IN SEARCH OF TSUNAMI DEPOSITS ALONG THE EASTERN COAST OF SICILY (Italy): STATE OF THE ART

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Abstract

Eastern Sicily has been affected in historical times by large earthquakes followed by devastating tsunamis, such as the 1169, 1693 and 1908 events.
In order to provide a long term assessment for tsunami recurrence and related hazard, we developed a multi-disciplinary study, with a paleoseismological approach, aimed to recognize and date historical and paleo-tsunami deposits.
Starting from information on the effects of known tsunamis (hit localities, inundation areas, run-up heights) and with a geomorphological approach, we selected several sites, such as coastal lakes, marshes and lagoons, potentially suitable for preserving tsunami deposits. In these sites 64 test gouge cores have been dug by hand and engine coring.
In order to reconstruct paleoenvironments and to identify potential paleo-tsunami deposits, sedimentological and paleontological analyses were carried out. Magnetic and X-ray analyses were used to highlight susceptibility variations and peculiar small-scale sedimentary structures not detectable trough the standard stratigraphic analysis. Moreover, radiocarbon dating and tephra identification provide age ranges of the tsunami deposits and constrains for sedimentation rates allowing the correlation with historical events.
At Capo Peloro in north-eastern Sicily, combining archaeological, historical, and C14 data, we associated two tsunami deposits, to the 1783 and 17 A.D. earthquakes. We collected also evidence for the occurrence of multiple inundations at sites in the eastern flank of Mt Etna: three events in the past 580 yr at Anguillara site and four events in the past 4000 yr at Gurna site. In south-eastern Sicily, in the Augusta bay, combining historical, tephrostratigraphical and C14 dating, we reconstructed a tsunami inundation history composed of six events in the past 4000 yr, the two most recent ones are related to the 1693 and 1169 earthquakes.

Keywords: Tsunami deposits, sedimentation processes, micropaleontology, tephra, environmental analyses, off-fault paleoseismology, coastal hazards.

Introduction

Geological records are increasingly being used to contribute to knowledge of past earthquakes and to provide estimates of the their probable occurrence, location and magnitude in the future (e.g., Pantosti et al., 2003 and papers therein). As a result of the increased worldwide awareness of coastal hazards, tsunami geology has recently received attention also in region such as the Mediterranean because of the density of population, infrastructures and economic activities that concentrate along the coasts (e.g., De Martini et al., 2003; Ruiz et al., 2005; Pantosti et al., 2008; Scheffers et al., 2008)

The active tectonic processes in Italy express the ongoing deformation through several important seismic sources responsible for earthquakes that occasionally locally generated tsunamis. However, Italian coastal areas are also exposed to tsunami waves originated from distant sources, such as those belonging to the Aegean subduction zone (e.g. the A.D. 365 Crete earthquake and the 1600 B.C. Santorin explosion).

Reliable Italian historical records of important inundation of the coastland cover about 2000 yrs. Eastern Sicily has been affected in historical time by large earthquakes (Fig. 1) that, as described in the historical reports (Table 1), were followed by devastating tsunamis such as the 1908, 1783, 1693, and 1169 earthquakes.

Although a significant number of large magnitude tsunamis are reported for the Italian region (Caputo and Faita, 1984; Tinti et al., 2001, 2004), a few investigations of the geological records of tsunamis have been undertaken along the Italian coasts. De Martini et al. (2003) identified tsunami deposits in the Gargano area; in the same region, Gianfreda et al. (2001) described the presence of three wide washover fans in the Lesina coastal barrier formed by three distinct tsunamis occurred in historical times. Mastronuzzi and Sansò (2000; 2004) explained boulders of Pleistocene calcarenites up to 80 t in weight scattered along the Ionian coast of Apulia, as related to three tsunamis occurred between the 15th and 18th centuries. Scicchitano et al. (2007) interpreted calcareous boulders scattered along wide terraces, 2-5 m a.s.l., between the towns of Augusta and Siracusa (Sicily), as detached and transported by historical tsunamis.

During the past years, we developed a multi-disciplinary study aimed to the recognition and dating of historical and paleo-tsunami deposits in eastern Sicily in order to provide new information on extent and frequency of tsunami inundation in the investigated areas.

Starting from a detailed analysis of coeval accounts, we have compiled a database storing information on the effects of known tsunamis (hit localities, maximum run-up, inundation areas, etc.). To select areas that can have been likely invaded by tsunami waves in the past, these data were used together with a geomorphologic approach, which took into account also past centuries coastline changes. Coring was preformed at several sites and the collected data were studied in detail to distinguish deposits of high-energy environments transported by tsunami waves in the local sediments of the site, generally deposited in a low energy environment.

2. Tsunami deposits

In the past twenty years, deposits of several recent and historical tsunamis have been analyzed and described in detail (e.g. Clague et al., 1994; Sato et al., 1995; Dawson and Shi, 2000; Pinegina and Bourgeois, 2001; De Martini et al., 2003; Cochran et al., 2005 and 2006; Pantosti et al., 2008; De Martini et al., 2008). These observations have contributed to a general understanding of the characteristics of tsunami deposits, and to the establishment of criteria for their recognition. The source of tsunami sediments is primarily beach sand eroded from the shoreline and deposited on vegetated surfaces (Jaffe and Gelfenbaum, 2007) (Fig. 2a). In some cases, a tsunami deposit can be represented by a single sheet-like layer of sand; elsewhere, it can be represented by chaotic sediment layers containing abundant stratigraphic evidence for sediment reworking and re-deposition. The tsunami deposits commonly exhibit evidence of rapid deposition, such as gradation or massive structure and can be locally patchy and not diffused over the entire inundated surface (Clague and Bobrowsky, 1994). Tsunamis can also produce erosion, particularly in proximal or unvegetated areas.

To synthesize, sandy layers are interpreted to be tsunami deposits based on the following characteristics:

- The layers are found beyond storm-wave influence; lack of storm-wave influence is identified by changes in vegetation from beach grasses to less tolerant plants and by the presence of (sand-poor) peat; by distance from the shoreline or reconstructed shorelines, generally farther than 250 m. This is true for the ocean storms, in the Mediterranean storms are substantially less powerful and their influence rarely exceed some tens of meters.
- The layers are similar to local beach sand, generally comprising well-sorted and well-rounded particles; and may include fragments of plants.
- Layers are sheet-like, with typical thicknesses of a few millimetres to a few centimetres, generally thinning away from the shoreline (Pinegina and Bourgeois, 2001); the sediments occurring immediately below the sand layer exhibit evidence of wave erosion whilst in some places, plant leaves rooted in the underlying peat extend upward into and through the sand or on occasions are matted down at the base of the sand indicating burial by flooding.
- Macro- and microfauna contained in the layer indicate a marine provenance. The macro-faunal content can range from fish remains to a wide range of shell debris. Microfauna includes a wide species range of diatoms and foraminifera (e.g. Dawson et al., 1996), several of which originate in deep water. One of the major characteristics of diatoms and foraminifera found in tsunami deposits is the presence of a majority of broken individuals due to the turbulent water transport (Dawson and Shi, 2000).

However, given the large variability in the nature of tsunami sediments and of coastal environments, it is not surprising if tsunami deposits are not univocally identifiable, and other types of deposits may share some of the characteristics. Storm deposits most closely resemble tsunami deposits, although onshore storm deposits often have more complex layering than tsunami deposits (Fig. 2b), do not extend inland more than ~100 m (Tuttle et al., 2004; Goff et al., 2004) and do not reach high elevations a.s.l. A further element of discrimination is the number of sandy layers in the sedimentary sequence: the storm deposits are generally more frequent than tsunamis thus, if the high energy layers were storm related they should be very numerous in the studied sequences (tens per 100 yrs). Also eolian deposits are sandy but they can be easily excluded because are typically very well sorted, made of very fine sand forming thicker, wedge-shaped layers; silt and very fine eolian sand are also disseminated in the peat. Flood deposits contains sand layers too but these are typically browner (contains organic matter) and muddier, and fluvial sediment are substantially less mature than those on the beach. Colluvium is poorly sorted, with angular grains (Pinegina and Bourgeois, 2001).

3. Historical tsunamis in Eastern Sicily

Because of the wealth of historical data available in Italy about the effects of seismicity of the past millennium, eastern Sicily and southern Calabria represent an exceptionally, favorable case for collecting, organizing and analyzing data on historical tsunamis. Recently, a database storing the effects of known tsunamis flooding the eastern Sicily and southern Calabria coasts has been compiled with the aim of reconstructing inundated areas and run-up distribution (Gerardi et al., 2008). In the following we summarize the historical data available for the main tsunamis (Table 1) with particular attention to the inundation extent.

3.1 1650 B. C. Santorin tsunami

A sequence of explosions involving vertical and lateral blasting episodes, atmospheric pressure perturbations, a cone collapse sequence, and mass edifice flank failures of the Volcano of Santorin - before, during and after the paroxysmal phase of its Bronze Age eruption in 1650 B.C. (+/- 50 years) - account for the catastrophic tsunami waves in the Aegean Archipelago and the Eastern Mediterranean during that period (Pararas-Carayannis, 1992)

3.2. The first century A.D. tsunami

Bonito (1691) and Mongitore (1743) report two earthquakes dated 14 and 33 A.D, respectively. The 33 A.D. earthquake is considered false because it coincided with the dead of Christ. Whereas for the 14 A.D. earthquake both Bonito and (1691) Mongitore (1743), quoting Plinio, report that the Tindari town was partly ruined and some towns were absorbed by the sea. This description is suggestive of the occurrence of a tsunami related to this earthquake. Due the uncertain dating for this historical period the 14 A.D. event could also coincide with the 17 A.D. earthquake that damaged many towns in Sicily and the area around Reggio Calabria (Guidoboni et al., 1994). The epicentral location of the A.D. 17 earthquake is roughly established in the northern side of Mt Etna and its maximum intensity is VIII-IX MCS that translates to a Maw = 5.14 (Working Group CPTI, 2004). No tsunami was described for the A.D. 17 event.

3.3. July 21 365 tsunami

According to Guidoboni et al. (1994) in his continuation of the Chronicon of Eusebiuos, written about 380 A.D. Jerome records: “There was an earthquake throughout the world, and the sea flowed over the shore, causing suffering to countless people in Sicily and many other islands”. The source of this earthquakes is located near Crete.

3.4. July 22 963 tsunami

G. Bucellino wrote: “An earthquake in Siria and Sicily, with destruction of towns, inundation of sea and thousands of casualties” (Mongitore, 1743). According to Guidoboni (1989) this event is false because it was impossible cross check this information in the Bucellino’s paper.

