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Active faulting and related tsunamis in eastern Sicily and south-western Calabria

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ABSTRACT The Calabrian arc and eastern Sicily are currently affected by large earthquakes and by an intense volcanic activity, related to ESE-WNW trending extensional tectonics. The main regional feature is given by a prominent normal fault belt (the Siculo-Calabrian rift zone) that runs more or less continuously for a total length of about 370 km along the inner side of the Calabrian arc, extending through the Messina Straits along the Ionian coast of Sicily as far as the Hyblean Plateau. The normal faults are characterized by a very young morphology and they control both the major mountain ranges of the region (Catena Costiera, Sila, Serre, Aspromonte, Peloritani, Hyblean Plateau), and the coastline of southern Calabria and eastern Sicily. The distinct fault segments are responsible for the large earthquakes (M~7) that have occurred in this region as the seismic sequences of 1783 in southern Calabria and of 1693 in eastern Sicily, and the 1905 (Monteleone) and 1908 (Messina) earthquakes. These events were caused by slip on 30-40 km long normal fault segments located mainly offshore that also generated the largest tsunamis ever in southern Italy.

1. Introduction

The most common cause of a tsunami is the displacement of the crust along active fault segments during underwater earthquakes which can impart high-potential energy to the overlying water column (Bryant, 2001). Earthquake-generated tsunamis are usually associated with seismic events with surface magnitude greater than 6.5. However, tsunamis can be also generated by small earthquakes or by earthquakes centred inland triggering large submarine landslides.

The Calabrian arc and eastern Sicily are currently affected by large earthquakes and by an intense volcanic activity. Active normal faulting contributes to a continuous extensional deformation from eastern Sicily to south-western Calabria [Siculo-Calabrian rift zone, Fig. 1; Monaco *et al.* (1997), Monaco and Tortorici (2000)], responsible for several historical crustal events (Postpischl, 1985; Boschi *et al.*, 1995, 1997; CMT and RCMT catalogues), the largest of which reached an MCS intensity of X-XI ($6<M<7.5$). The epicentres of these earthquakes (as the 1693 south-eastern Sicily earthquakes, the 1783 southern Calabria sequence, the 1905 Monteleone earthquake and the 1908 Messina earthquake) outline a seismic belt that runs mainly along the Tyrrhenian coast of Calabria and the Ionian coast of Sicily. Although these coastal areas have been repeatedly struck by large tsunamis in historical times (see Table 1; Tinti *et al.*, 2004), the location of the seismogenic sources is still being debated.

The aim of this study is to describe the major offshore normal fault segments of the Siculo-Calabrian rift zone and to characterize their Late Quaternary activity in order to constrain the

Table 1 - Tsunamis that occurred in eastern Sicily and western Calabria during the last millennium according to the catalogue of Tinti *et al*. (2004). Reliability: 0 very improbable; 1 improbable; 2 questionable; 3 probable; 4 definite. Cause: EA earthquake associated; VA volcano associated; EL: earthquake landslide; ER submarine earthquake. Intensity of tsunami: 1 very light; 2 light; 3 rather strong; 4 strong; 5 very strong; 6 disastrous. Earthquake intensity (MCS scale) and equivalent moment magnitude from Gruppo di lavoro CPTI (2004).

Id Code	Year	Month	Day	Subregion	Reliability	Cause	Earthquake Intensity	Earthquake magnitude	Tsunami Intensity
3	1169	2	4	Eastern Sicily	4	ER	10	6.6	4
4	1329	6	28	Eastern Sicily	2	VA			3
10	1638	3	27	Western Calabria	2	EA	11	7	2
12	1649	1		Messina Straits	1	EA	6.5	5	3
14	1693	1	9	Eastern Sicily	2	ER	8.5	6	2
15	1693	1	11	Eastern Sicily	4	ER	11	7.4	5
26	1783	2	5	Western Calabria	4	EA	11	6.9	3
27	1783	2	6	Messina Straits	4	EL	8.5	5.9	6
28	1783	2	7	Western Calabria	1	EA	10.5	6.6	2
29	1783	3	1	Western Calabria	3	EA	9	5.9	2
30	1783	3	28	Western Calabria	3	EA	10	6.9	2
32	1784	1	19	Messina Straits	4	ER	6	4.1	3
38	1818	2	20	Eastern Sicily	4	EA	9	6	2
50	1894	11	16	Western Calabria	4	EA	8.5	6.1	3
51	1905	9	8	Western Calabria	4	EA	11	7.1	3
54	1908	12	28	Messina Straits	4	ER	11	7.2	6
66	1990	12	13	Eastern Sicily	4	ER	7	5.7	2

seismogenic and tsunamigenic potential and their long- and short-term effects on the landscape. This study is supported by mapping of the onshore fault segments, interpretation of aerial photographs and elaboration of satellite SPOT and LANDSAT 5 TM imagery. As regards the offshore segments, available seismic profiles and bathymetric maps have been interpreted. Structural and morphological data have been compared to historical documents and published catalogues (Postpischl, 1985; Soloviev, 1990; Boschi *et al.*, 1995, 1997; Soloviev *et al.*, 2000; Tinti *et al.*, 2004; CMT and RCMT catalogues) to verify if tsunamigenic events with local sources could be associated to each structure.

2. Geological setting

The Siculo–Calabrian rift zone (Monaco *et al.*, 1997; Monaco and Tortorici, 2000) accommodates an ESE-WNW trending regional extension, as deduced from structural analysis (Lanzafame and Tortorici, 1981; Tortorici *et al.*, 1995; Monaco *et al.*, 1997; Jacques *et al.*, 2001), seismological data (Cello *et al.*, 1982; Gasparini *et al.*, 1982; Anderson and Jackson, 1987; Frepoli and Amato, 2000; Pondrelli *et al.*, 2004; Jenny *et al.*, 2006; CMT and RCMT catalogues) and from VLBI (Ward, 1994) and GPS (D'Agostino e Selvaggi, 2004; Goes *et al.*, 2004) velocity fields. Normal faults extend continuously along the western coast of Calabria and, crossing the Messina Straits, along the eastern coast of Sicily. This regional fault belt is about 370 km long and is made up of fault segments with lengths ranging from 10 to 45 km (Fig. 1) that during the

