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Combining inland and offshore paleotsunamis evidence: the Augusta Bay (eastern Sicily, ITALY) case study

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Introduction

Eastern Sicily (Italy) was repeatedly hit by tsunami waves related to large local historical earthquakes (e.g. 1908, 1693, 1169, CPTI Working group, 2004) as well as to far-field sources (e.g. AD 365 Crete earthquake, Jerome, 380). Along the eastern Sicily coasts, we selected the Augusta Bay (Fig. 1), a natural gulf about 15 km wide and with a 25 km-long shoreline, as the key area of this study because it is one of the locations where both information available from historical written reports on tsunami effects (Gerardi et al., 2008) and local geomorphology suggest it is very favorable for the research of the geological signature of past tsunamis. We are all aware of the fact that tsunami sedimentation can take place in both off-shore and in-land environments and since the tsunami behaviour depends strongly on bathymetric and topographic configurations, different sedimentation patterns can occur depending on the differences in these environments (Sugawara et al., 2008), asking for a multidisciplinary approach. Lowlands and lagoons characterize the Augusta Bay coastal area, providing an excellent and convenient restricted condition for recognizing and identifying tsunami deposits (Shiki et al., 2008), while a relatively wide continental shelf with a thick late-Holocene record has been investigated offshore through the acquisition of a tight grid of CHIRP-sonar profiles. Well-targeted sediment samples have been collected both offshore and inland. The integrated interpretation of the geophysical and geological data has been carried out in order to recognize, date and correlate key-layers in the sediment column that may be directly or indirectly related to tsunami events.