3.5. February 4, 1169 tsunami

The known inundated shoreline was between the Messina town and the Simeto river (Fig. 1a). In the Messina town the run-up overcame the city walls, inundating the streets (Fazello, 1560). Guidoboni and Comastri (2005) affirm that a contemporary chronicler, Roger of Hoveden reports that the sea receded from the shore in Catania, leaving many fishes behind on the sand to suddenly flow back. Effects of inundation were also described at the Simeto river mouth in the Catania plain (Sciuto Patti, 1896). Mongitore (1743) reports, quoting

Tarcagnotta, that “the earthquake caused 25000 victims and many other were killed by the sea wave rising along the whole shore of the island” and citing Morigia, that “a river run back fast drowning more than 5000 people”.

3.6. June 28, 1329 tsunami

Many strong seismic shocks occurred after the beginning of an Etna eruption, in the western and eastern flanks of the volcano. Moreover anomalous sea movements were reported in Mascali beach where some boats were carried into the sea by the waves (Fazello, 1560).

3.7. December 10, 1542 tsunami

The earthquake, with estimated magnitude M_{aw} = 6.6 (Working Group, CPTI4), hit many locality in south-eastern Sicily producing damage in an area of about 6000 kmq (Boschi et al., 2000). Several localities (Sortino, Melilli, Lentini) were destroyed and the shock was felt in almost all the island (Barbano and Rigano, 2001). After the earthquake the town of Augusta was covered by the sea (Lacisio, 1858)

3.8. January 11, 1693 tsunami

The M_{aw} = 7.4 (Working Group, CPTI4) 1693 earthquake caused destruction and heavy damage in most of eastern Sicily (Boschi et al., 1995). After the earthquake a large tsunami struck the whole eastern coast of Sicily between the Aeolian Islands and the old Port of Marina di Ragusa, Mazzarelli (Campis, 1694), in the southern Sicilian coast (Fig. 1). The known length of inundated shoreline was of about 230 km (Gerardi et al., 2008).

The sea withdrew 60 steps (~100 m) and returned back overflowing the dock (Anonymous, 1693) at the Messina harbour. The largest inundation is described at Mascali, where the sea flooded the shore for about 1 mile inland (Boccone, 1697). The sea flooded Catania, inundating San Filippo square (now Mazzini square) and the farms around the town (Boccone, 1697). In the town of Augusta, the sea withdrew completely from the harbour and then violently came back over-passing the coast line of about 30 cubits (~165 m) (Bottone, 1718) and inundated the city as far as the San Domenico Monastery (Boccone, 1697).

3.9. February 5 and 6, 1783 tsunamis

The 1783 seismic sequence was composed of 5 strong shocks occurred between February and March in southern Calabria (Fig. 1). The earthquakes ruined many towns in Calabria and north-eastern Sicily causing also important geomorphological changes (Boschi et al., 1995).

Tsunamis were observed after the two shocks of 5 February (Maw = 6.9) and 6 Feb (Maw = 5.9) (Working Group, CPTI4).

The 5 February tsunami hit the Ionian side of the Calabria coast from Bianco to Roccella Ionica (Graziani et al., 2006). The shore was flooded for about 1 mile inland at some locations (Galimi, 1783). On the Tyrrhenian coast small inundations at Scilla (Palestino in De Lorenzo, 1877), Punta del Pezzo (Sarconi, 1784), and two high sea waves at Nicotera (Minasi, 1785) were observed. The known length of inundated shoreline was of about 40 km in the Ionian coast and 45 km in the Tyrrhenian one (Gerardi et al., 2008).

The 6 February tsunami affected the Sicilian coast from Messina to Torre Faro and the Calabria coast from Reggio Calabria to Scilla (Fig. 1a) for a total length of 40 km (Gerardi et al., 2008). The worst tsunami wave was about 16 m high and hit Scilla killing 1500 people. The sea water penetrated as far as 647 palms (~170 m) in the Livorno stream valley (Vivenzio, 1783). At Torre Faro, the tsunami wave flooded the shore for about 400 steps (~400 m) inland depositing a large amount of silt and dead fishes (Sarconi, 1784). In Messina the sea penetrated inland as far as to the fish-market (Vivenzio, 1783).

3.10. December 28, 1908 tsunami

The 1908 Messina earthquake (M_w = 7.1, Pino et al., 2000), is the most catastrophic event occurred in the 20th century in Italy; it produced extensive destruction over an area embracing southern Calabria and north-eastern Sicily (Boschi et al., 2000 and references therein). The tsunami violently hit the southern Calabrian and the eastern Sicilian coasts causing further damage and causalities (Platania, 1909; Sabatini, 1910). The tsunami wave was also observed along the Tyrrhenian coast of the island and in the Sicily Channel as far as the Malta Islands (Fig. 1a, Platania, 1909; Baratta, 1910). The tsunami flooded up to 250 m in the north-eastern Sicilian coast between Scaletta and Acitrezza (Platania, 1909).

In Messina the tsunami inundated the harbour-office and the St. Salvatore fortress, whereas at the Portalegni stream mouth the inundation penetrated 250 m inland (Platania, 1909). The waves flooded the town of Catania for more than 100 m inland depositing algae, posidonie, madrepore and millepore fragments, molluscs and many dead fishes; the shore was overflowed for about 700 m inland at the mouth of the Simeto river (Baratta, 1910). At Brucoli about 8 minutes after the shock the sea withdrew for more than 200 m, then the sea flooded for about 50 m the field depositing boats, small fishes, echinoderms, crabs (Platania, 1909). In Augusta "Around 20 minutes after the shock, inside the arbour a rumpus similar to that produced by the waves braking against rock-cliffs was felt; after few second the sea flooded the beach with several waves, the greatest of which, the first one, raised to m. 1.75. Out of the harbour the waves raised over 2 meters and propagated onshore for about 15 meters. The tsunami damaged the Salt pan (Baratta, 1910). In Siracusa, after the downdrown, the wave raised about 2 m. Waters covered the banks and only some boats were damaged. (Baratta, 1910). The known southernmost affected locality in Sicily was Capo Passero (Platania, 1909).

4. Methodological approach

On the basis of the historical reports, through the analysis of satellite images and aerial photographs, and field surveys along the eastern Sicilian coast, five areas such as coastal lakes, marshes, lagoons and abandoned river's channels were selected (Fig. 3). These areas are potentially suitable for preserving tsunami deposits because they are characterized by coastal sedimentary traps, low-energy natural environment, continuous deposition, low erosion and accumulation of organic matter. These types of environment allow the recognition of the high-energy tsunami deposits that will appear completely anomalous and will contrast substantially with respect to those of low-energy commonly deposited.

~~Of the selected areas we investigated with more detail those that appeared to be more propitious for the preservation of tsunami deposits.~~

In the selected areas we explored several sites and carried out coring field surveys using both hand auger equipment and a vibracoring (gasoline powered percussion hammer). Preliminary stratigraphical and sedimentological observations, together with photographs of the core deposits, and sampling for environmental and dating analyses, were performed directly in the field (Smedile et al., 2006; 2007). Once an interesting stratigraphic sequence was found we were properly equipped to collect undisturbed samples (within specific pvc tubes), 100 cm-long, 5 cm in diameter, down to 5 m total maximum depth. Coring was always accompanied by GPS surveys for the exact positioning of samples with respect to the sea distance. A total of 64 test gouge cores have been dug for a total length of 105.65 m.

Magnetic and X-ray analyses were performed on some selected cores sampled with pvc tubes to look for susceptibility variations and peculiar small-scale sedimentary structures (e.g. sharp contacts, convoluted layers, etc.). Then, cores were opened to perform accurate sedimentological descriptions and collection of all the needed samples for isotopic dating, paleontological, and electron microscope analyses (SEM-EDS). Macrofossils and foraminifers were analyzed at most sampled horizons. Samples have been submitted to washing with sieves of 63 µms, subsequently dried in oven, and analyzed with optic microscope. At least 100 foraminifera tests were counted from each sample where adequate concentration were present, whereas a qualitative analysis on macrofossils content was carried out. The main aim of all these analyses was to reconstruct the paleoenvironment of the site and to highlight possible anomalous deposits of marine provenance that can be interpreted as layers deposited by tsunami waves.
Finally, tephra characterization and radiocarbon analyses were used to constrain the age of the deposits, to derive sedimentation rates and to attempt correlation of the interpreted tsunami deposits with the historical events or to provide an age range of occurrence for the other events.
Radiocarbon dating was performed on charcoals, organic sediment and shells generally selected from the layers just above or below a suspicious layer. Occasionally, materials were selected from the layers themselves. We dated 11 samples (Table 2) through accelerator mass spectrometry (AMS) at the Poznan Radiocarbon Laboratory. Measured ages were dendrochronologically corrected according to Calib REV5.0.2 (Stuiver and Reimer, 2005).
Because we have a few radiocarbon datings from each site, some tsunami deposits are roughly constrained in age using average sedimentation rates. Each inferred tsunami deposit has been numbered from the top with the site label (e.g. GUR, ANG, etc.) and a progressive number.
If all the characteristics of tsunami deposits are fully satisfied (certain marine origin, high energy event etc.) we attribute to the anomalous layers a high level of confidence; whereas if they show only some of the tsunami deposit characteristics or these are not certain (i.e. we cannot verify their origin) we assign a medium or low level of confidence (Table 3).

5. Study areas and results

The Ionian coastline of Sicily extends about 250 km from Capo Peloro to the north to Capo Passero to the south (Fig. 3). The morphology of the coast and the local sedimentary environments (beach, dune, marshes, deltas, etc.) are strictly related to the geological setting of the island. In fact, to the north the coastline cross the south-verging thrust belt of the Peloritani mountains, and is characterized by fast uplift-rates (≥ 1 mm/a) (Catalano and De Guidi, 2003), steep cliffs, narrow beach stretches and development of hydrographic basins drained by streams with short length (< 20 km). More to the south the coastline develops onto the eastern flank of the Mount Etna, that is characterized by moderate uplift-rate (≤ 0.6 mm/yr, Di Stefano and Branca, 2002), basaltic lava flows, Holocene debris flow deposit and limited coarse-grained beaches. Southward, the eastward prograding deltaic system of the Simeto river (Catania alluvial plain), develops onto the tectonic depression of the Gela Foredeep, with the development of wide beaches, dunes and marshes. Finally, the southernmost part of the coast line develops onto the carbonatic sequences belonging to the moderate-to-low uplifted Hyblean foreland (Lentini et al., 1986) (Fig. 3). In this area, several small lagoons developed along the coast.
Reconstruction of past environments on the coastal area of eastern Sicily shows changes from tidal inlet conditions to lagoons, dunes and alluvial deposits. We found peat environment only

at one site (Fiumefreddo Natural Reserve), probably because of the local typical climatic conditions (temperature, precipitation, humidity, solar radiation, wind) as well as soil hydrology and chemistry.
Most of the sediments in the analyzed sequences represent steady-state deposition in relatively low energy regime coastal environments. However, in the dug cores we found also several anomalous units that may represent high-energy depositional events unexpected in a low energy environment.
In the following we describe, from north to south, the studied areas, the sampled sequences and the characteristics of the anomalous high-energy layers.