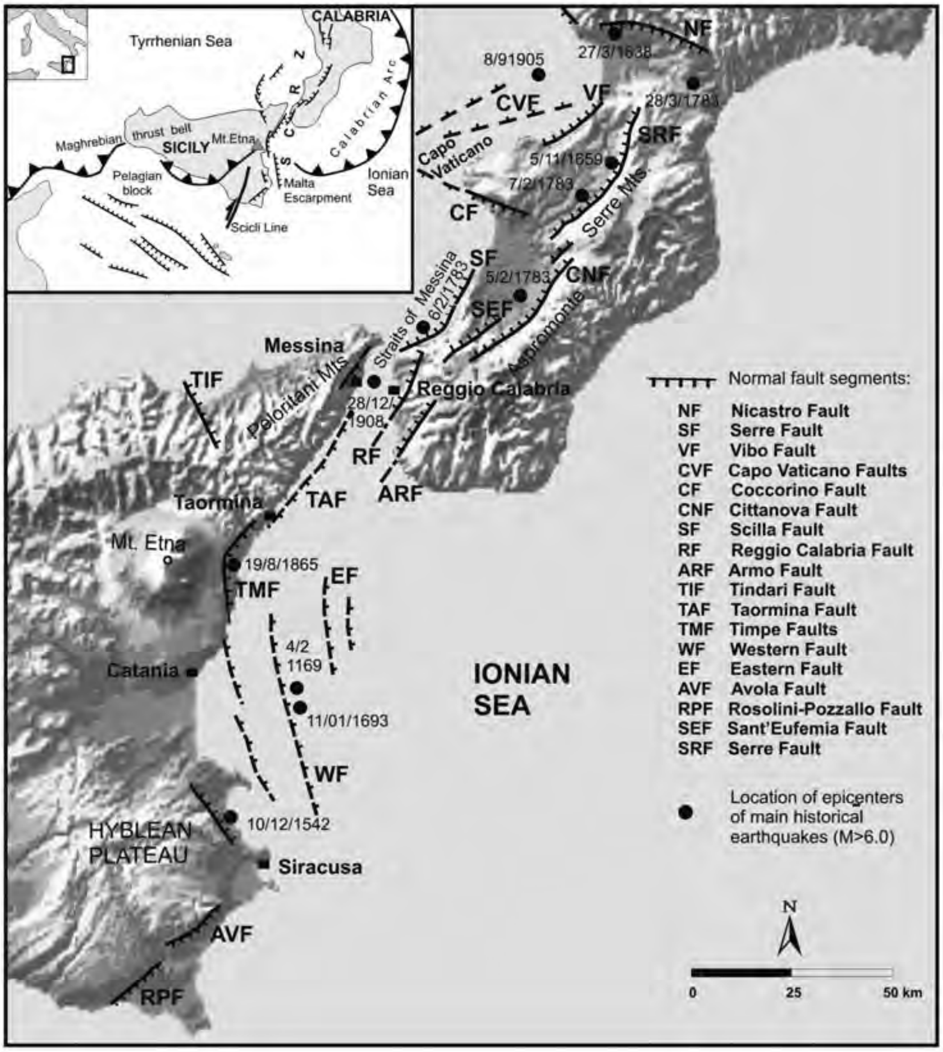

Fig. 1 - Morphotectonic map of southern Calabria and eastern Sicily. Inset: tectonic sketch map of central Mediterranean; lines with triangles indicate the front of the thrust belt, lines with barbs the main Quaternary faults. SCRZ: Siculo-Calabrian rift zone.

Plio-Pleistocene controlled the overall evolution of several sedimentary basins. The distinct fault segments are characterized by a very young morphology and control both the major mountain ranges of the region (Catena Costiera, Sila, Serre, Aspromonte, Peloritani, Hyblean Plateau) and the coastline of south-western Calabria (Capo Vaticano, Scilla and Messina Straits). In eastern Sicily, the fault system is mostly located offshore and controls the Ionian coast from Messina to Taormina, bordering the uplifted Peloritani mountain range and joining the system of the Malta Escarpment from the lower eastern slope of Mt. Etna to the south, where it circles the Hyblean Plateau. Morphological observations and stratigraphic data indicate that the different fault segments are characterized by long-term (since Middle Pleistocene) vertical slip rates ranging between 0.5 and 1.2 mm/yr (Westaway, 1993; Tortorici *et al.*, 1995; Stewart *et al.*, 1997). Values of about 2.0 mm/yr characterize the fault segments located in the volcanic district of the Aeolian archipelago and at Mt. Etna (Monaco *et al.*, 1997).

The development of the Siculo-Calabrian rift zone was coupled with a strong regional uplifting of the whole Calabrian Arc, which probably represents the isostatic response to the removal of a high-density mantle lithosphere root due to the detachment of the Ionian subducted slab (Westaway, 1993; Wortel and Spakman, 1993; De Jonge *et al.*, 1994; Tortorici *et al.*, 1995; Monaco *et al.*, 1996) or the isostatic response to erosion driven by the Pleistocene climate change (Westaway, 2002). Alternative hypotheses sustain that the upheaval of the Calabrian Arc originates from the overthrusting of the Tyrrhenian crust onto the Ionian crust, simultaneously with normal faulting (Ghisetti *et al.*, 1982), or from the intrusion of a fluidized mantle from an asthenolith dome into the crust-mantle boundary (Locardi and Nicolich, 1988; Miyauchi *et al.*, 1994; Gvirtzman and Nur, 1999; Doglioni *et al.*, 2001). According to Westaway (1993), 1.67 mm/yr of post-Middle Pleistocene uplift of southern Calabria is partitioned into ~1 mm/yr due to regional processes and the residual to displacement on major faults. However, the most evident consequence of the widespread Quaternary raising process is the occurrence, up to 1200 m a.s.l., of both Plio-Pleistocene marine sequences and spectacular flights of marine terraces downslope.

The Siculo-Calabrian rift zone is also one of the most active seismic belts of the central Mediterranean region. The distribution of crustal seismicity shows that most of the earthquakes that occurred in this area, including the major events with $M>6$, are located in the hanging-walls of the distinct Quaternary normal fault segments. Available structural and seismological data carried out in the last years on different portions of this region (Shick, 1977; Cello *et al.*, 1982; Gasparini *et al.*, 1982; Ghisetti *et al.*, 1982; Mulargia and Boschi, 1983; Ghisetti, 1984, 1992; Hirn *et al.*, 1997; Anderson and Jackson, 1987; Bottari *et al.*, 1986, 1989; De Natale and Pingue, 1991; Valensise and Pantosti, 1992; Westaway, 1992, 1993; Tortorici *et al.*, 1995; Sirovich and Pettenati, 1999; Bianca *et al.*, 1999; Azzaro and Barbano, 2000; Monaco and Tortorici, 2000; Jacques *et al.*, 2001; Galli and Bosi, 2002; Catalano and De Guidi, 2003; Catalano *et al.*, 2003; Tortorici *et al.*, 2003; De Guidi *et al.*, 2003; Goes *et al.*, 2004; Argnani and Bonazzi, 2005; Ferranti *et al.*, 2006; Jenny *et al.*, 2006) have given constraints to formulate different large scale seismotectonic models. In particular, as regards the tsunamigenic sources, different hypotheses have been proposed, sometimes relating tsunami events to ruptures along faults located inland (Tinti and Armigliato, 2000, 2001, 2003; Piatanesi and Tinti, 1998, 2002). The following sections are dedicated to the analysis of historical tsunami events and possible local sources identifiable on offshore seismic profiles. In the regions where these are not available, the occurrence of flights of raised Late Quaternary palaeo-shorelines and marine terraces represents a useful tool to define the short- and long-term vertical deformation which can be associated with offshore normal faults. These structures mainly border the Capo Vaticano Peninsula, the Palmi-Bagnara-Scilla High, the Messina Straits in south-western Calabria and the Peloritani mountain range, the Mt. Etna-Hyblean region in eastern Sicily.

3. Active faulting and related tsunami

3.1. Capo Vaticano Peninsula

The Capo Vaticano area is a horst structure bound by two antithetic, NE-SW striking, Tropea and Mileto normal faults (Fig. 2), showing a steep coastal morphology. To the northeast, the