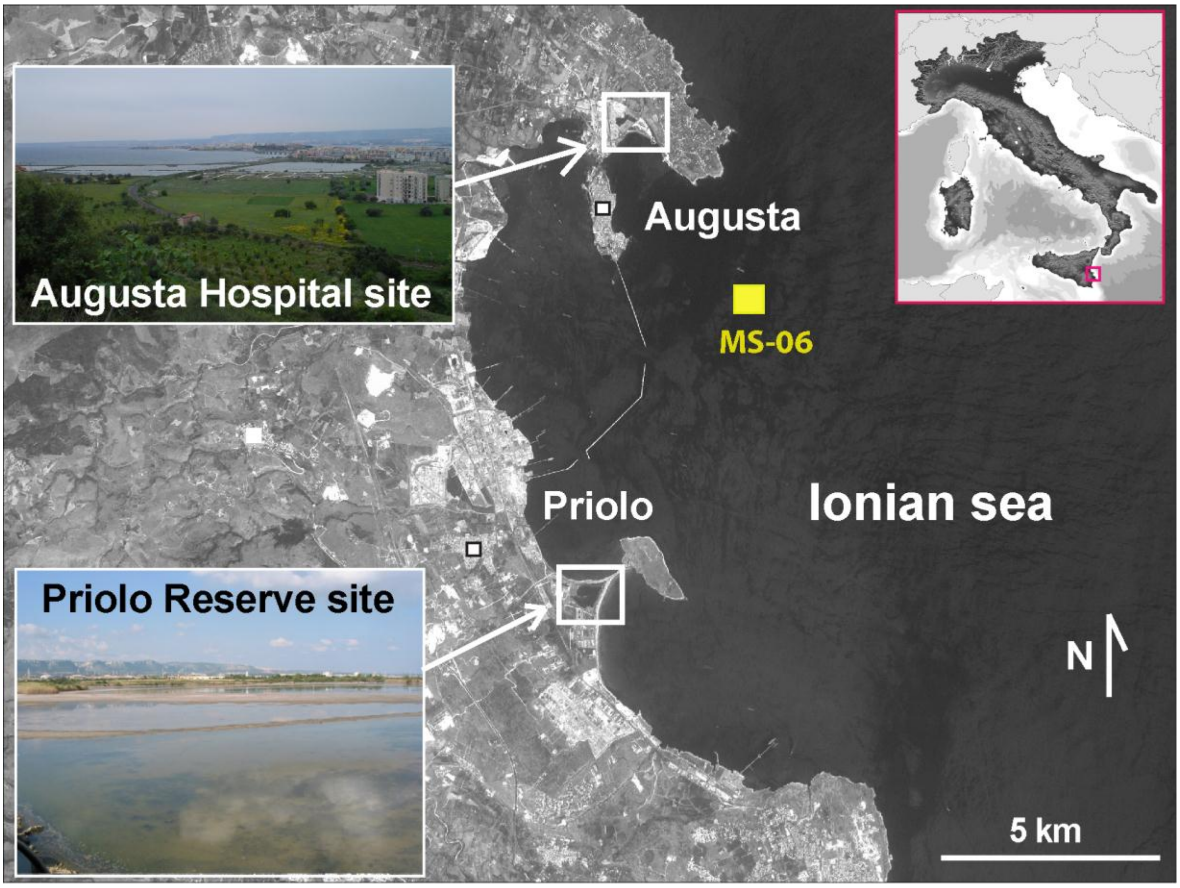

Figure 1: The Augusta Bay area in eastern Sicily, Italy. The Augusta Hospital and Priolo Reserve sites are marked with white empty rectangles, while a yellow box locates the offshore coring site (MS-06). Two panoramic pictures of the in-land investigated sites are also shown.

In-land evidence for tsunamis

As for the inland research we adopted an approach that includes:

a) detailed re-analysis of all the available historical reports on tsunami effects (hit localities, inundated areas and run-up distribution) along the Augusta Bay and surroundings;

b) geomorphologic and geological studies of the Augusta Bay, through aerial-photographs, satellite images interpretation and field surveys, to identify sites favorable to sedimentation, preservation and dating of tsunami deposits;

c) coring campaigns, using both hand auger equipment and a vibracoring (gasoline powered percussion hammer), always accompanied by GPS surveys for its exact positioning with respect to the present shoreline;

d) laboratory analyses on collected sediments (X-ray, physical properties, grain size, micropaleontological, radiometric datings and morphoscopic and glass chemistry on thepra).

Historical data

From the historical records we learned that the investigated area experienced at least four tsunamis (in 1908, 1693, 1542 and 1169) during the past millennium (period for which we believe that the historical tsunamis record can be considered complete, at least for the main events). As already known from the Italian seismic historical catalogues, the Middle Age period is quite scarce of information due to unstable social and economical conditions and thus the historical tsunami record is very poor before 1000 AD. However, it is well known that the large 365 AD Crete earthquake-generated tsunami hit the Augusta Bay area (Jerome, 380) as supported also by numerical modeling (Lorito et al., 2008; Shaw et al., 2008). An historical average tsunami recurrence interval (ATRI) of about 250 years for the past millennium in the Augusta Bay can be derived from written reports (a ~400 years long ATRI is obtained considering the ca 2 ka long historical dataset).

Geological data

Given the high variability in the nature of tsunami sediments, it is not surprising if tsunami deposits are not uniquely identifiable, and other kinds of deposits, storm- or hurricane derived, may share most of their characteristics. In recent years, only a few studies were designed to compare sedimentological characteristics of historical tsunami and storm deposits at the same or nearby site in order to reduce sediment and landscape variability (Nanayama et al., 2000; Goff et al., 2004; Tuttle et al., 2004; Kortekaas and Dawson, 2007). A recent review paper (Morton et al., 2007), on the physical criteria for the abovementioned distinction, uses several modern examples to describe idealized tsunami and storm deposits. The presence of a relatively thin deposit (average <25 cm) often made by normally graded sand consisting of a single (or few) structureless bed, sometimes with rip-up clasts, strongly favor a tsunami origin; on the other hand, a moderately thick sand bed (average >30 cm) composed of several planar laminations with foreset and ripples clearly favor a storm origin. Moreover, the geological approach may be complicated by erosion/deposition process related to storms (Morton et al., 2007) and by the possible presence of a tsunami-related erosion/bypass zone (no deposition), usually as far as 150 m inland (Gelfenbaum and Jaffe, 2003).

In order to avoid most of these problems we selected only sites wide enough to perform our coring campaigns starting from a minimum distance of 200 m from the present shoreline and moving further inland as possible. We concentrated our study on the sites of Augusta Hospital and Priolo Reserve, about 10 km apart (Fig. 1). The Augusta Hospital site is placed on an alluvial surface (1 to 5 m a.s.l.) gently dipping towards a large salt marsh, bounding the sea, while the Priolo Reserve site is a 0.5 km^2 shallow coastal lagoon separated from the sea by sand dunes, up to 4.5 m high.

A total of 22 cores were collected inland in these two sites, at a maximum distance of 530 m from the present coastline (De Martini et al., 2010). The dominant fine to very fine stratigraphy is intercalated by at least 6 high-energy depositional layers, repeatedly found in several cores. These relatively thin (about 10 cm) single massive and structureless beds with abrupt erosional lower contact are made of coarse to fine sand with sharp basal contacts (Fig. 2A) and present a bioclastic component (sometimes predominant) made of microfauna (benthic and planktonic foraminifera, from both shallow and open marine environment) and shell fragments both suggestive of a marine provenance (Fig. 2B).