5.1 North eastern Sicily

The Capo Peloro Peninsula, located in the Sicilian side of the Messina Strait, is characterized by the presence of two littoral lagoons, the Faro and the Ganzirri lakes; between the two lagoons we find a lowland area hosting the Margi marsh. This latter developed 4.6 ka ago parallel to the coastline with the progressive development of the dune which sealed off it from the sea (Antonioli et al., 2004). In this area off-shore bathimetry shows an abrupt deepening with a slope up to 20-25° for the first 200 m. The morphology of the coast, the low dynamics of the environment and the presence of a subsident area hosting the lakes and the marsh, are suitable for preserving tsunami deposits. Although the strong anthropization since Roman age (IV B.C.- IV A.D), we made some hand cores in the lowland area of the Margi marsh (Fig. 3a).
The geological survey coupled with seven cores distributed in three sites (Fig. 3a), revealed an old brackish lagoonal paleoenvironment evolving towards wetlands, in the uppermost part characterized by a coarse grained sedimentation. Although in the coastal plain of Ganzirri there is a suitable paleoenvironment for the preservation of tsunami deposits, no evidence of high energy events was found in the gouge cores.
However, in this area two anomalous clean, well sorted, sandy layers, interbedded in a organic colluvial sequence containing anthropogenic material, have been found at Torre degli Inglesi (TIA) archaeological excavation (Fig. 3a) of Capo Peloro (Pantosti et al., 2008) and interpreted as tsunami deposits. The first anomalous layer (TIA-T2, Unit 90 in Pantosti et al., 2008) consists of a fine sand, made of inorganic components (sandstone remnants, quartz and micas), with sharp lower and upper contacts; it contains shell fragments (molluscs and corals), some planktonic and benthic foraminifera and algae remnants. The second and uppermost sandy layer (TIA-T1, Unit 1 in Pantosti et al., 2008) contains pebbles of decimetric size along with shell fragments. The age of these layers has been constrained both with radiocarbon and archaeological dating. The age of the oldest layer is consistent with an earthquake occurred during the first century, probably the 17 A.D. earthquake that affected Reggio Calabria but for which no tsunamis was reported until now. The youngest layer is likely related to the 1783 February 6 earthquake (Pantosti et al., 2008) for which several report of tsunami exist (Table 1).

5.2 North eastern flank of Mt. Etna

In the North eastern flank of Mt. Etna area, three sites located behind an Holocene coastal dune have been analyzed: the Fiumefreddo Natural Reserve, Gurna and Anguillara (Fig. 3b). These lowland sites were filled by clastic sediments derived from the erosion of the Peloritani Mts and the Etna lavas, and usually show high sedimentation rate related to the local fluvial environment. The slope of the beach is around 5-6° while the bathymetry reveals about 8-10° of slope for the first 500 m of the offshore. The presence of strong marine currents induces a distribution of the sediments parallel to the coastline. The emersion of sand bars above which

the sand dunes start, causes the preservation of this particular environment, suitable for the presence of tsunami deposits.
The Gurna and Anguillara areas (Fig. 3b) are characterized by two different types of paleoenvironment: in the first one a fresh-water shallow pond developed and persisted up to the present, while in the Anguillara site we found an alluvial environment, probably related to flow of the Macchia stream. Moreover, the Fiumefreddo Natural Reserve is characterized by a lacustrine environment.

5.2.1 Fiumefreddo Natural Reserve

This area has been investigated at one site (RIF) (Fig. 3b), where we dug one core (RIF-S01) down to 2.5 m, located 500 m from the sea. The stratigraphic sequence appeared dominated by peat deposits. The presence of a 4 cm thick silty sand layer at about 130 cm depth (RIF-T1), characterized by rare planktonic foraminifera (*Orbulina universa*, *Globigerinoides* sp.) suggests a tsunami origin for this deposit (Smedile et al., 2006). Unfortunately, no dating is available yet.

5.2.2 Gurna sites

The Gurna area has been investigated at two sites (Gurna north and south) (Fig. 3b), where we dug four cores (GUR-S01-03 and GUR-S10) down to a maximum depth of 4.2 m, and at a max distance of 340 m from the sea. The stratigraphic sequence is composed mainly by fine sediments, clayey silt and silty clay (Fig. 4), interrupted by four distinct coarse layers of sandy silt to coarse sand/fine gravel. These layers were found at depths of 42-48 cm (GUR-T1), 107-134 cm (GUR-T2), 170-178 cm (GUR-T3), made of quartz, volcanic clasts and with few vegetal remains in almost all the samples, and at 400-408 cm (GUR-T4) where some lens of sand with the same characteristics, were found. Morphoscopic analyses on clasts indicate that no primary Etna tephra deposits has been preserved in these sites. Unfortunately, all the samples collected for paleontological analysis are barren, but we can tentatively interpret them as tsunami deposits.
Radiocarbon dating, performed on a charcoal collected within the deepest layer (GUR-T4) (GUR-S10-403, Table 2), constrains its age of deposition at 2310-2135 B.C., confining the occurrence of the four hypothesized tsunamis within the past 4000 yrs. Assuming limited erosion, the radiocarbon dating yields an average sedimentation rate of 0.8 mm/yr, excluding the tsunami deposits from the calculation, or 1.0 mm/yr, including them. Under these assumptions, the sedimentation rate can be used to constrain the age ranges for the other anomalous layers that result for GUR-T3 between 225 B.C. -220 A.D.; for GUR-T2 between 320-660 A.D. and for GUR-T1 between 1400-1520 A.D. Comparing the inferred ages of these tsunami deposits with the historical tsunami catalogue, we can tentatively associate the two younger tsunami layers to the 365 A.D. Crete tsunami and the 1542 event or more likely the 1693 tsunami, considering the error contained in our estimate and that for the 1693 event we have historical information about inundation of this part of the coast. The GUR-T3 event could be the same paleo-event found in the Augusta site (see paragraph 5.4.1).

5.2.3 Anguillara site

The Anguillara area has been investigated at one site (ANG) (Fig. 3b), where we dug three cores (ANG-S01 to S03) down to a maximum depth of 5.2 m, at a distance of 280 m from the sea. The stratigraphic sequence is monotonous and mainly composed by fine sediments, dark grey clay and brown clayey silt, with the exception of two well distinctive coarse layers made by fine sand to sand, at 60-70 cm (ANG-T1) and 195-200 cm (ANG-T2) depth. Morphoscophic analysis on several samples indicates that most of sediments contain a high amount of volcaniclastic material (scorias, lava clasts and crystals), nevertheless no primary fallout deposit has been preserved. All the samples collected for paleontological analysis are barren (quartz, volcanic clasts and few vegetal remains are predominant in almost all the samples) except for a very interesting detritic sample collected at 350-356 cm depth (ANG-T3), made by metamorphic rounded clasts in a dark grey silty-clay matrix, where two echinoderms fragments and high concentration of roots and seeds have been observed (Fig. 5). We interpret the two coarse layers and the abovementioned detritic deposit as sediments possibly left by tsunami waves.

Radiocarbon dating was performed on two charcoals sampled in the ANG-S01 core just below the deepest sandy layer at 195-200 cm and below the detritic layer at 350-356 cm depth, respectively (Table 2). The ages of samples ANG-S01-220 (1455-1635 A.D.) and ANG-S01-357 (1425-1510 A.D.) partially overlap suggesting a common local source for the two charcoals. If this is the case we are forced to use the age of the deepest sample as reference for our calculations.

Even though the uncertainties are large given the local environment, we can derive an average sedimentation rate from the sample ANG-S01-357 (1425-1510 A.D.) of 6-7 mm/yr for the past 580 yrs, excluding or including the tsunami deposits from the calculation, respectively.

On this basis we can infer an age of deposition for the two anomalous layers: ANG-T3 just after 1425-1510 A.D., ANG-T2 in the range 1660-1710 A.D. and ANG-T1 in the range 1880-1920 A.D. Comparing these ages with the historical tsunamis, we can hypothesize that the ANG-T3, ANG-T2 and ANG-T1 anomalous layers found at the Anguillara site are associated to the 1542, 1693 and 1908 tsunamis.

5.3 Catania plain

The Catania plain is the widest alluvial plain of Sicily (Fig. 3) which extends from the southern flank of Mt Etna to the northern boundary of the Hyblean Mts as part of the Quaternary Gela foredeep (Lentini et al., 1986). The drainage system, composed by a complex hydrographic network, is dominated by the Simeto, Dittaino, Gornalunga and San Leonardo rivers, which created the thick Holocene alluvial infill of the plain. This area is characterized by fluviatile environment and by subsidence, with some part of the ground surface sink below the sea level. It was selected following the historical records, that describe important inundation of the plain, and geomorphological observation that suggested the presence of possible trap-sites for tsunami deposits in an apparently marsh environment, e.g. the relict fluvial meanders to the north of the present Simeto delta and the abandoned channels of the Gornalunga river to the south of Simeto (Longhitano and Collella, 2007). Behind the anthropized littoral dune facing the Ionian Sea, we performed several cores (four sites and thirteen cores, Fig. 3c) but, although the apparent condition of trap-sites, no suitable environment to preserve tsunami deposits was found: sedimentological and paleontological analyses of collected samples pointed out an extensive, thick alluvial and fluvial sedimentation showing a migration toward south of the coarser sediments from the Simeto river thought the time. Therefore, no anomalous layers were identified. It is interesting to notice that in this area tephrostratigraphic investigation reveals that no primary tephra deposits are preserved despite the frequent historical explosive eruptions of Mt Etna that has produced copious lapilli and ash fallout in this area favourably located in the direction of the dominant local winds. This latter information may confirm that the Catania Plain is not a suitable area for preservation of primary deposits due to high energy processes related to the Simeto River.