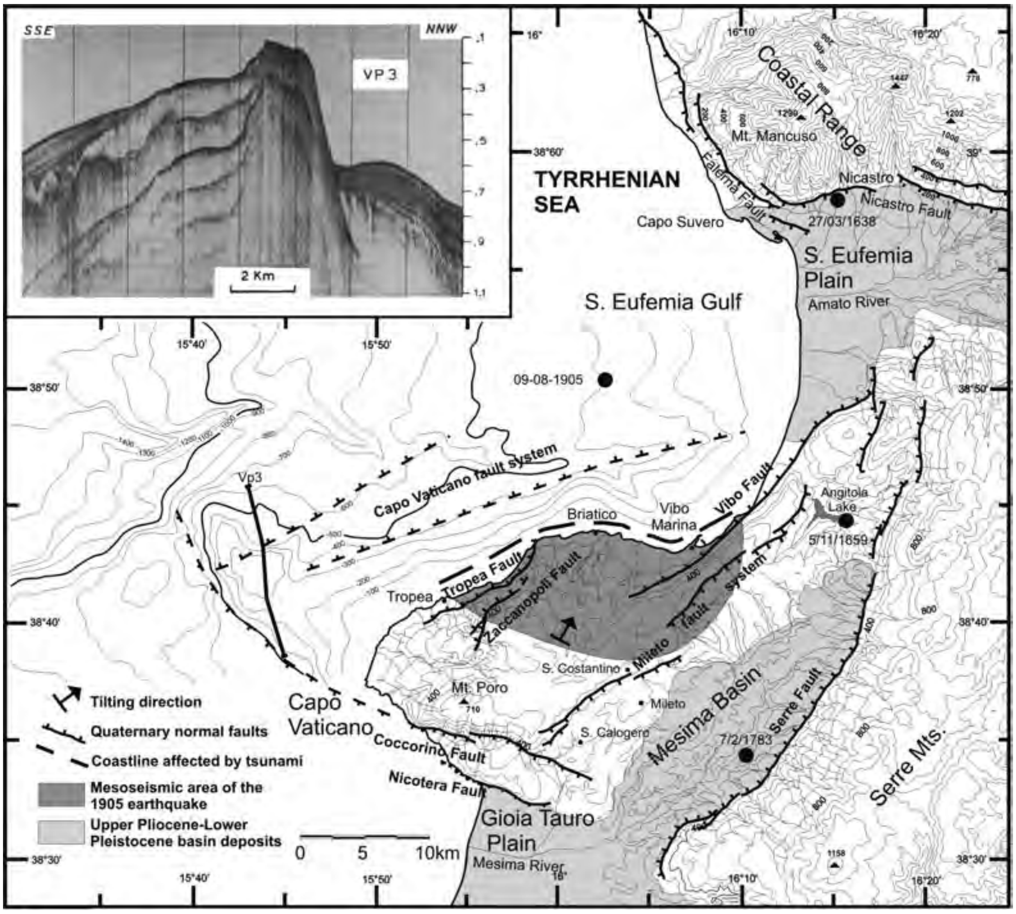

Fig. 2 - Structural map of the area of Capo Vaticano peninsula and S. Eufemia Plain, comprising the Tyrrhenian offshore (see location in Fig. 1). Bathymetry from Argnani and Trincardi (1988, modified). The epicentre of the 1905 earthquake [black circle; from Postpischl, (1985)] is also shown. Inset: seismic profile Vp3 (from Trincardi *et al.*, 1987) showing a normal fault scarp in the north-western offshore of the Capo Vaticano peninsula (for the trace of profile see the figure). Vertical scale is two travel time in seconds.

Briatico area represents the overlap zone between the en-echelon Tropea and Vibo normal faults. This area, interpreted as a “bridge zone” or “relay ramp” by Tortorici *et al.* (2003), is characterized by a slightly inclined morphological slope and a well developed stream-channel pattern. The occurrence of a NE-SW striking, NW-facing normal fault system in the north-western offshore has been proved by a SSE-NNW striking single-channel seismic profile (Vp3, see inset in Fig. 2) carried out by Trincardi *et al.* (1987), that illustrates an active normal fault affecting the sea-bottom and creating a roughly 300 m high scarp located at about 10 km from the coastline. The bathymetric map (Fig. 2) constructed by Argnani and Trincardi (1988) shows an ENE-WSW trending scarp, located at about 5 km from the coastline, which can be interpreted as the eastern extension of the system [Capo Vaticano Fault, Monaco and Tortorici (2000)]. To the south-west, the promontory is abruptly truncated by two main WNW-ESE striking, SSW-dipping normal faults (Coccorino and Nicotera faults) which separate the Capo Vaticano structural high from the Gioia Tauro Basin, filled by a thick Upper Pliocene-Quaternary sedimentary succession (Ghisetti, 1981). The isobath pattern of Fig. 2 strongly suggests the offshore continuation of the Coccorino Fault (see below) which interrupts the continuity of the NE-SW fault system. Landwards, to the south-east, antithetical SE-facing fault segments (Mileto faults) separate the Capo Vaticano horst from the Mesima Graben (Fig. 2), a basin filled by a thick Upper Pliocene-Lower Pleistocene marine succession (Ghisetti, 1981), capped by several marine and fluvial terraces.

The geological backbone of the Capo Vaticano peninsula is mainly made up of a Palaeozoic basement, covered by remnants of Miocene and Pliocene carbonate and terrigenous deposits (Burton, 1971), on top of which at least six distinct orders of well preserved Quaternary marine terraces have been recognized (Westaway, 1993; Miyauchi *et al.*, 1994; Tortorici *et al.*, 2003). The marine terraces consist of a Middle-Late Pleistocene flight of wave-cut surfaces and/or thin-depositional platforms, usually bounded landwards by well developed inner edges representing the palaeo-shorelines related to the main sea level high-stands. They show an overall good morphological continuity and extend with a concentric geometry around the structural high being characterized by elevations regularly increasing to the south-west (Tortorici *et al.*, 2003).

The geometry of the palaeo-shorelines indicates that the raising process has been characterized by uplift rates increasing toward the south-west. For example, in the Vibo Marina area, located at the hanging-wall of the Vibo Fault (Fig. 2), the palaeo-shoreline of the last interglacial high stand (125 kyrs) is located at elevations of 75 m a.s.l., indicating an average uplift rate (corrected for the original sea level of +6 m) of 0.5 mm/yr in the last 125 kyr; to the south-west, in the Capo Vaticano area at the foot-wall of the Coccorino Fault, the same palaeo-shoreline is located at an elevation of 300 m a.s.l., indicating an average uplift rate of 2.3 mm/yr in the same period.

On September 8, 1905, at around 01:43 a.m. local time, a large earthquake with an MCS intensity X-XI and M~7.0 (Postpischl, 1985; Boschi *et al.*, 1995) occurred offshore the Capo Vaticano Peninsula (Gasparini *et al.*, 1982). This event severely damaged towns and villages all around the Tyrrhenian coast (557 dead, more than 2000 injured and about 300,000 homeless), from Capo Vaticano to Capo Suvero (Fig. 2), where several ground effects such as cracks, landslides and sand craters were caused, and it was accompanied by a tsunami that flooded the northern coast of the Capo Vaticano Peninsula (Piatanesi and Tinti, 2002). The tsunami was not catastrophic [I=3, Table 1; Tinti *et al.* (2004)], but it was observed both in the open sea and along the coast (Baratta, 1906; Mercalli, 1906; Rizzo, 1907; Platania, 1907; see also Tinti *et al.*, 2004). Along the northern coast of Capo Vaticano a lot of dead fish were found on the beaches and inundation by some tens of meters was reported in several villages with fishing boats carried inland. The tsunami waves propagated out to the Tyrrhenian Sea to large distances from the source region, as recorded by the tide-gauges of Milazzo (80 cm), in north-eastern Sicily and Naples (18 cm).

There is no agreement regarding the epicentre of the 1905 earthquake (Fig. 2), as it is reported offshore by Postpischl (1985) and onshore by Boschi *et al.* (1995). According to Piatanesi and Tinti (2002), there are two active fault segments intersecting the epicentral area that can be considered good candidates for the source of both the earthquake and the tsunami, namely the Capo Vaticano and the Vibo Valentia faults. Also the numerical modeling of Piatanesi and Tinti

