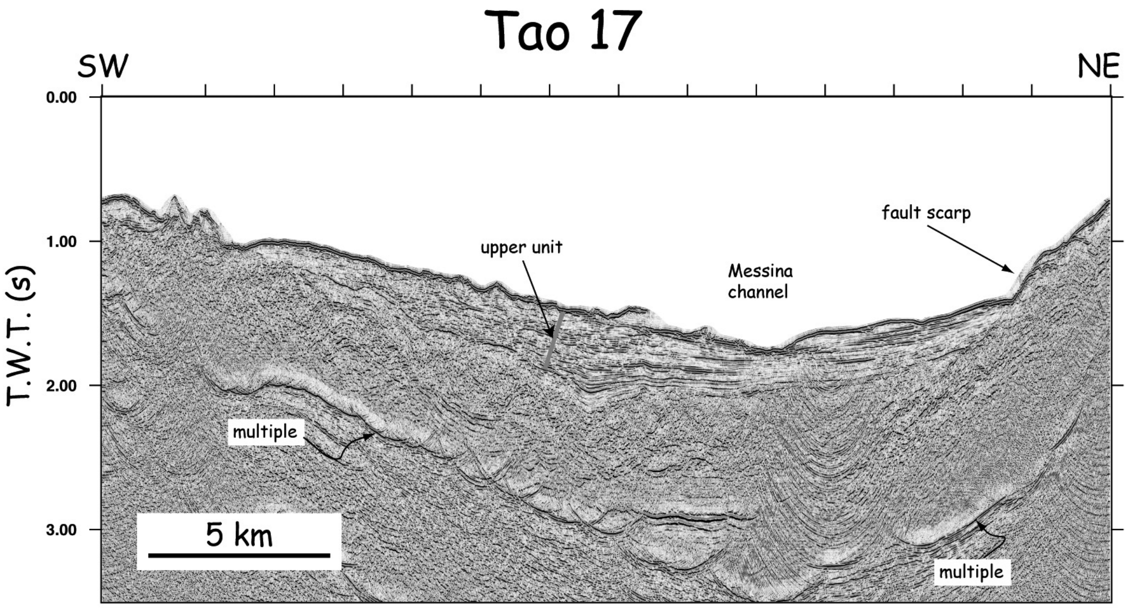

Fig. 6 - Seismic profile TAO 17 (migrated) showing the fault scarp on the Calabrian side (NE), whereas no major faulting affects the Quaternary sedimentary package over the rest of the profile. Profile acquired with the long streamer. See Fig. 2 for location.

angle fault located within the straits (Amoruso *et al*., 2002; DISS Working Group, 2006). In fact, assuming that the epicentre is located above the deeper and seismogenic portion of the fault, a low-angle east-dipping fault would equally be a candidate to match the macroseismic effects related to the1908 earthquake. With the same line of resoning, the fault that we found offshore southern Calabria is unlikely to originate an earthquake that satisfies the 1908 intensity observables, also because a preliminary depth-migration processing indicates that the west-dipping fault plane has a low-angle (within 20-30°). At present, the structural interpretation for the northern part of the Messina Straits is still at a preliminary stage. Whereas the occurrence of a long fault rupturing the sea floor can be discarded, it is difficult to see evidence indicating the occurrence of a blind east-dipping fault, possibly because of limitations of seismic imaging. However, given the large magnitude of the 1908 event, the fact that more than one fault were activated at the same time (see e.g., Mulargia and Boschi, 1983) cannot be ruled out. In this event, the long fault observed offshore southern Calabria can be responsible for the tsunami related to the 1908 earthquake; the tsunami waves observed all along the coast of Sicily, in fact, are hardly compatible with a blind fault located within the northern part of the Messina Straits (Tinti, 2007).

The Etna submarine slide

A large submarine slide has been imaged offshore Mt. Etna, in a region where a chaotic seismic response was previously identified [Fig. 2; Argnani and Bonazzi (2005)] and where the occurrence of a large submarine slide complex has been recently reported (Pareschi *et al*., 2006b). The potential effects related to the emplacement of such a slide complex have been extensively discussed in Pareschi *et al*. (2006a) who envisaged a catastrophic tsunami travelling