5.4 Gulf of Augusta area

The Gulf of Augusta is located along the Ionian coast of the Hyblean mountain range, on the footwall of the Hyblean escarpment (Bianca et al., 1999). From a geomorphological point of view this area is characterized by high and low sectors tectonically controlled; in the low areas salt marshes are found which are particularly favourable for the deposition and preservation of the tsunami deposits. Two sites, characterized by the presence of salt marshes, have been surveyed: Augusta (Fig. 3d) and Priolo (Fig. 3e).

5.4.1. *Augusta site*

In Augusta site (OSA), located near the local Hospital, we dug nine cores (OSA-S01-09) down to a maximum depth of 4.3 m, as far as 460 m from the sea (Fig. 3d).

At this site we found one of the best evidence of paleotsunami deposit. In fact, the core OSA-S06 (Fig. 6, core), a monotonous grey to dark grey fine silty deposit of brackish lagoonal environment, with abundant ostracods (*Cyprideis torosa*), whole gastropods (*Hydrobia* spp., *Pirenella conica*) and well preserved benthic foraminifera (*Ammonia parkinsoniana*, *A. tepida*, *Haynesina germanica*), is abruptly interrupted at a depth of about 190 cm by a yellowish bioclastic layer (OSA-T2) (Fig.7 photo core). The latter is made of rare whole gastropods (*Hydrobia* spp., *Pirenella conica*), abundant shell fragments (mollusks, corals and echinoderms), rare ostracods, often broken benthic (*Ammonia* spp., *Bolivina* sp., *Cassidulina laevigata*, *Cibicides lobatulus*, *Haynesina germanica*, *miliolidae*, *Pullenia bulloides*, *Rosalina* spp.) and few badly preserved planktonic (*Globigerina* spp., *Globigerinoides* spp., *Globorotalia inflata*, *Turborotalita quinqueloba*) foraminifera (Smedile et al., 2007). This assemblage, supporting a clear marine origin for the bioclastic layer, coupled with the fact that it shows a sharp erosional basal contact and no evidence for layering or grading, allows us to interpret it as a tsunami deposit (De Martini et al., 2009). A similar fauna association has been detected in nearby cores (OSA-S10) although the morphoscopic evidence is not so clear.

Furthermore, a gravel layer rich in vegetal remains (Fig. 7), angular calcarenites clasts and shell fragments, was detected at a depth of 162-173 cm (OSA-T1), it presents a sharp, most probably erosional, basal contact. However, no microfauna could be used to univocally establish the marine origin for this layer.

Radiocarbon dating was performed on 3 samples, collected just above, within and below OSA-T2 (Fig. 7); OSA-S06-187, 193 and 198 (Table 2) gave coherent results, constraining the paleotsunami age to the interval 975-800 B.C. The radiocarbon dating of the three samples yields ages within 300 yrs c., validating the hypothesis of a sudden inundation rather than a gradual transition to higher energy environment (De Martini et al., 2009). Non sono sicura che valga la pena lasciare questa frase che e’ comunque ambigua, del resto lo sharp contact alla base ce lo diceva lo stesso. Se la vogliamo lasciare va detto che le eta’ sono nei 100 anni in 10-15 cm di distanza

We also performed radiocarbon dating on two charcoal fragments at 96 cm and 158 cm depth (OSA-S06-96 and OSA-S06-158 in Table 2), that yield calibrated ages of 650-770 A.D. and 40 B.C.-120 A.D., respectively. So they allowed constraining the age of the gravel deposit (OSA-T1) between 900 B.C. and 120 A.D.

Radiocarbon dating performed on OSA-S06-187 and OSA-S06-158 samples suggests an average sedimentation rate of 0.2-0.3 mm/yr (these values are calculated taking into account or excluding the 11 cm thickness of the proposed tsunami deposit OSA-T1) that seems to be coherent with a lagoonal environment. On the basis of average sedimentation rate calculated considering the 14 cm thick silt deposit separating sample OSA-S6-187 and the base of the OSA-T1 layer, the age of the gravel deposit OSA-T1 can be narrowed 430-100 B.C.

5.4.2. *Priolo Oasis site*

The Priolo area has been investigated at one site (OPR) (Fig. 3e), where we dug seventeen cores (OPR-S01-17) down to a maximum depth of 4.2 m, as far as 530 m from the present coastline. In general, the stratigraphy is composed mainly by a monotonous sequence of fine sediments, from clay to silt. This is interrupted by four anomalous layers: two distinctive bioclastic layers (OPR-T1 at 10-15 and OPR-T2 at 30-40 cm depth), one detritic deposit at about 90 cm depth (OPR-T3) (Fig. 8) and one sandy layer (OPR-T4, at about 160 cm depth). Combining micropaleontological and x-ray analyses (Fig. 8) we made the following observations: a) the entire stratigraphic sequence appears to belong to a lagoonal environment; b) both bioclastic layers, OPR-T1 and OPR-T2, are characterized by sharp basal contact and present an abnormal concentration of shell fragments and entire gastropods (all arranged in a chaotic pattern) of marine origin, c) OPR-T2 shows an increment in the benthic foraminifera specific diversity; d) the detritic deposit (OPR-T3, 2-3 cm thick) shows an anomalous assemblage made by macromammal bone fragments (personal communication of Prof. A. Kotsakis) together with rare and badly preserved benthic (*Cassidulina carinata*, *Cibicidoides pseudoungerianus*, *Melonis barleeanum*, *Planulina ariminensis*) and one planktonic (*Globigerinoides* sp.) foraminifera; e) in the 160 cm deep sandy layer (OPR-T4) marine microfauna appear well preserved, differently from the association characterizing the fine to very fine deposits above and below. Because of the marine provenance and fauna association and macroscopic evidence, we may interpret all the four layers as tsunami deposits (De Martini et al., 2009)..

Dating of the deposits in the cores was performed both on the basis of tephra analysis and radiocarbon.

Petro-chemical and morphoscopic analyses on a black volcanic coarse sand, normally graded, found in six cores at about 70 cm of depth, allowed us to correlate it with the tephra from the 122 B.C. plinian eruption of Mt Etna (Coltelli et al., 1998). In Figure 10, glass compositions of tephra recovered in Priolo site (De Martini et al., 2009) are compared with those of the 122 B.C. eruption. On the basis of the Total Alkali Silica classification diagram (TAS, Le Maitre, 1989), they show alkaline affinity suggesting Etnean provenance and a similar chemical composition to the 122 B.C. products.

Radiocarbon dating was performed on 2 shell specimens and one charcoal (Table 2): these yielded an age of 1420-1690 A.D. at a depth of 43 cm (OPR-S11-43), 225 B.C.-220 A.D. at 66 cm (OPR-S11-66), and 2100-1635 B.C. at 158 cm (OPR-S09-158) (Fig. 8). The age of the charcoal OPR-S11-66 (225 B.C.-220 A.D.) is in good agreement with the122 B.C. deposition age of the tephra found at 70 cm depth. Sample OPR-S09-158 constrains the age of the lowermost tsunami layer (OPR-T4 at 158-161 cm depth) at 2100-1635 B.C. The deposition of OPR-T3 occurred after 2100-1635 B.C and before the 122 B.C. (De Martini et al., 2009). The deposition of OPR-T2 occurred after the 122 B.C. Etna eruption and before 1420-1690 A.D. Finally, the radiocarbon dating performed at about 43 cm depth (OPR-S11-43) constrains the age of the youngest tsunami deposit (OPR-T1 at 30-40 cm depth) immediately after 1420-1690 A.D.

To attempt narrowing the age ranges of the tsunami layers OPR-T2 and OPR-T3 that are very wide, by combining tephrostratigraphic and C14 data in core OPR-S09-S11 and the 122 B.C. tephra, we estimated average sedimentation rates ranging from 0.25 mm/yr to 0.35 mm/yr (De Martini et al., 2009).

By using these rates, we obtain 500-1200 A.D. for OPR-T2 and 760-580 B.C. for OPR-T3. Comparing the ages of events with the historical tsunamis, the layers at 30-40 cm (OPR-T1) can be associated to the 1693, whereas OPR-T2 at 50-60 cm depth could be the 1169 event (fig. 5); whereas no historical events can be related to OPR-T3 and OPR-T4, which could be paleotsunami events.

5.5 South eastern Sicily.

The SE-Sicily area is located on the Hyblean foreland. There were found two areas with suitable morphologic characteristics to preserve tsunami deposits, the Vendicari Regional Natural Reserve (Fig. 3f) and, more to the south,, some ponds and salt marshes in Marzamemi and Porto Palo sites (Fig. 3g). Both at Vendicari and Marzamemi/Portopalo a littoral dune separates marshes usually used as salt-pans from the coast.

The geomorphological characters of the Vendicari Oasis shows a very recent tidal environment in the central part with an older brackish marine lagoonal behind, disturbed by the sedimentation of a local river in the southern part. We dug six cores down to a maximum depth of 2 m, at a maximum distance from the coastline of 800 m (Fig. 3f). In the northernmost cores (VEN-S01-03), at a maximum distance from the coastline of 200 m, the stratigraphic sequence is composed by coarse sand to sand at the bottom and by clay to silty clay deposits above; whereas in the cores (ROV-S01-03) at a maximum distance from the coastline of 800 m the sedimentological analysis revealed a mostly silty clay sequence. No anomalous layers were identified.

The site tested in Porto Palo showed shallow ponds, predominately fresh water with marine inlet until the present day. This area has been investigated at one site (RAP) (Fig. 3g), where we dug three cores (RAP-S01-03) down to a maximum depth of 1.2 m, as far as 150 m from the sea. The stratigraphic sequence is composed by coarse sand to sand at the bottom and by clay to silty clay deposits above. Within the latter deposits, two thin and loose sandy beds with sharp lower contacts have been found at about 8 and at 12 cm depth. Both layers present badly preserved shallow marine benthic foraminifera with some planktonic foraminifera, similarly to what observed in all samples below. However, the deepest fine sand contains some well preserved deep marine benthic foraminifera, sponge’s spicules, macrofossils and ostracods remnants indicating a marine provenance and a possible association with a tsunami event. No data about rates of sedimentation at this site are available yet but, taking into account the very shallow depth of these sands, we have tentatively associated them to the 1908 tsunami.

6. Conclusions

The research of paleotsunami deposits in eastern Sicily is a new line of research only recently undertaken in Italy but also in the broad Mediterranean. Therefore, approaches to apply for the identification and dating of tsunami deposits need severe testing, systematization and formalization. This work was carried out following a multi-theme approach and testing several different methodologies. Interesting and promising results came from an original combination of geomorphological, paleontological, X-ray, petro-chemical, morphoscopic and magnetic analyses.