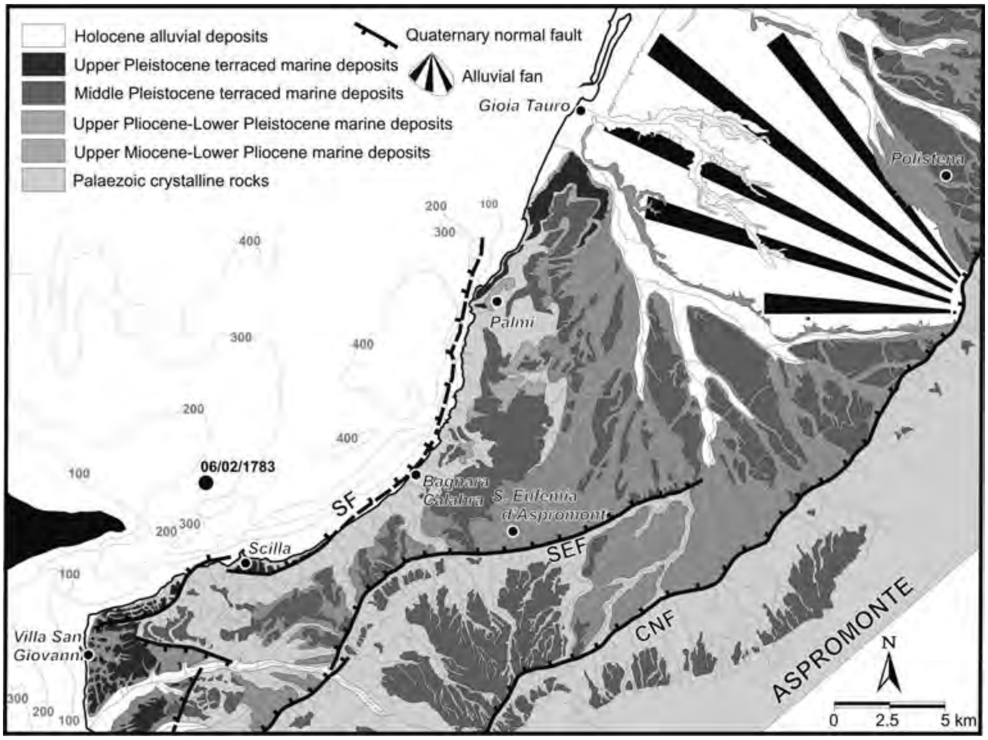

Fig. 3 - Structural map of south-western Calabria (see location in Fig. 1), showing the epicentre of the February 5, 1783 earthquake [black circle; from Jacques *et al.* (2001)]. SF: Scilla Fault; SEF: S. Eufemia Fault; CNF: Cittanova Fault. Bathymetry from Selli *et al.* (1978-79, modified).

(2002) cannot discriminate between the two faults. However, the mesoseismic area concentrated along and near the northern coast of Capo Vaticano (Fig. 2) and all the isoseismals opening seawards suggest an epicentre located offshore along the Capo Vaticano Fault. Moreover, the overall deformation pattern of palaeo-shorelines in the Capo Vaticano Peninsula, also constraining short-term accelerations and decelerations in the uplift rates [see Tortorici *et al.* (2003) for a more complete discussion], confirms the occurrence of an important tectonic component in the total amount of uplift, related to the Late Quaternary activity of the normal fault segments bounding the Capo Vaticano structural high offshore. In particular, seismic profiles (see inset in Fig. 2) show that the Capo Vaticano fault has been active in very recent times.

3.2. South-western Calabria

To the south, the normal fault belt bounds the Aspromonte mountain range from where, with a right hand en-echelon arrangement, it reaches the Messina Straits area where the southernmost Scilla fault occurs (Fig. 1). It was traced mostly offshore, on the basis of coastal findings and bathymetry considerations (Fig. 3). The NW dipping, 30 km long Scilla fault runs along the Tyrrhenian shore from Palmi to Bagnara, bordering the Palmi high with a NNE-SSW direction (Figs. 1 and 3). In this sector, the escarpment forms an up to 600 m high cliff, at the top of which a Middle Pleistocene marine terrace (Ghisetti, 1981; Dumas *et al.*, 1982), tilted towards the southeast, overlies the crystalline rocks of the uplifted footwall (Burton, 1971). Southwest of Bagnara the fault turns to a ENE-WSW direction penetrating onshore as far as Scilla. West of Scilla the fault jumps back offshore, through an en-echelon overlap link (Fig. 3), leaving the Middle-Late Pleistocene terraces in the footwall block. At least four orders of marine terraces have been found southwest of Scilla (Fig. 3), referring to the OIT stages 11, 9, 7 and 5 corresponding to Middle-Upper Pleistocene sea level high-stands (Valensise and Pantosti, 1992; Westaway, 1993; Miyuachi *et al.*, 1994; Tortorici *et al.*, 1995; Jacques *et al.*, 2001). East of Villa San Giovanni, the OIT 5 stage terraced deposits (125 kyr) have been offset by about 90 m by the southwestern portion of the Scilla fault, thus suggesting a vertical slip rate of about 0.7 mm/yr in the last 125 kyr (Jacques *et al.*, 2001).

The recent activity of the Scilla fault is testified by the occurrence, on its footwall, of a Holocene marine platform and beaches rocks uplifted up to 4 m, whose radiocarbon age ranges from 1.9 to 3.9 kyr (Antonioli *et al.*, 2004). According to these authors, the Late Holocene uplift-rate of the Scilla coastline, corrected for eustatic changes and glacio-hydroisostatic adjustments (Lambeck *et al.*, 2004), is ~1.6-2.1 mm/yr almost equally balanced between the steady and the stick-slip components. Abrupt displacements, mostly accommodated by a footwall uplift (1-2 m), have been attributed to two co-seismic events (~1.8 and ~3.5 kyr) constrained in distinct coastal sites (Ferranti *et al.*, 2006). Empirical relationships between fault length and displacement per event (Wells and Coppersmith, 1994) suggest the occurrence of M~7 earthquakes with a ~1.6-1.7 kyr recurrence time.

Between February 5 and March 28, 1783, a sequence of five large earthquakes devastated the southern part of Calabria, from Reggio di Calabria to Catanzaro (Fig. 4). This remarkable sequence started with a catastrophic event at 12h 45min, on February 5, 1783 [I=XI-XII, M=7; Jacques *et al.* (2001), see also Postpischl (1985), Boschi *et al.* (1995, 1997)] which damaged about 400 villages and caused 25,000 victims. Inland, at the western foot of the northern Aspromonte, towns and villages were completely destroyed and several landslides occurred (Vivenzio, 1783; Hamilton, 1783; De Dolomieu, 1784; Baratta, 1901; Cotecchia *et al.*, 1969), and villages closer to the Tyrrhenian coast (Palmi, Bagnara, Scilla) were seriously damaged (Fig. 4). Even if the epicentre of this shock was been located inland, along the Cittanova fault in the Aspromonte piedmont [see Jacques *et al.* (2001) for a more complete discussion], it was followed by a rather strong tsunami [I=3, Table 1; Tinti *et al.* (2004)] which mostly affected the Calabrian coastal area from Nicotera to Catona and the lowland from Messina to Punta Faro (on Capo Peloro, Sicily north-easternmost cape). Sea water flooded these coastal areas several times and fishing boats were turned upside-down.

On February 6, 1783, at 1h 06min, a second large shock [I=X-XI, M=6.5; Jacques *et al.* (2001)] struck, mostly, the coastal area between Scilla and Palmi, bringing the cumulative damage in this area to a level almost comparable to that in the Aspromonte piedmont. Major rock-slides along the cliff, west of Scilla (part of Monte Paci and Campallà fell into the sea) and a tsunami wave which affected principally the Scilla coastal area and the lowland of Punta Faro were clearly triggered by that second earthquake. The following disastrous tsunami [I=6, Table 1; Tinti *et al.* (2004)] killed some 1500 people that, frightened by the first shock, sheltered on the Marina Grande beach near Scilla where 6-9 m high waves were observed (Sarconi, 1784). Although De Dolomieu (1784), and Baratta (1901), among others, disagree on whether the

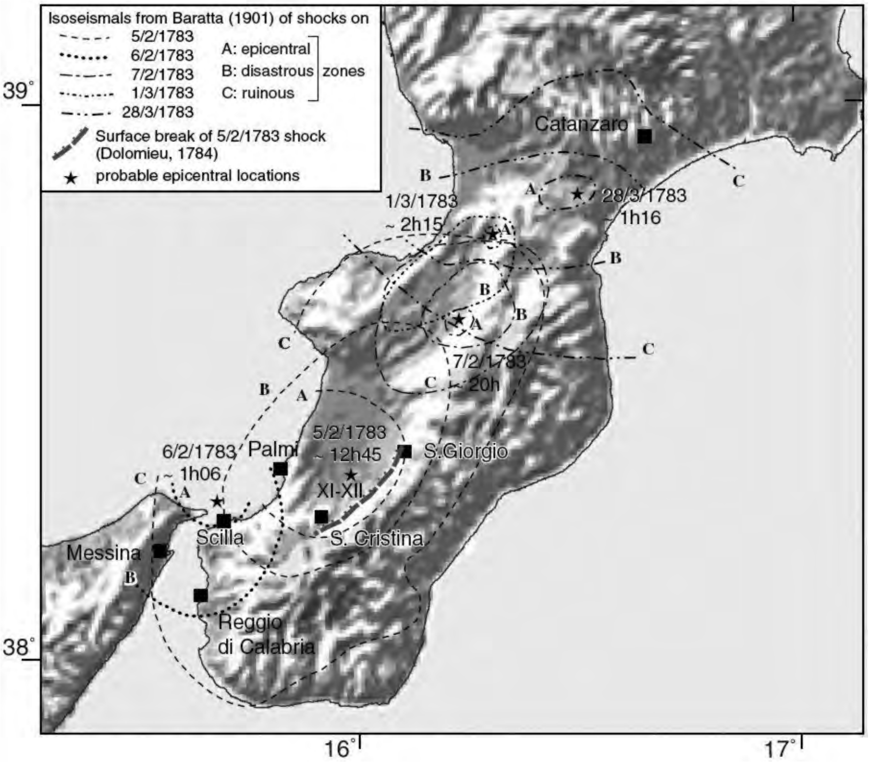

Fig. 4 - Isoseismal and epicentral locations of the five principal shocks of the 1783 earthquake sequence (after Baratta, 1901; Jacques *et al*., 2001).