Figure 2: Two tsunami deposits found in the Augusta Bay sites. A) picture of a yellowish bioclastic layer (event AU-02) composed by few whole gastropods (*Hydrobia* spp., *P. conica*), abundant shell fragments (mollusks, corals and echinoderms), few ostracods, often broken benthic (*Ammonia* spp., *Bolivina* sp., *Cassidulina laevigata*, *Cibicides lobatulus*, *Haynesina germanica*, *Pullenia bulloides*, *Rosalina* spp., miliolids) and few badly preserved planktonic (*Globigerina* spp., *Globigerinoides* spp., *Globorotalia inflata*, *Turborotalita quinqueloba*) foraminifera; this layer shows a sharp erosional basal contact and no evidence for layering or grading. B) picture of a bioclastic layer with sharp (probably erosional) basal contact (event PR-02), with a huge amount of shell fragments, gastropods (*P.a conica*, with abrasions probably due to high energetic transport) and ostracods, benthic and few planktonic foraminifera (with a peculiar increment in the benthic foraminifera specific diversity with respect to adjacent deposits).

Chronological constraints on the age of these deposits are based on 8 AMS radiocarbon datings and on the attribution of a tephra layer to the 122 BC Etna eruption (thanks to petro-chemical and morphoscopic analyses). C14 derived data include measured and calibrated ages (according to Calib REV5.0.2 by Stuiver and Reimer, 2005) of the samples collected in the cores. For the marine shells we adopted the reservoir correction for marine samples (400 yrs according to the calibration data set marine04.14c, see Calib REV5.0.2 by Stuiver and Reimer, 2005) and a difference ΔR in reservoir age of the study region, to accommodate local effects.

On the basis of the combination of all the data collected on the marine inundations that hit the Augusta Bay area, we suggest that evidence for at least six tsunami events was found at the Augusta Hospital (AU- events) and Priolo Reserve (PR- events) sites during the past 4 ka (De Martini et al., 2010). In terms of tsunamis timing, we could list them as follow: younger than 1420-1690 AD (PR-01), 650-770 AD (AU-00), 160-320 AD (PR-02), 600-400 BC (AU-01), 800-600 BC (PR-03), 975-800 BC (AU-02) and 2100-1635 BC (PR-04). Three of the tsunami deposits found at the Priolo Reserve site may be associated to historical tsunamis: PR-01 to the 1693 local event, PR-02 to the 365 AD Crete event and PR-04 to the ca. 3600 BP Santorini event. These results appear to confirm studies performed on inland-displaced boulders (Scicchitano et al., 2007; Barbano et al., 2010) and coarse marine sediments (Scicchitano et al., 2010) developed in the same area and surroundings on the 1693 tsunami. For the 365 AD Crete tsunami and the Late Minoan Santorini event, our findings may represent the first onshore evidence in the central-western Mediterranean area. On the basis of these results we can assume a geologic ATRI of about 600-700 years for the past 4 ka in the Augusta Bay (De Martini et al., 2010).

Offshore evidence for tsunamis

As for the offshore research we adopted an approach that includes:

a) geophysical survey of the Augusta Bay, through close-spaced grid of seismic reflection chirp-sonar profiles covering the 150 km^2 of the bay (morphobathymetry, seismic reflection, seafloor reflectivity), to identify an ideal location to sample a potentially complete stratigraphic record;

b) coring campaign, in order to collect a long sediment gravity core;

c) laboratory analyses on collected sediments (X-ray, physical properties, grain size, micropaleontological, radiometric datings and morphoscopic and glass chemistry on thepra).