In general, lagoonal environments and marsh areas are favourable sites to recognize tsunami deposits because of the presence of a peat or mud stratigraphy that allow to preserve and to more easily identify tsunami deposits than in the alluvial areas. In fact, in the alluvial areas high-energy processes, erosion and intermittent deposition make the preservation of the thin tsunami deposits unlikely. Furthermore, the low sedimentation rate characterizing marsh environments provides in a few meters of sediments, the record of longer interval of times (i.e., more tsunami events)

The tsunami deposit research in eastern Sicily shown evidence for clear tsunami inundations at the sites of Capo Peloro, Augusta and Priolo (Fig. 11). At Capo Peloro and Priolo sites, evidence of both historical and paleotsunamis were recognized; whereas at the Augusta site, we identified deposits associated to previously unknown inundations. Probable tsunami deposits were discovered both at Gurna and Anguillara sites. Three possible inundations in the past 580 yr occurred at Anguillara site, whereas, four events in the past 4000 yr were recognized at the Gurna site (Fig. 11). No evidence of tsunami inundations in the Ganzirri area, in the Catania Plain and in the Vendicari Oasis have been found.

The deposits interpreted as tsunami related are rarely sharing the same characteristics (Table 3). These depends substantially from the depositional environment, from the local geomorphology and the type of the beach and offshore deposits. In general the tsunami deposits represent layers different from of the normal stratigraphic sequence, often coarse-grained chaotic units as a result of high-energy depositional events. When microfauna has been available, micropaleontological analysis confirmed the marine origin of these anomalous units. Dating of the tsunami units and their correlation with known historical tsunamis represents a critical issue for the final results of tsunami deposit studies. In this work we have largely employed radiocarbon dating on charcoal fragments or shells and tephra analysis.

The results obtained in this work are summarized in figure 11.

Interestingly we did not find evidence for the well-know 1908 tsunami, with exception for the Anguillara site and probably the Porto Palo site. This is likely because of the reconstruction activity after the 1908 Messina Strait earthquake and the intense 20th century urbanization of the costal areas that did not allow the preservation of the tsunami deposits. We identified the tsunami deposit associated to the 1783 event only at Capo Peloro site, confirming historical information that confines the effects of this tsunami in the northern part of the Messina Strait. Moreover, in this site we recognized an anomalous layer left by an inundation occurred in the 1st century A.D., suggesting a possible similarity with the 1783 tsunami source.

We distinguished the deposit of the 1693 tsunami at Priolo site and probably also in Anguillara site where an anomalous layer probably associated to the 1542 tsunami was identified but no evidence of oldest events have been discovered because of the high sedimentation rate. In the Gurna site, a deposit associable with the 1542 tsunami or more probably with the 1693 tsunami was detected. At Priolo, a tsunami deposit most likely related to the 1169 inundation was found, whereas at Gurna the evidence of an inundation occurred 320-660 A.D. could be related to the 365 tsunami, confirming that events with a far source could reach the coast of eastern Sicily (Fig. 10).

We collected interesting evidence of paleoinundations occurred between 225 B.C. - 220 A.D. at Gurna site, between 430-100 B.C. and 975-700 B.C. at Augusta, 760-580 B.C. at Priolo, and finally between 2300-1635 B.C. at Gurna and Priolo sites (Fig. 11).

By recognizing geological evidence of historical and paleo-tsunamis (useful to obtain tsunami recurrence time, maximum inundation distance, elapsed time since the last tsunami event, etc) through a multi-disciplinary study, we developed experimental approaches useful to identify and date tsunami deposits and in addition we provided a contribution for Civil Protection applications. The relevance of this type of studies for Civil Protection is immediate in the field of tsunami scenario and modelling, and for time-dependent hazard assessment. This is especially true for eastern Sicily, that is a very densely inhabited coastland and, where some areas, such as Augusta and Priolo have an important role as main national military and industrial sites or as Capo Peloro has been chosen for building the bridge crossing the Messina Strait.

Acknowledgements

This work was funded by the Italian Dipartimento della Protezione Civile in the frame of the 2004-2006 agreement with Istituto Nazionale di Geofisica e Vulcanologia – INGV (Seismological Project S2) and partially by the EU project TRANSFER. We are indebted with L. Gasperini, from ISMAR-CNR-Geologia Marina, Bologna, for the help provided for the susceptibility and X-ray analyses. Many thanks also to E. Lipparini and G. Marozzi for the technical support kindly offered in the ISMAR-CNR labs. R. Azzaro, E. Baroux, M. Cosentino, G. D'Addezio, A. Mostaccio and some students, helped with core logging and site survey. E. Gliozzi is thanked for assistance with ostracodes and mollusks analyses. F. Cilea LIPU for the study of Priolo area; A. Cavallo, C. Freda and L. Miraglia for SEM analyses assistance; M. Mancini for stratigraphic analysis. We also wish to thank J. Bourgeois for useful discussion on tsunami deposits.

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Figure Captions

Fig. 1. a) Epicentres (unfilled circles) of main earthquakes from the CPTI4 catalogue (Working group CPTI, 2004). The known areas affected by main tsunamis are also shown.

Fig. 2. a) Conceptual model of tsunami sedimentation (from Jaffe and Gelfenbaum, 2007). b) On the left, deposit from 17 July 1998 tsunami in Papua New Guinea overlying brown muddy soil. The sandy tsunami deposit is graded (larger grains at bottom of the deposit) and contains mud clasts ripped up from the soil (Morton et. al., 2007). On the right, storm deposits (Katrina 2005) form Outer Barrier Island, Mississippi (courtesy of J. Bourgeois).

Fig. 3. Map of SE Sicily showing main structural domains. Rectangles refer to the investigated areas: a) North eastern Sicily: black triangles show the location of the gouge cores in the Ganzirri area; black dot is the archaeological excavation at Torre degli Inglesi (Capo Peloro site). b) North eastern flank of Mt Etna: black triangles show from north to south the location of the gouge cores in the Fiumefreddo Oasis, Gurna and Anguillara sites. c) Catania plain: black triangles show the location of the gouge cores. Gulf of Augusta area: d) Augusta, e) Priolo, triangles show the location of the gouge cores. South eastern Sicily f) Vendicari sites; g) Porto Palo site: triangles show the location of the gouge cores.

Fig. 4. Gurna site: stratigrafic sequence of GUR-S10 log from 0 to -425 cm depth.

Fig. 5. Anguillara site: stratigraphic sequence of ANG-S01 log from 0 to -460 cm depth.

Fig. 6. Augusta site: stratigraphic sequence of OSA-S06 log from 0 to -210 cm depth.

Fig.7. Augusta site: picture of the OSA-S06 core between -140 cm and -200 cm.

Fig. 8. Priolo area: OPR-S11 log from -20 cm to -80 cm, compared with X-Ray film (on the left) and the picture (on the right), please note how the bioclastic and volcanic layers show up on the film.

Fig. 9: Priolo area: OPR log

Fig. 10. Total Alkali Silica classification diagram (modified after De Martini et al., 2009) showing glass compositions of tephra recovered in Priolo site (OPR-S6 and OPR-S10 cores) and from the 122 BC plinian eruption of Etna (Coltelli et al., 1998). Dashed line includes the composition of Mt Etna volcanics (Corsaro and Pompilio, 2004).

Fig 11. Space-temporal distribution of tsunami deposits identified in different sites along Eastern Sicilian coast to be compared with historical tsunamis. The tsunami deposits are marked with a box and the core label: black boxes = high level of confidence (the layer has the most of the identification characters of tsunami deposit); medium grey boxes = medium level of confidence (the layer has many of the identification characters of the tsunami deposit); light grey boxes = low level of confidence (the layer has some of the identification characters of the tsunami deposit). Black vertical lines indicate event calibrated range ages from radiocarbon dating (Table 2). Grey vertical lines indicate span-time constrained by sedimentation rate (dashed lines is the complete time interval from radiocarbon dating). E1, E2, … E11 are the inundation events for which the relative deposits were found in Eastern

Sicily, marked with horizontal lines, whose length indicates inundated area: black lines = historical tsunamis identified with their dates; grey lines = paleotsunami events. Dotted horizontal line marks the 122 B.C. tephra found in the Priolo site and in the Augusta off-shore (Smedile et al., 2008).

Table 1. Main known historical tsunamis in the eastern coast of Sicily

date	Seismic source	Hit localities/areas	Main sources
14, 17, 33,	unknown	Sicily	Bonito, 1695; Mongitore, 1743
365 July 21	Crete-Gortyna	Sicily and many other islands	Jerome 380
963 July 22	unknown	Siria and Sicily	G. Bucellino in Mongitore, 1743
1169 February 4	South-eastern Sicily	Messina, Catania, Sicily	Falcando, 12th cent.; Fazello, 1558; Mongitore, 1743
1329 June 29	Etna eruption and quake	Mascali (eastern Sicily)	Fazello, 1558
1542 December 12	South-eastern Sicily	Augusta	Lacisio, 1543
1693 January 11	South-eastern Sicily	Messina, Giardini, Mascali, Agnone, Augusta, Siracusa, Marina di Ragusa	AGdS, 1693; Burgos, 1693; Campis, 1694; Boccone, 1697
1783 February 5-6	Southern Calabria	Torre Faro, Messina, Scilla and Southern Calabria	Sarconi, 1784; Vivenzio, 1788; De Lorenzo, 1895
1908 December 28	Messina Straits	Eastern Sicilian coasts and southern Calabria	Platania, 1909 Baratta, 1910

Table 2. Measured and calibrated ages (according to Calib REV5.0.2 by Stuiver and Reimer, 2005) of the samples collected in the excavation wall and cores. ANG = Anguillara site, GUR = Gurna site, OSA = Augusta site, OPR = Priolo site. S is the core label; after the core label, the number indicate sample depth in cm.

Sample	Type	Measured age B.P.	Calibrated age 2 σ
GUR-S10-403	Charcoal	3790 ± 30	2310-2135 B.C.
ANG-S01-220	Charcoal	335 ± 30	1455-1635 A.D.
ANG-S01-357	Charcoal	425 ± 30	1425-1510 A.D.
OSA-S06-96	Charcoal	1320 ± 30	650-770 A.D.
OSA-S06-158	Charcoal	1960 ± 30	40 B.C.-120 A.D.
OSA-S06-187	Organic sediment	2685± 30	900-800 B.C.
OSA-S06-193	Shells	3310 ± 30	1265-825 B.C.
OSA-S06-198	Organic sediment	2745 ± 30	975-820 B.C.
OPR-S11-43	Shells	890 ± 30	1420-1690 A.D.
OPR-S11-66	Charcoal	2460 ± 35	225 B.C.-220 A.D.
OPR-S09-158	Shell	3970± 35	2100-1635 B.C.