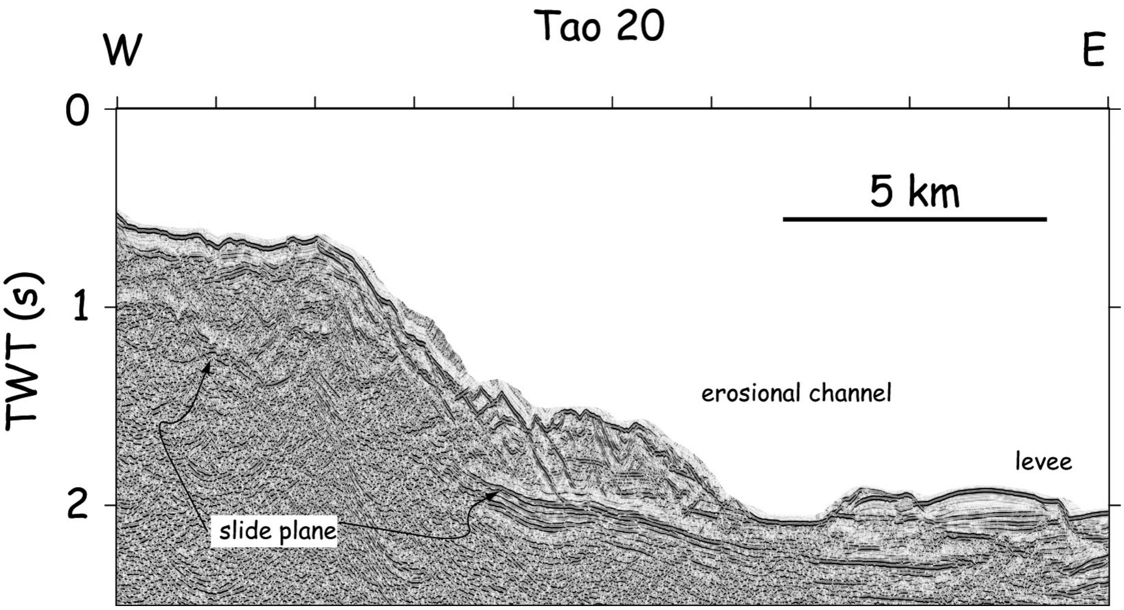

Fig. 7 - Part of seismic profile TAO 20 (migrated) illustrating the geometry of the large submarine slides located offshore Mt. Etna. Stratified sediments are imaged towards the toe of the slides, to the west of the erosional channel. Note that the strata within the toe of the slide show and angle of about 20° with the underlying, seaward-sloping substrate. Profile acquired with the long streamer. Location in Fig. 2.

across the whole of the eastern Mediterranean about 8,000 years ago. Leaving aside the timing of the emplacement of the slide complex, which seems at present still poorly constrained, our data can possibly contribute to better estimating the size and volume of the slide. In fact, Pareschi *et al*. (2006b) presented only limited portions of their seismic data, showing several small scale submarine slides clustered to form a larger complex, and the same appears on their map, where slides are separated and only in very few instances their thickness is over 200 ms (TWT).

Our data, instead, show a huge submarine slide, longer than 10 km and thicker than 400 m located offshore Mt. Etna (Figs. 5 and 7); in particular, at the NE side of Mt. Etna, where the Chiancone unit crops out. The Chiancone is interpreted as the product of the Valle del Bove collapse (Calvari and Groppelli, 1996), and wasting from the Valle del Bove has been considered as a major contributor also to the submarine slide complex (Pareschi *et al*., 2006b). The two deposits have been interpreted as coeval, reaching a total volume of about 20-25 km^3 (Pareschi *et al*., 2006a). The occurrence of chaotic seismic facies within the slide complex has been described by Pareschi *et al*. (2006b); however, our sesimic data show that stratified sediments are extensively involved in the lower part of the slide (Fig. 7), suggesting that submarine sediments, likely deposited along the slope, might represent a large part of the slide. These results point to a slide volume possibly larger than that estimated by Pareschi *et al*. (2006b), if a single sliding event has occurred on the eastern flank of Mt. Etna. On the other hand, if most of the observed landslide deposit has been emplaced by submarine sliding, a reduced tsunamigenic effect should be expected when compared to a slide entering the sea from onshore, as in Pareschi *et al.* (2006a). Such issue too, deserves further investigation.

5. Conclusions

To sum up, the data collected during the TAORMINA-2006 survey should contribute to the undestanding of the recent and active tectonics of the Messina Straits and its marine surroundings. Preliminary results, although still waiting a thorough check, appear to open some intersting questions concerning the position, direction and extent of active faults within the Messina Straits. Moreover, the TAORMINA-2006 seismic survey can help characterize the slide complex located offshore Mt. Etna, and better assess its tsunamigenic potential.

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