tsunami was a mere consequence of the rock-slide or generated by the earthquake, most chroniclers concur in locating the “centre” of this second shock offshore (Figs. 3 and 4), not far from Scilla [see also Jacques *et al.* (2001)]. Recent investigations (Bosman *et al.*, 2006) allow us to infer a submarine landslide in continuity with the Mt. Paci sub-aerial collapse as a possible cause. Whatever the case, in our opinion, the second shock of the 1783 earthquake sequence may be correlated to a slip along the Scilla fault segment which could have triggered the large landslide on the footwall. According to Ferranti *et al.* (2006), the palaeo-seismological record suggests that the last rupture on the Scilla fault during the February 6, 1783 earthquake, not accompanied by evident coastal uplift, was at the expected time but did not release the entire loaded stress.

The following shocks of the 1783 sequence (February 7, March 1 and 28, see Table 1) were located inland at the piedmont of the Serre mountain range (Fig. 4) and locally triggered light tsunami waves along the Calabrian coasts [I=2 according to Tinti *et al.* (2004)].

3.3. Messina Straits

In the Messina Straits area, the major normal faults extend along the Calabrian side (Fig. 1). The main segment is represented by the 15 km-long NNE-SSW trending Reggio Calabria fault that during the Early Pleistocene has controlled the Middle-Late Pleistocene evolution of the

Reggio Calabria half graben (Ghisetti, 1981; Barrier, 1987; Tortorici *et al.*, 1995). The fault offset 125 kyr old sediments whereas the youngest deposits, cropping out in the downthrown block, are made up of continental alluvial which, covering the marine sequence unconformably, represent the remnants of large gently sloping alluvial fans of Wurmian age (Dumas *et al.*, 1979). These deposits progressively onlap the fault plane thus suggesting faulting activity during that period. In addition, a flight of marine terraces, ranging in age from 118±13 kyr to 64±8 kyr (Balescu *et al.*, 1997), assigned to the 5.3-3.3 OIT stages (Catalano *et al.*, 2003), occur at different elevations on both upthrown and downthrown blocks. The fault plane dips steeply westwards and deforms both crystalline rocks and Middle-Upper Pleistocene sediments. The fault trace runs more or less continuously near the coastline as far as Reggio Calabria (Fig. 5) from where it seems to continue offshore for about 10 km (Ambrosetti *et al.*, 1987). Morphologically it is defined by a 70-100 m-high escarpment which extends discontinuously at the boundary between the mountain front and the adjacent coastal plain and is characterized by one set of triangular facets showing heights ranging from 50 m to 70 m. All these observations indicate a recent activity of the Reggio Calabria fault with slip-rates of up to 0.6 mm/yr (Ghisetti, 1992; Westaway, 1993; Tortorici *et al.*, 1995).

On December 28, 1908, one of the largest earthquakes of southern Italy struck the Strait of Messina area (Fig. 5). This event of MCS intensity XI and M=7.1-7.2 (Postpischl, 1985; Boschi *et al.*, 1995, 1997; Gruppo di Lavoro CPTI, 2004) completely destroyed the entire Straits of Messina area, killing about 70,000 people (Baratta, 1910). The area, devastated by the main shock, was mostly located on the Calabrian side of the strait extending to the Sicilian coast along a narrow belt including the town of Messina. In Calabria, the mesoseismal area formed two wide NE-oriented lobes extending to the hanging-walls of the normal fault segments affecting the area (Armo and Reggio Calabria faults, Fig. 5). Towns and villages located within this area (including the town of Reggio di Calabria) were completely destroyed suffering damage ascribed to an MCS intensity ≥X (Boschi *et al.*, 1995). In this area, the percentage of ruined buildings was higher than 90% as reported from the chronicle of Baratta (1910). Many other villages, located within a narrow belt (3-4 km wide) surrounding the mesoseismal area, were extensively damaged suffering a percentage of ruined buildings ranging between 45% and 90% (Baratta, 1910) indicating an MCS intensity of IX (Boschi *et al.*, 1995). Several landslides occurred inland in the surroundings of Reggio di Calabria and along the sea-cliff from Scilla to Bagnara. Together with the occurrence of sand fountains, related to liquefaction reported in the Reggio di Calabria area, one of the most impressive coseismic effect was the permanent subsidence, estimated at about 0.7-1.0 m, of the entire coastline from Lazzaro to Bagnara (Baratta, 1910). In Sicily, the mesoseismal area was confined near the coast along a few km wide (1-4 km) belt where the town of Messina and surrounding villages were completely ruined by shacking and subsequent tsunami (Fig. 5). Villages with damage ascribed to an MCS intensity of IX (Boschi *et al.*, 1995) define a narrow belt that envelops the mesoseismal area to the west. Sand fountains spurted water from linear fractures and cracks developed on the coastal plain from Messina to Ganzirri (Baratta, 1910). Several fractures affected the entire quay of the harbour of Messina depicting an overall arc-shaped geometry (Baratta, 1910). These fractures, that also occurred during the main shock of the 1783 earthquake sequence, may be interpreted as the surface evidence of the re-activation of the main scarp at the crown of a submarine landslide.

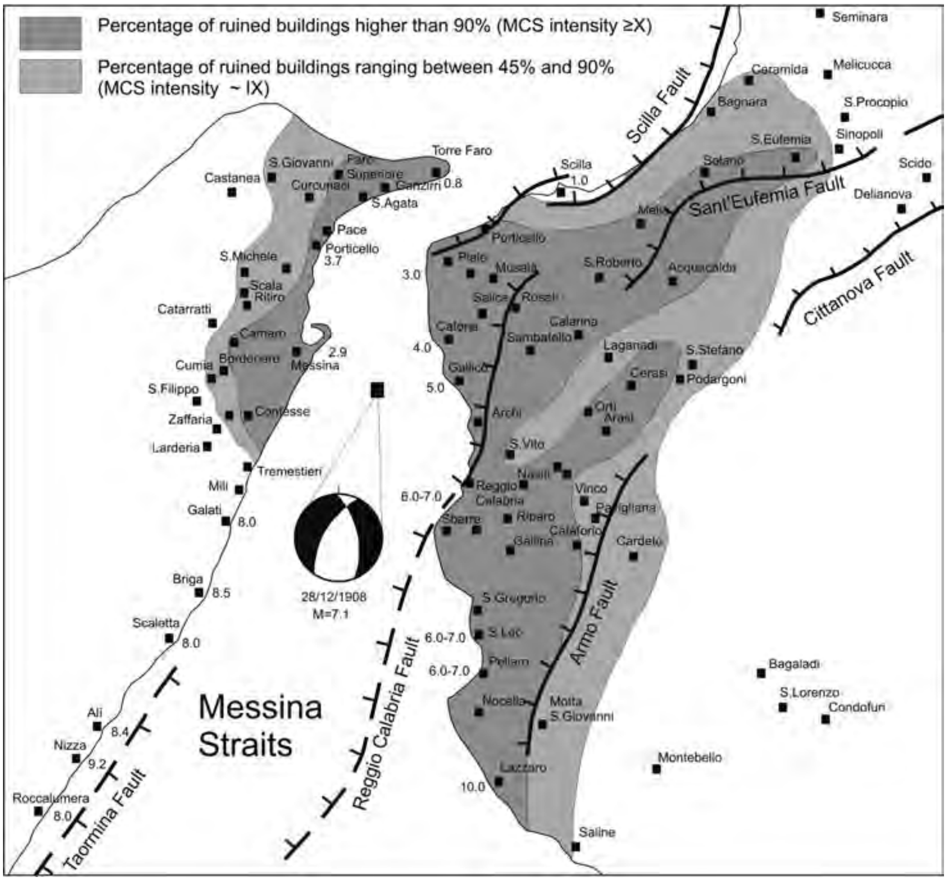

Fig. 5 - Cartoon showing epicentre and damage distribution of the December 1908 earthquake [data from Baratta (1910) and Boschi *et al*. (1995)] and the main faults (from Ghisetti, 1992; Tortorici *et al*., 1995; Monaco and Tortorici, 2000; Jacques *et al*., 2001) of the Messina Straits area (see location in Fig. 1). The maximum height (in metres) reached by the tsunami waves is also indicated [data from Baratta (1910)].