Table 3. Characteristics of the probable tsunami deposits found in eastern Sicily.

Anomalous units (depth cm)	Layer characteristics	Macro and micro fauna and vegetal content	Confidence level
TIA-T1 ( )	Well sorted, silicoclastic sand layer containing flat well-rounded cobbles all arranged in a chaotic pattern	Shell fragments	High
TIA-T2 ( )	Grey clean silicoclastic well sorted sandy layer, with sharp, erosional contacts at base and top	Shell fragments of mollusks and corals, benthonic and planktonic foraminifera together with algae remnants	High
RIF-T1 (130-134)	Silty sand layer	Rare planktonic foraminifera	Low
GUR-T1 (42-48)	Well sorted fine sand with volcanic clasts; sharp basal contact	Vegetal remains; no macro-micro fauna	Low
GUR-T2 (107-134)	Well sorted fine sand	Vegetal remains; no macro-micro fauna	Low
GUR-T3 (170-178)	Fine gravel in a silty-clay matrix, sharp basal contact	Vegetal remains; no macro-micro fauna	Low
GUR-T4 (400-408)	Very fine sand	Vegetal remains; no macro-micro fauna	Low
ANG-T1 (60-70)	Sand	Few vegetal remains; no macro-micro fauna	Low
ANG-T2 (195-200)	Fine sand	Few vegetal remains; no macro-micro fauna	Low
ANG-T3 (350-356)	Metamorphic rounded clasts in a dark grey silty-clay matrix	Echinoderms fragments and high concentration of roots and seeds	Medium
OSA-T1 (162-173)	Gravel, sharp basal contact	Vegetal remains; no macro-micro fauna	Medium
OSA-T2 (187-195)	Bioclastic layer	Rare whole gastropods, abundant shell fragments (mollusks, corals and echinoderms), rare ostracods, often broken benthic and few badly preserved planktonic foraminifera; vegetal remains	High
OPR-T1 (10-15)	Bioclastic layer with a sharp basal contact	Abnormal concentration of shell fragments and entire gastropods (all arranged in a chaotic pattern) of marine origin	High
OPR-T2 (30-40)	Bioclastic layer with a sharp basal contact	Abnormal concentration of shell fragments and entire gastropods (all arranged in a chaotic pattern) of marine origin; increment in the benthic foraminifera specific diversity	High
OPR-T3 (90-)	Detritic deposit	Anomalous assemblage made by macromammal bone fragments together with rare and badly preserved benthic and one planktonic foraminifera	Medium
OPR-T4	Sand	Marine microfauna appears well	Medium

(158-161)		preserved, differently from the association characterizing the fine deposits above and below	
RAP-T1 (8-10)	Lens of fine sand in a clay layer with sharp basal contact	Badly preserved shallow marine benthic foraminifera with some planktonic foraminifera	Low
RAP-T2 (12-14)	Lens of fine sand in a clay layer with sharp basal contact	Some well preserved deep marine benthic foraminifera, sponge's spicules, macrofossils and ostracods remnants	Low

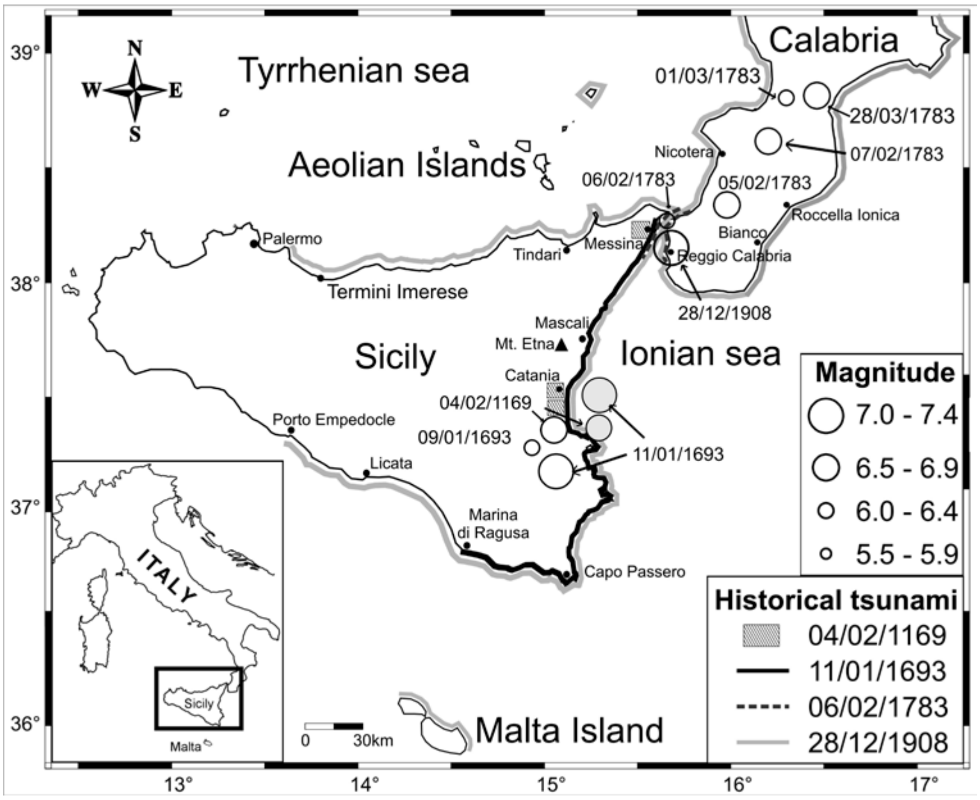

Figure 1

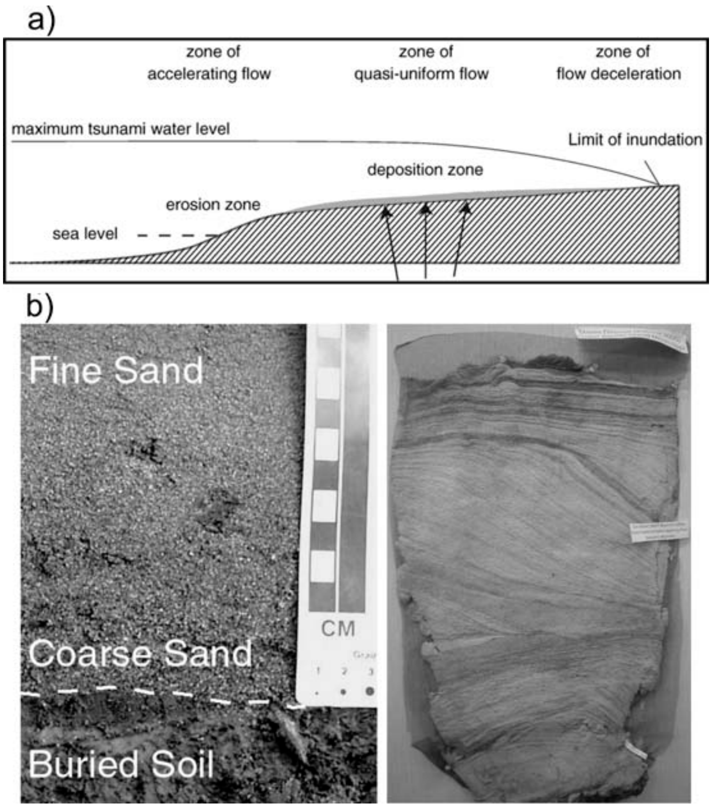

Figure 2

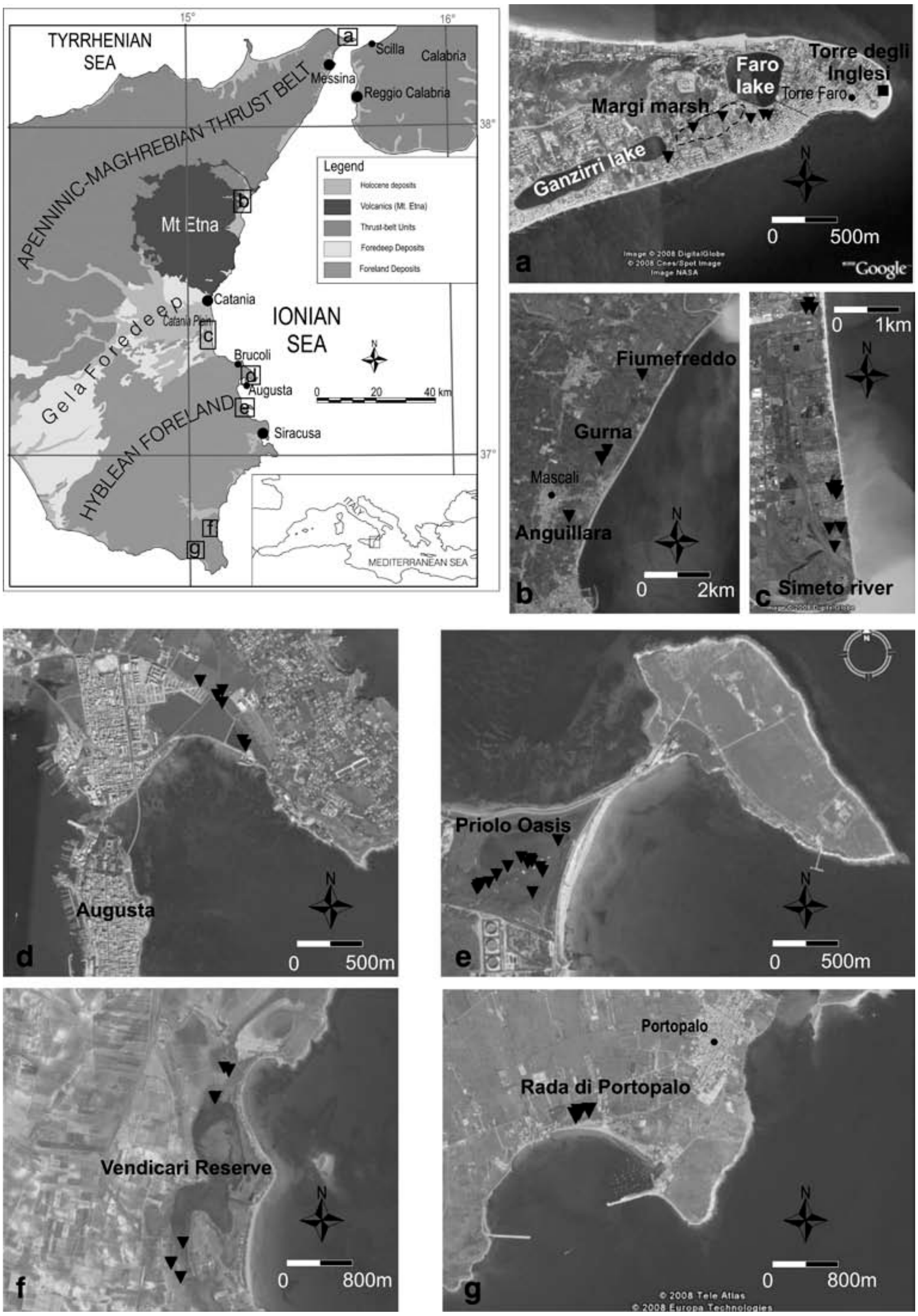
TYRRHENIAN SEA
APENNINIC-MAGHREBIAN THRUST BELT
Scilla
Calabria
Messina
Reggio Calabria
Mt Etna
Legend
Holocene deposits
Volcanics (Mt. Etna)
Thrust-belt Units
Foredeep Deposits
Foreland Deposits
Catania
Catania Plain
Gela Foredeep
IONIAN SEA
Brucoli
Augusta
HYBLEAN FORELAND
Siracusa
MEDITERRANEAN SEA
Faro lake
Torre degli Inglesi
Torre Faro
Margi marsh
Ganzirri lake
0 500m
Fiumefreddo
Gurna
Mascali
Anguillara
0 2km
0 1km
Simeto river
Augusta
0 500m
Priolo Oasis
0 500m
Vendicari Reserve
0 800m
Portopalo
Rada di Portopalo
0 800m
© 2008 Tele Atlas
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Figure 3