Geological data

Offshore studies offer an interesting alternative to the investigation of tsunami’s signatures because marine environments can assure a relatively undisturbed continuous record and, therefore, are potentially more sensitive to anomalous events (*i.e.*, earthquakes and tsunamis). Although the marine environment might represent a new source for field-based tsunami evidence, very little has been done on the study of tsunami transport and deposition in offshore zones or in shallow-shelf areas (Weiss and Bahlburg, 2006; Dawson and Stewart, 2007). Coarse-grained deposits and, more generally, high-energy processes were used as offshore evidence for past tsunamis (Van der Bergh et al., 2003; Reinhardt et al., 2006; Abrantes et al. 2008; Goodman-Tchernov et al., 2009). In addition, these studies highlighted the difficulty of differentiating a tsunami effect from that of normal storms, and faced the problem of a subtle mixing of the two processes in the nearshore zone. With the aim of exploring new offshore approaches for the paleotsunami research, we started an investigation off the shore of Augusta Bay (Smedile et al., 2011). We planned to integrate local in-land tsunami studies (De Martini et al., 2010) with offshore coring, to highlight any subtle anomaly in sediments, fauna assemblages, physical properties, etc., that could represent a proxy for tsunami occurrence.

Differently from previous offshore studies in this area (Di Leonardo et al., 2007; Budillon et al., 2005; 2008) that considered only the recent part of sediments (i.e. the first 30 cm bsf), we presents new data (Smedile et al., 2011) from a 6.7 m-long piston-core (MS-06) sampled 2 km offshore the Augusta harbor at 72 m water depth, in the northern part of the bay (Fig. 1), in shelf mud deposits where no evidence of gravitational processes and anthropogenic disturbances (both in terms of sediment quality and of local sedimentation rate due to dumping) exist. The MS-06 core is made of 6.7 m of almost homogeneous mud, interrupted by a 3-4 cm thick black medium-coarse sandy layer at ~3 m below the top (Fig. 3C). A quite thick *Posidonia oceanica* rich layer appears as a discrete interval just below the top core, also highlighted as a darker horizon by X-Ray imaging (Fig. 3A). Further dark layers, likely related to the compaction of *P. oceanica* remains, are recognizable in a qualitative way along the core from X-ray imaging, as well as localized concentrations of molluscs (mainly *Turritella communis*), sometimes arranged without directional pattern (Fig. 3B). The gamma density profile shows a homogeneous pattern with minor fluctuations, confirming that the core was sited in a low energy environment with a monotonous deposition dominated by fine-grained sediments (Fig. 3). The magnetic susceptibility profile highlights the presence of a single layer very rich in magnetic minerals, coinciding with the black medium-coarse sandy layer highlighting its volcanic origin (Fig. 3).