This event also generated a large tsunami [*I*=6, Table 1; Tinti *et al.* (2004)] that devastated both sides of the Strait of Messina, causing hundreds of victims and severe damage to buildings, ships and the environment. It was recorded along the Tyrrhenian coast of Sicily as far as Termini Imerese and up north as far as Naples, the entire Ionian coast of eastern Sicily and part of the northern and southern coasts of the island, as far as Malta. The tsunami was characterized by an initial sea withdrawal (up to 200 m) followed by at least three distinct large waves that with a maximum height of 2.9 m inundated the town of Messina and with a height of 6-7 m the town of Reggio Calabria (Platania, 1909). The maximum height reached by the wave in southern Calabria was 10 m at Lazzaro where the sea water penetrated inland for 250 m and a run-up of about 13 m was recorded (Baratta, 1910). The maximum amplitude of the tsunami wave along the Ionian coast of Sicily was recorded from Furci to Galati Marina with values estimated from 6.4 to 9.2 m (Baratta, 1910). To the south, along the coast of the Catania Plain, waves were less than 3 m high but penetrated about 700 m inland (Tinti and Armigliato, 2003). The effects of the tsunami are still recognizable near Siracusa where boulders up to 182 ton in weight, encrusted by barnacles dated at about 100 years, were removed and transported inland at a distance of up to 70 m (Monaco *et al.*, 2006). It is worth noting that the wave heights estimated for the transport of these boulders (2.4-3.0 m) are well constrained by values reported by the Siracusa harbour office (*Regia Capitaneria di Porto*), which estimated a 2 m high wave (Baratta, 1910).

Different sources have been proposed for the 1908 earthquake but all agree on dominant normal faulting on planes trending nearly parallel to the Messina Straits (see also Anderson and Jackson, 1987; Ghisetti, 1982; Valensise and Pantosti, 1992). The displacement caused a coseismic down-warping of the area which was documented by a levelling survey performed one year before and immediately after the earthquake (Loperfido, 1909). Based on inversion of the levelling data, a low angle, east–dipping normal fault, merging at the surface on the Sicilian coastline, has been proposed (Capuano *et al.*, 1988; De Natale and Pingue, 1991; Boschi *et al.*, 1989; Valensise and Pantosti, 1992; Amoruso *et al.*, 2002). However, the above-mentioned observations produce a clear macroseismic picture that strongly suggests that this event could be related to ruptures occurring along the NE trending, west-facing Reggio Calabria fault including its offshore propagation on the Strait of Messina (see also Schick, 1977; Bottari *et al.*, 1986; Ghisetti, 1984; Westaway, 1992; Tortorici *et al.*, 1995). The area of major damage was in fact located along the Calabrian side of the Straits where permanent subsidence and ground fractures were recorded, whereas the damage at the Sicilian side was mostly related to the occurrence of the destructive tsunami. This interpretation is supported by the analysis of the focal mechanism that shows a slip occurring along a NNE trending, west-facing nodal plane (Riuscetti and Schick, 1975; Shick, 1977) and is consistent with the regional structure of the Messina Straits area, characterized by master faults on the Calabrian side and associated antithetic faults on the Sicilian side (Ghisetti, 1984; Montenat *et al.*, 1991; Tortorici *et al.*, 1995). However, as the source model of a low-angle blind normal fault merging at the surface on the Sicilian side has to be reconciled with the strong rates of deformation on the high-angle west-dipping morphogenic fault along the Calabrian coastline, an alternative model can be represented by displacement on two antithetic structures (see also Mulargia and Boschi, 1983; Bottari *et al.*, 1989). Finally, according to the numerical modelling simulations performed by Tinti and Armigliato (2000, 2001, 2003) on the basis of an east-dipping source, the tsunamigenic earthquake source is certainly placed under the Messina Straits, where it caused subsidence of the sea floor, and extends under the Ionian Sea to the south of the Straits.

3.4. North-eastern Sicily

In eastern Sicily, the Siculo-Calabrian rift is formed by a few fault segments mostly running along the Ionian coastline, and striking both NNE and NNW. The major fault segments (Fig. 1) include the Taormina fault located offshore between Messina and Taormina, the Timpe fault system along the lower eastern flank of the Mt. Etna volcano and the western fault offshore, between Catania and Siracusa.

The existence of the east-facing, 40 km-long, Taormina Fault at the piedmont of the Peloritani Mts. [“Messina-Fiumefreddo System” of Ghisetti and Vezzani (1982), also reported in Bosi *et al.* (1983) and Scandone *et al.* (1991)] has been suggested by the long-term deformation pattern of the marine terraces (Catalano and De Guidi, 2003), and its recent activity is documented by a ~5

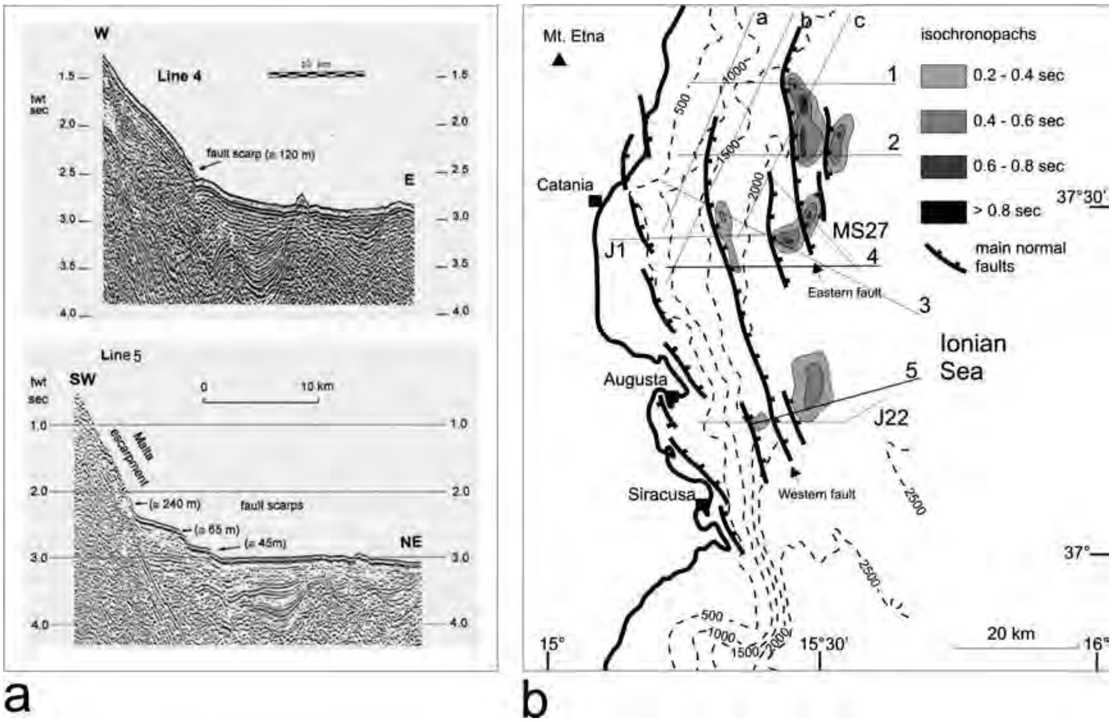

Fig. 6 - a) Reflection profiles showing the Western Fault along the Malta Escarpment accompanied by minor synthetic faults. Note the seafloor offset and the syn-rift basin eastwards (for location see Fig. 6b). b) Structural sketch map of the Ionian offshore zone of eastern Sicily (see location in Fig. 1) derived from the analysis of seismic reflection profiles. Location of seismic profiles (see Scandone *et al*., 1981; Sartori *et al*., 1991; Hirn *et al*., 1997; Bianca *et al*., 1999) used to draw the map is also showed. Isochronopachs of the seismostratigraphic interval included between the basal horizon of Middle Pleistocene-Holocene deposits and the seafloor show the overall geometry of the main eye-shaped syn-rift basins developed along the hanging wall of the major normal fault segments (from Bianca *et al*., 1999).