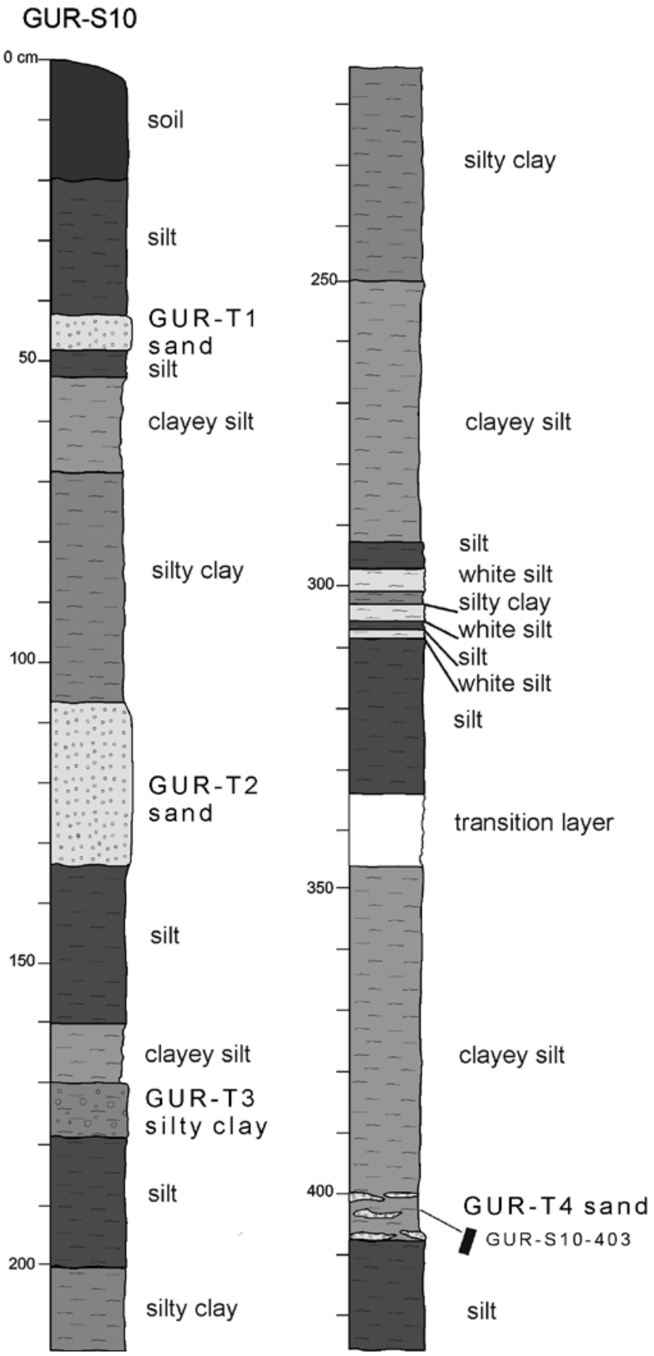
GUR-S10
0 cm
50
100
150
200
250
300
350
400
soil
silt
GUR-T1
sand
silt
clayey silt
silty clay
GUR-T2
sand
silt
clayey silt
GUR-T3
silty clay
silt
silty clay
silty clay
clayey silt
silt
white silt
silty clay
white silt
silt
white silt
silt
transition layer
clayey silt
GUR-T4 sand
GUR-S10-403
silt

Figure 4

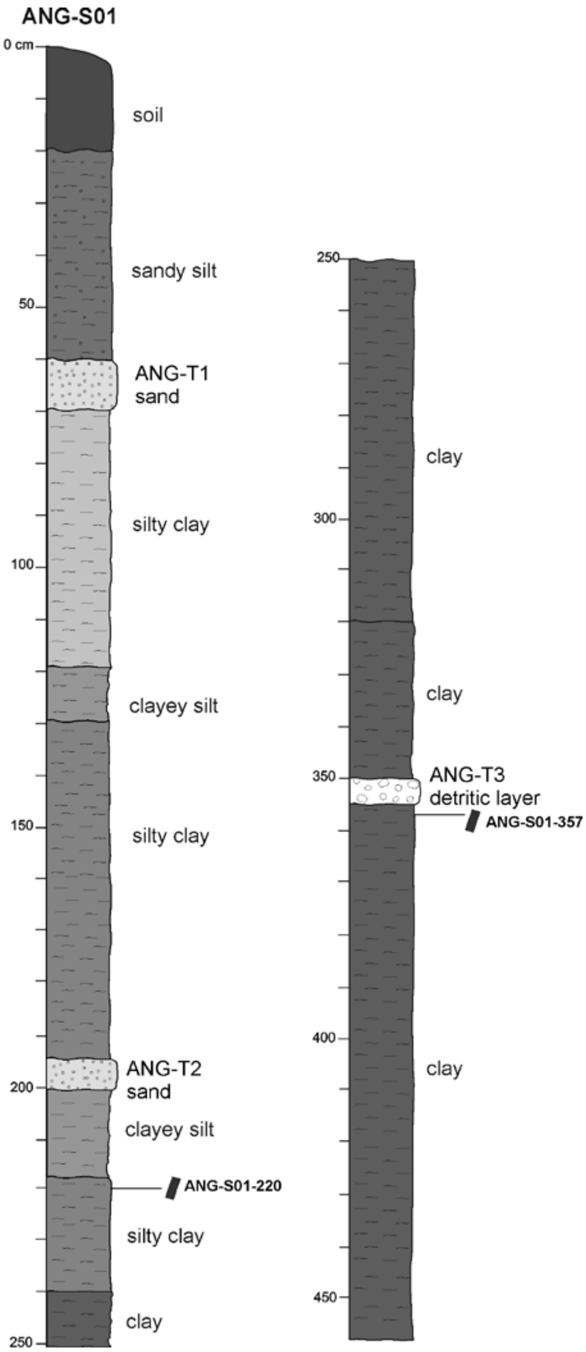
ANG-S01
0 cm
50
100
150
200
250
soil
sandy silt
ANG-T1
sand
silty clay
clayey silt
silty clay
ANG-T2
sand
clayey silt
ANG-S01-220
silty clay
clay
250
300
350
400
450
clay
clay
ANG-T3
detritic layer
ANG-S01-357
clay

Figure 5

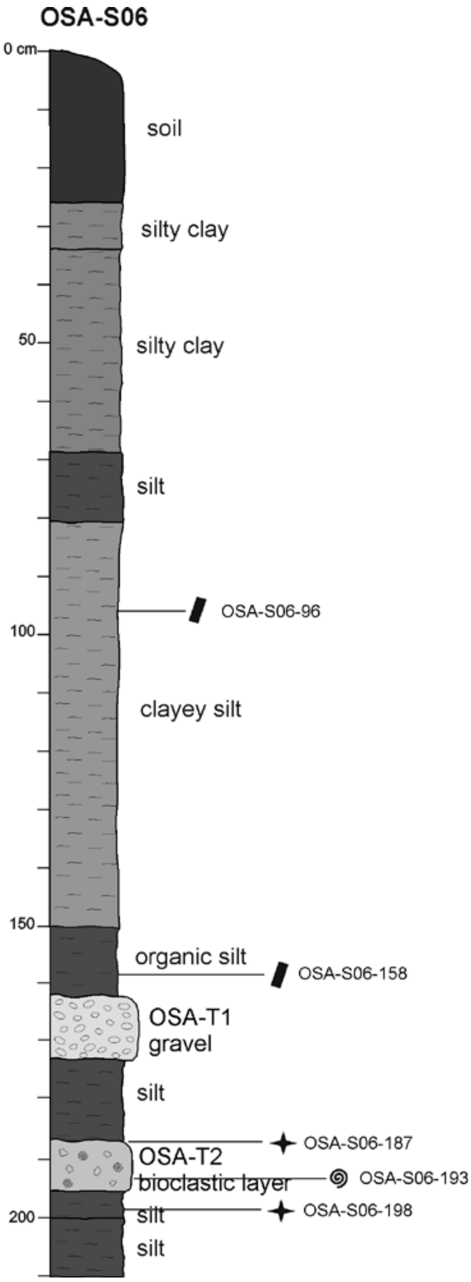
OSA-S06
0 cm
50
100
150
200
soil
silty clay
silty clay
silt
OSA-S06-96
clayey silt
organic silt
OSA-S06-158
OSA-T1
gravel
silt
OSA-S06-187
OSA-T2
bioclastic layer
OSA-S06-193
silt
OSA-S06-198
silt