kyr long co-seismic uplift recorded by development of a stepped array of limestone tidal notches (Firth *et al*., 1996; Stewart *et al.,* 1997; Rust and Kershaw, 2000; De Guidi *et al*., 2003). The Holocene coastal morphology in the Taormina region is in fact characterized by three major elevated notches that suggest the occurrence of three major seismic events that produced 1-2 m of vertical coseismic displacement of the coast at about 5, 3.2 and in <3.2 kya B.P. (De Guidi *et al*., 2003). Taking into account the Holocene co-seismic displacements of the Taormina coastal area and empirical relationships between fault length and displacement per event (Wells and Coppersmith, 1994), earthquakes with *M*~6.5 and *M*~7 can be inferred for the minor and major events, respectively. Nevertheless, seismic historical data for this sector of eastern Sicily (see Boschi *et al*., 1995, 1997; Baratta, 1901, 1910; Postpischl, 1985) indicate a very low-level-to-absent seismicity since the ancient Greek times (VIII century B.C.).

3.5. South-eastern Sicily

South of Taormina (Fig. 1), the fault belt penetrates onshore where it is represented by the 25 km-long, NNE and NNW trending Timpe fault system (Monaco *et al*., 1997; Azzaro, 1999).

From Catania to Siracusa, the fault belt continues offshore, where it includes several segments striking NNW-SSE. These segments, as shown by several seismic profiles carried out on the Ionian offshore (Scandone *et al.*, 1981; Sartori *et al.,* 1991; Hirn *et al.* 1997; Bianca *et al.*, 1999; Argnani and Bonazzi, 2005), are represented by two main east-facing normal faults that affect the entire crust and define, in the hanging-wall, well developed wedge-shaped basins infilled with Middle-Upper Quaternary syn-rift clastic wedges thickening towards the boundary faults (Fig. 6a). The most prominent fault segment of this branch of the Siculo-Calabrian rift is represented by the Western Fault (Fig. 6b), that extends parallel to the coastline for a total length of about 45 km. This fault segment cuts the thinned crust of the Ionian domain and, re-activating the Malta escarpment to the south, offsets the sea-floor creating well-developed steep scarps that reach heights of 80-240 m (Bianca *et al.*, 1999). Its activity caused the slow uplift of the Hyblean Plateau as testified by the occurrence of a flight of Quaternary terraces ranging in age from 400 to 60 ky (Bianca *et al.*, 1999).

Between January 9 and 11, 1693 the whole of south-eastern Sicily was devastated by two large earthquakes of MCS intensities VIII-IX and XI, respectively. The first shock occurred at about 9 p.m. (GMT) and caused severe damage (Boschi *et al.,* 1995) along a narrow belt (Fig. 7a) extending at the foot of the eastern border of the Hyblean Plateau (Avola and Climiti Mounts). No relevant tsunami was induced by this event (see Tinti and Maramai, 1996; Tinti and Armigliato, 2003). The second and main shock occurred at about 1:30 p.m. (GMT) and was catastrophic [M between 7 and 7.5, according to Postpischl (1985), Westaway (1992), Bianca *et al.* (1999), Azzaro and Barbano (2000), Gruppo di Lavoro CPTI (2004)] devastating the entire south-eastern part of Sicily and killing about 54,000 people (Boccone 1697; Baratta 1901). Towns and villages located close to the south-eastern coast of Sicily (Fig. 7b), such as Catania, Lentini, Carlentini, Augusta, Melilli, Floridia, Canicattini, Avola Antica and Noto Antica, which had already been seriously affected by the event of January 9, were completely destroyed suffering damage ascribed to an MCS intensity greater than X (Boschi *et al.,* 1995). Many other towns, located in an area extending from the eastern foot of Mt. Etna to the southern coast of the Hyblean Plateau were extensively ruined, defining the area characterized by an MCS intensity of X (Boschi *et al.,* 1995). The overall distribution of the effects of the main shock shows, however, a few anomalies because of local seismic responses related to both geological and morphological conditions (Fig. 7c). The maximum ground-shaking region defines a 90 km long zone which, extending in a NE-SW direction along the coast, roughly corresponds to the area ascribed to the MCS intensity greater than X where large landslides and ground fractures also occurred (Fig. 7c). The shock was particularly violent along the coast and it was felt as a roar in the towns of Catania, Augusta and Siracusa. In these localities (Boccone, 1697; Bottone, 1718; Baratta, 1901) people were thrown up, massive floors and foundation stones were dislodged, walls, together with their foundations, were shifted from their groundings, thus indicating a particularly strong vertical acceleration.

The main shock also generated a large tsunami [I=5, Table 1; Tinti *et al.* (2004)] recorded along the whole coast of eastern Sicily, between Messina and Siracusa (Fig. 7c), and on the Island of Malta (Anonymous, 1693; Boccone, 1697; Bottone, 1718; Baratta, 1901; Piatanesi and Tinti, 1998; Tinti and Armigliato, 2003). In the harbour of Catania the sea retreated several metres leaving boats stranded on the sea-floor. When the sea returned, the wave, like "*a furious and rapid*