Figure 6

Figure 7

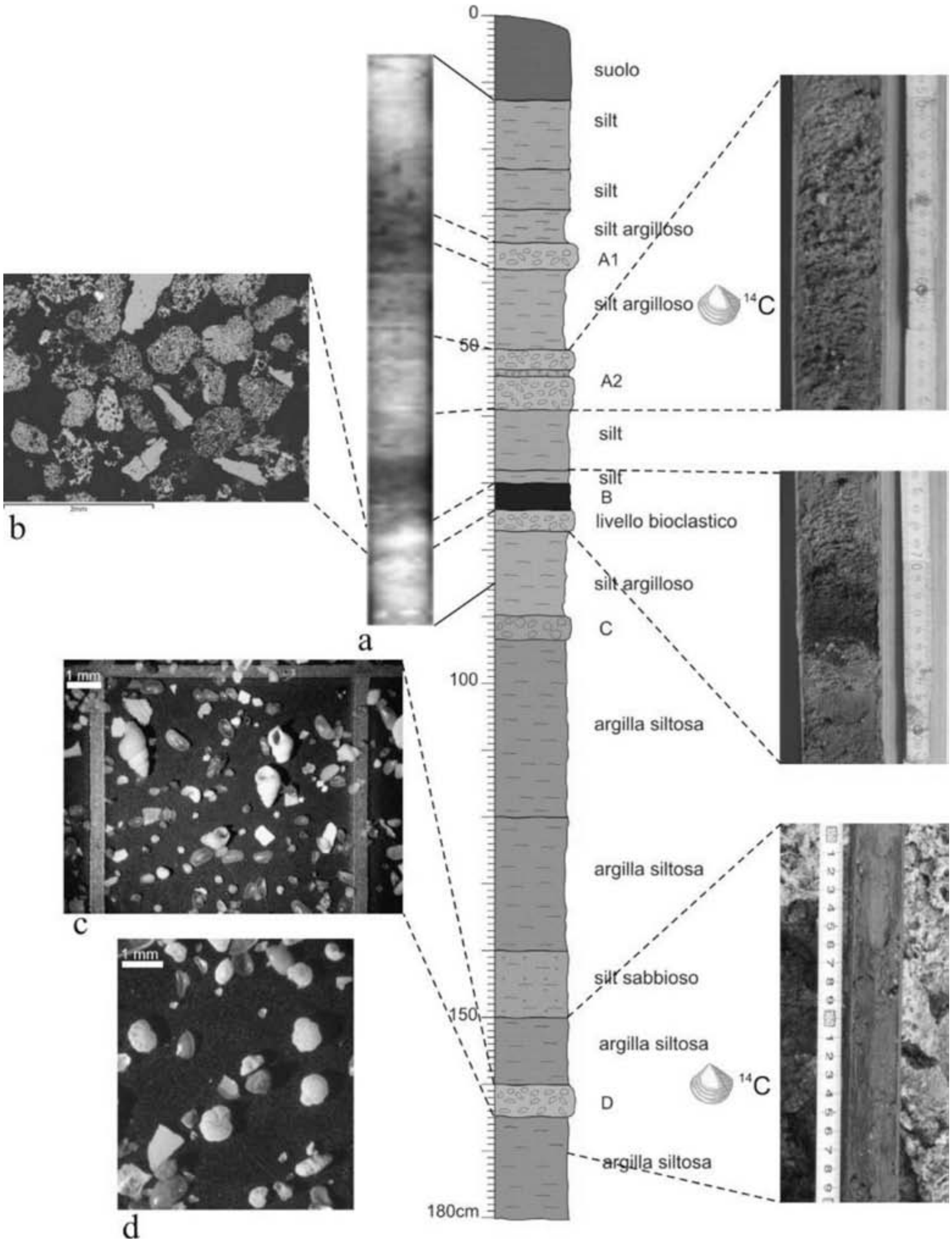
0
suolo
silt
silt
silt argilloso
A1
silt argilloso
14C
50
A2
silt
silt
B
livello bioclastico
silt argilloso
C
100
argilla siltosa
argilla siltosa
silt sabbioso
150
argilla siltosa
14C
D
argilla siltosa
180cm
a
b
1 mm
c
1 mm
d

Figure 8

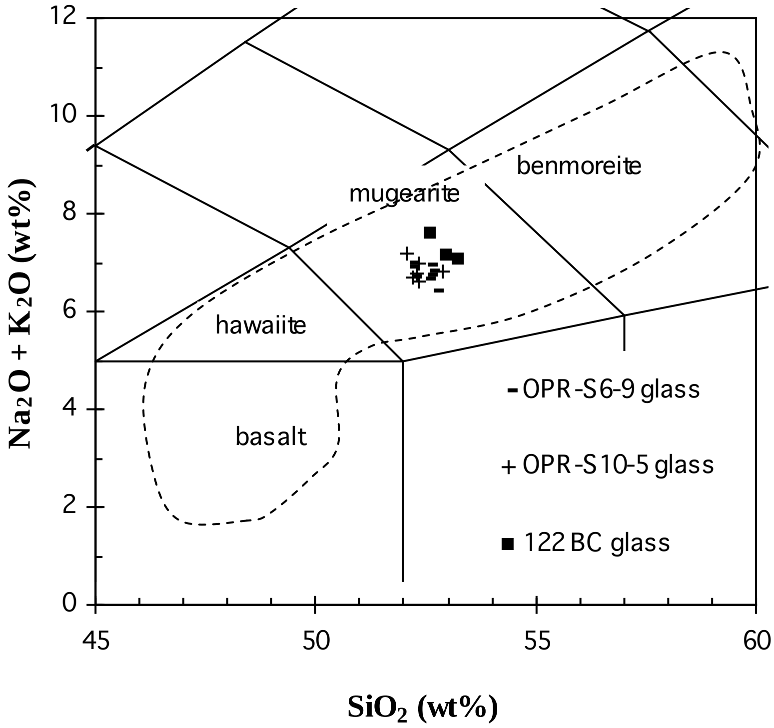
12
10
8
6
4
2
0
45
50
55
60
Na2O + K2O (wt%)
SiO2 (wt%)
mugearite
benmoreite
hawaiite
basalt
OPR-S6-9 glass
OPR-S10-5 glass
122 BC glass

Figure 10

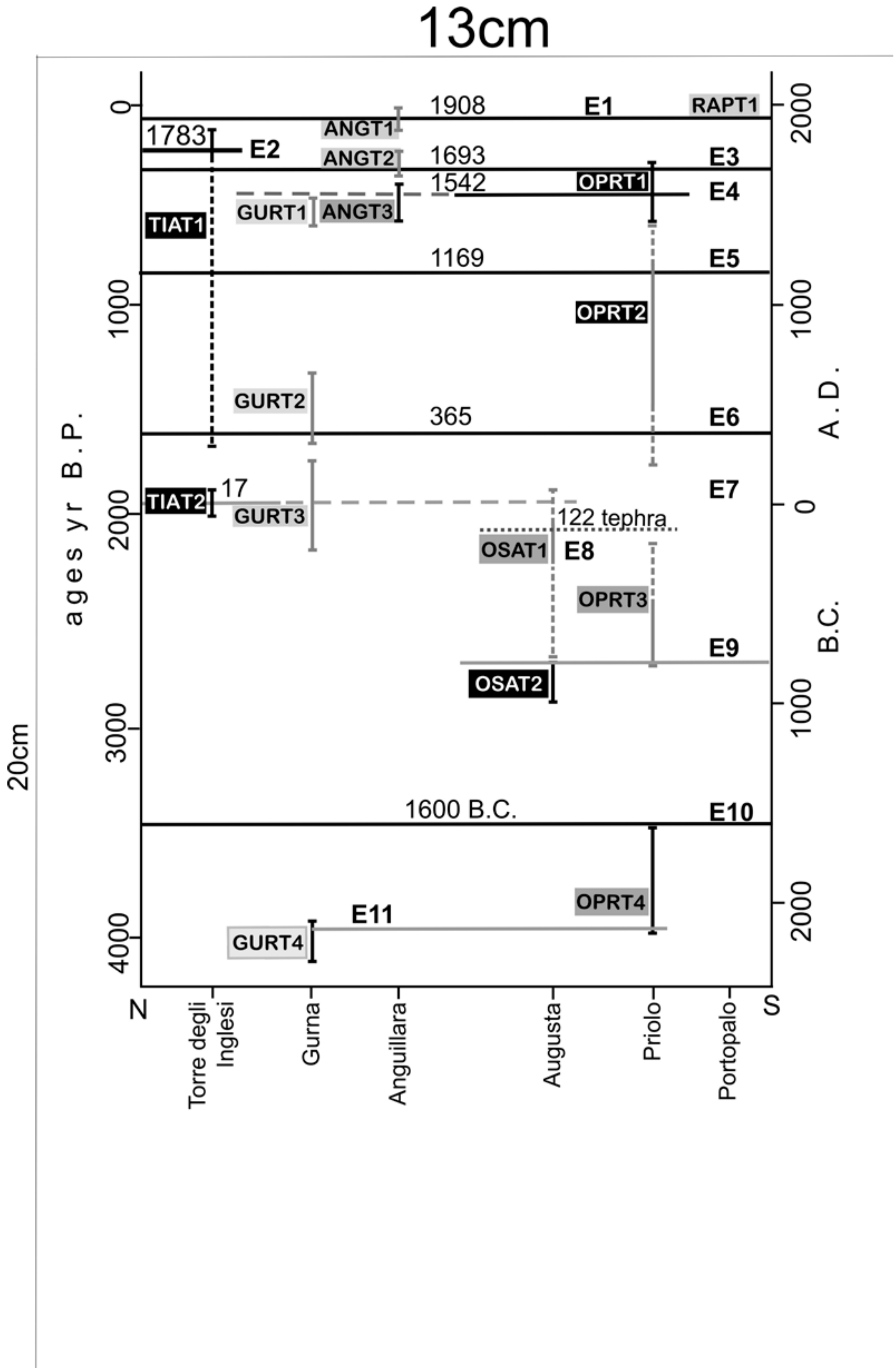
13cm
20cm
ages yr B.P.
A.D.
B.C.
1908
E1
RAPT1
1783
E2
ANGT1
ANGT2
1693
E3
1542
OPRT1
E4
TIAT1
GURT1
ANGT3
1169
E5
OPRT2
GURT2
365
E6
TIAT2
17
GURT3
E7
122 tephra
OSAT1
E8
OPRT3
E9
OSAT2
1600 B.C.
E10
E11
OPRT4
GURT4
N
Torre degli Inglesi
Gurna
Anguillara
Augusta
Priolo
Portopalo
S

Figure 11