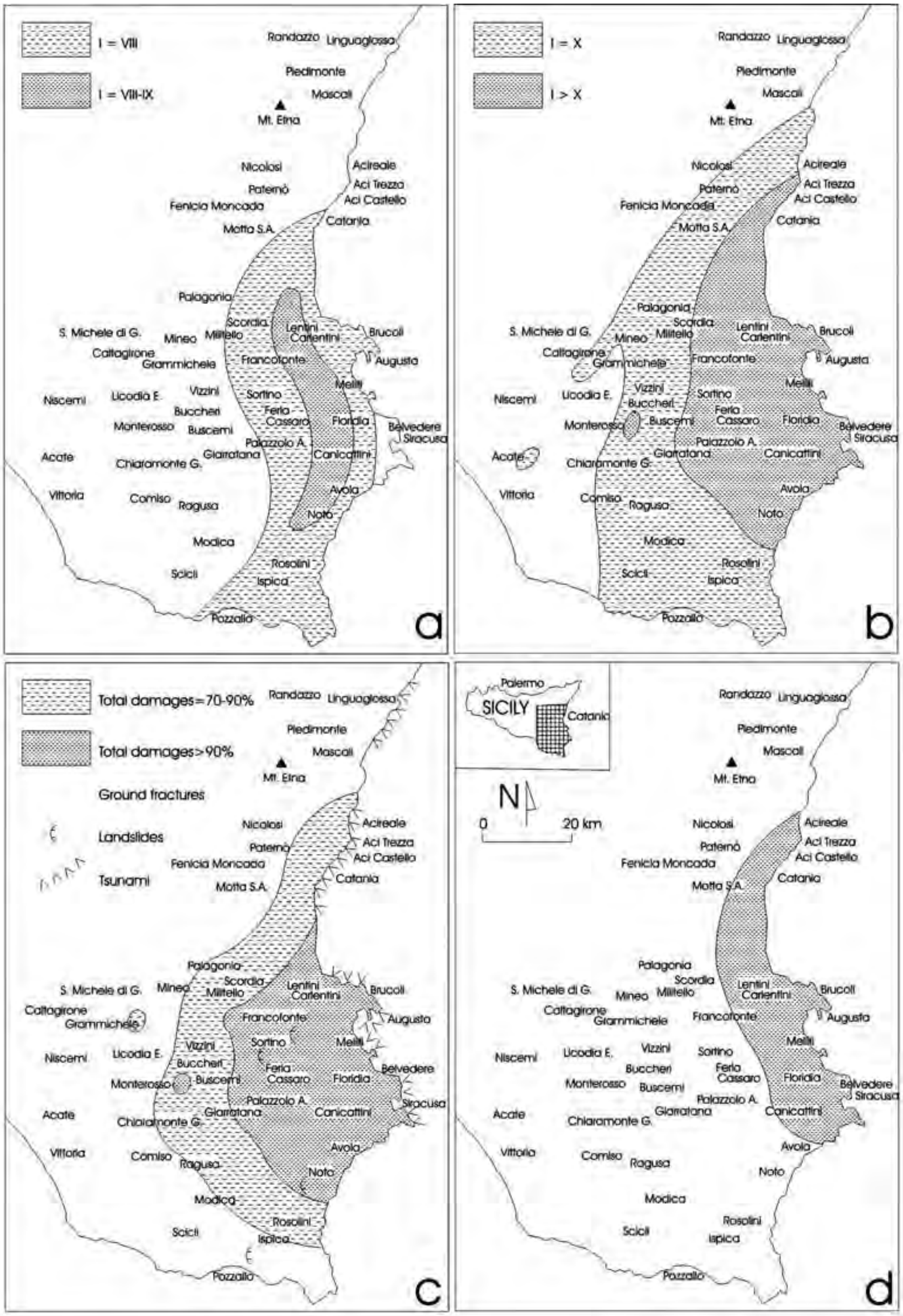

Fig. 7 - Cartoon showing the main features characterizing the January 1693 earthquakes (from Bianca *et al*., 1999): a) mesoseismic areas (MCS scale) related to the January 9 shock [data from Boschi *et al*. (1995a)]; b) mesoseismic areas (MCS scale) related to the main shock of January 11 [data from Boschi *et al*. (1995)]; c) effects on the environment and contour map of equal total damages of the main shock of January 11 [data from Boccone (1697), Bottone (1717), Baratta (1901)]; d) areas struck by 1693-1696 aftershocks [data from Boccone (1697), Bottone (1717), Mongitore (1743), Baratta (1901)].

stream" (Anonymous, 1693), flung the boats beyond the walls, into the town. At Augusta and Siracusa (Boccone, 1697; Bottone, 1718) the sea retreated 30 (60 m) and 50 (100 m) paces, respectively, then returned in a wave which reached heights of 30 cubits (about 12 meters). Galley ships of the Knights of Malta, anchored in the harbour of Augusta, ran aground on the sea floor because of the waves (Baratta, 1901). The tsunami was characterized by the occurrence of at least three distinct waves which penetrated inland for about 50 paces (90- 100 metres) at Siracusa, 75 metres at Augusta where they lapped the walls of the monastery of San Domenico, about 250 metres in Catania where the sea reached Piazza San Filippo (present Piazza Mazzini), and about 1 mile (1.5 km) at Mascali [Baratta (1901) and references therein]. Several aftershocks (Fig. 7d), felt in the villages and towns located close to the coastline extending between Catania and Siracusa, occurred up to 1696 (Boccone, 1697; Bottone, 1718; Mongitore, 1743; Baratta, 1901).

Data reported suggest that the two shocks had distinct epicentres. The first shock has been located inland, probably along the Avola fault [Fig. 1; Bianca *et al.* (1999)] or north of Siracusa (Azzaro and Barbano, 2000). As regards the main shock, it has been located inland, along the northern margin of the Hyblean Plateau, by D'Addezio and Valensise (1991) and Boschi *et al.* (1995), or along the Scicli Line (see inset in Fig. 1) by Sirovich and Pettenati (1999). However, on the basis of macroseismic information and tsunami modelling, it may be reasonably related to a rupture occurring along a normal fault located about 12 km offshore from Catania to Siracusa (Barbano and Cosentino, 1981; Barbano, 1985; Bianca *et al.*, 1999; Azzaro and Barbano, 2000), possibly the Western Fault (Fig. 6b) of Bianca *et al.* (1999), which is consistent with the numerical modelling simulations performed by Piatanesi and Tinti (1998) and Tinti *et al.* (2001). Reactivation of this fault could have triggered also the tsunami that occurred during the February 4, 1169 earthquake [I=4, Table 1; Tinti *et al.* (2004)]. The analogies between the 1169 and the well known 1693 event suggest, in fact, a similar location and magnitude for both events (Lombardo, 1985; Azzaro and Barbano, 2000).

4. Discussion and conclusions

Integration of instrumental and historical seismological data with seismic profiles and morphotectonic observations allowed us to define the possible sources of the tsunami waves occurring during the last few centuries in eastern Sicily and south-western Calabria. The coastal areas of these regions are controlled by offshore active faults (Capo Vaticano, Scilla, Reggio Calabria, Taormina, Timpe and Western Fault along the Malta Escarpment), some of which (e.g. Capo Vaticano and Malta Escarpment) clearly displayed by seismic profiles and bathymetric maps. Inland, Holocene palaeo-shorelines and Pleistocene marine surfaces represent natural tiltmetres which allow the evaluation of the short- and long-term footwall deformation. In particular, our data strongly suggest that the largest earthquakes ($M > 6$) with associated tsunami could be related to ruptures along the 30-40 km long Late Quaternary fault segments located offshore. The January 11, 1693 earthquake was generated by the slip of a normal fault extending about 12 km offshore from Catania to Siracusa and caused a large tsunami that devastated the entire coast from Messina to Siracusa with waves which reached heights of 30 cubits (about 12 meters). The February 6, 1783 earthquake has been related to displacement along an offshore fault located along the coast from Villa S. Giovanni to Palmi. The fault displacement probably triggered a huge submarine landslide in continuity with a subaerial collapse which in turn caused a tsunami that, with waves reaching heights of 6-9 meters, destroyed all the villages placed along the Messina Straits. The September 8, 1905 Monteleone earthquake has been attributed to a slip occurring along a fault segment located offshore the Capo Vaticano Peninsula. The main shock was followed by a large tsunami that hit the northern coast of the peninsula with a few meter high waves. Finally, the most recent and known tsunami occurred during the 1908 Messina earthquake that has been related to a rupture along the west facing Reggio Calabria fault that partially extends offshore south of Reggio Calabria. This event was characterized by waves that reached the maximum heights of 10 meters in the Calabrian side of the Straits of Messina, inundating large portions of the eastern Sicilian coast.

Taking into account the high density of population living on the coastal plains of the areas in question, tsunami waves triggered by offshore fault displacement thus represent one of the major factors of geological risk. Notwithstanding this, with the exception of a few studies, available information is not enough to define the effective seismic and tsunamigenic potential of active faulting. Useful data on seismic sources, on maximum expected magnitude, and on recurrence times require more detailed knowledge on the geometry, kinematics and mode of deformation of the different fault segments of the Siculo-Calabrian rift zone. Analyses capable of defining those fault segments prone to be re-activated, essentially associated with characteristic earthquakes and separated by stable areas, are still in their infancy. In fact, considering that the distinct fault segments of the Siculo-Calabrian rift zone are characterized by comparable lengths and deformation rates (Monaco and Tortorici, 2000), the possible fault-earthquake relations point to the occurrence of seismic gaps along the normal fault belt. Seismic quiescence for events with $M>6$ in the last 1000 yr has been in fact observed along distinct fault segments located both in northern Calabria and eastern Sicily (Monaco and Tortorici, 2000), especially on offshore structures, as the Taormina fault, which could originate strong tsunamis. This implies that further studies of these fault segments must be carried out in order to define the possible largest earthquake associated with each fault segment and its recurrence interval.

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