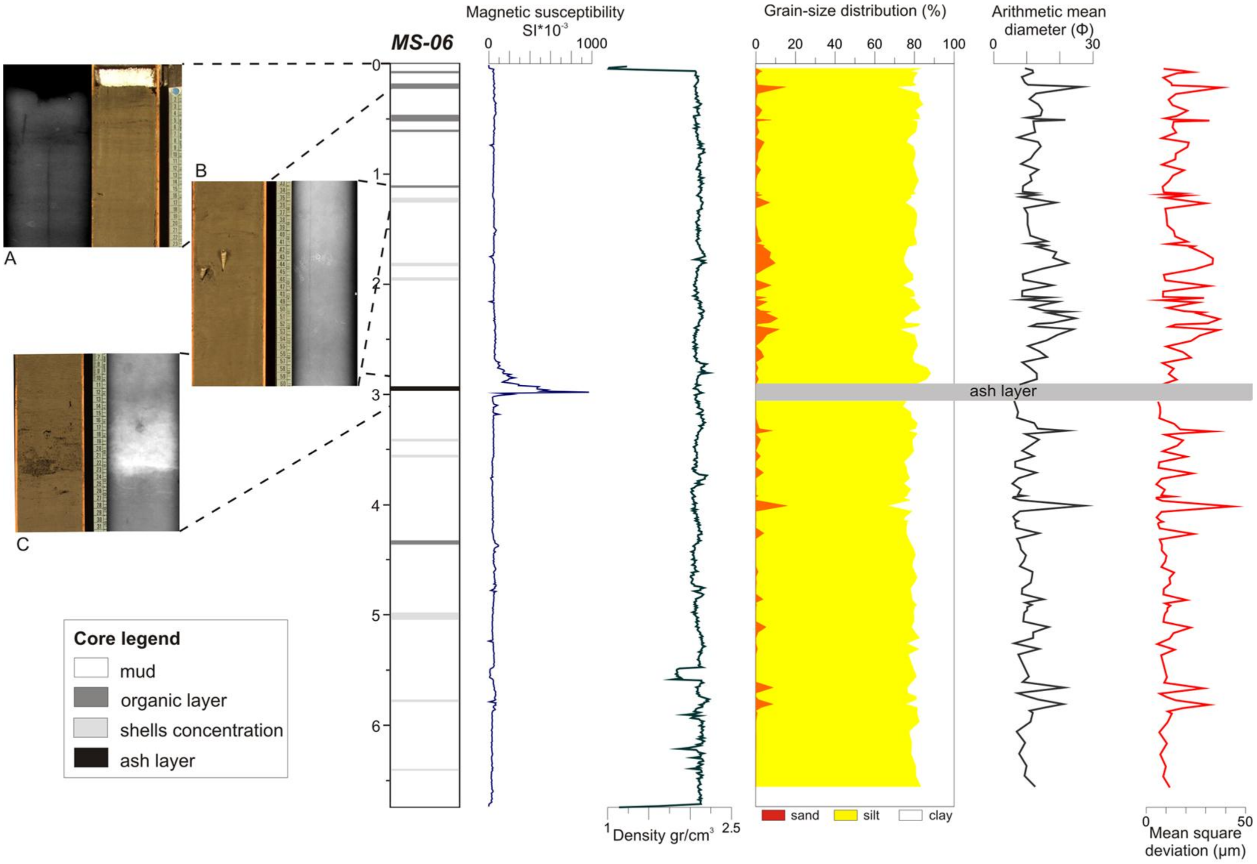

Figure 3: Simplified lithology of MS-06 core coupled with magnetic susceptibility, γ density logs and grain size distribution with some derived parameters (modified after Smedile et al., 2011). On the left side some details of sediments and X-ray; images A) uppermost portion with organic rich layer in *Posidonia* fibers, B) shells concentration layer and relative X-ray image, C) ash layer consisting of black fine lapilli and coarse ash.

Through the analysis of tephrostratigraphy, 10 AMS radiocarbon datings and radioactive tracers (^{210}Pb and ^{137}Cs), the entire core sequence has been dated back to the last 4500 yrs. C14 measured ages were dendrochronologically corrected according to the radiocarbon calibration program OxCal 4.1 (Bronk Ramsey, 2009), using a marine calibration curve that incorporate a time-dependent global ocean reservoir correction of about 400 years (Reimer et al., 2009). Moreover, the marine palaeo-reservoir effect was subjected to the local effect (ΔR offset) that, in the Mediterranean Sea, appears to be relatively constant for the past 6 or 7 ka (Reimer and McCormac, 2002). The appropriate ΔR offset can be selected from the Chrono Marine reservoir Database (Reimer and Reimer, 2001). Moreover, results from benthic foraminiferal assemblage analysis (Smedile et al., 2011) have shown up to 12 intervals in which displaced epiphytic foraminifera are present with abundance >25% of this whole assemblage. An opposite trend was found in the P/B ratio that shows a negative deflection in correspondence of almost all benthic displacement cases. This is tentatively explicable with a likely drowning of the total living assemblage caused by the external heavy inputs of displaced epiphytic specimens from the nearshore. Moreover, the sedimentological analysis (Smedile et al., 2011) highlights sandy inputs in these 12 anomalous intervals. These microfaunal anomalies were generally accompanied by significant amount of vegetal remains in the washed fraction, by localized concentration of mollusks and by darker organic-rich stripes. Thus, the 12 anomalous layers should have been caused by high-energy events, with back-wash tsunami waves as best candidates, related to an uncommon mechanism able to transport epiphytic species at greater depths (72 m bsl), relative to their living zone (up to 35-40 m bsl considering the depth limit of the *P. oceanica*), along with some amount of sand characterized by a peculiar bimodal grain-size distribution (interpreted as the result of different depositional mechanisms and/or different sources for the sand). In terms of tsunamis timing, we could list them as follow: E1 (AD 1820-1920), E2 (AD 1430-1810), E3 (AD 930-1170), E4 (AD 590-800), E5 (AD 430-660), Ex (AD 90-370), E6 (BC 350-130), E7 (BC 580-320), E8 (BC 660-400), E9 (BC 800-560), E10 (BC 1130-810), E11 (BC 1720-1200). One further element that supports the tsunami driven mechanism is the coincidence between 5 of the event ages (E1, E2, E3, Ex and E11) and the known tsunamis that hit the area (1908, 1693, 1169, AD 365 Crete, ca. 3600 BP Santorini). Considering the whole set of events occurred during the past 3700 yrs, a first approximate offshore ATRI of 330-370 yrs for tsunami inundations in the Augusta Bay can be estimated (Smedile et al., 2011).

These results suggest that our approach in the study of tsunami records is promising to define a cause-and-effect relationship between tsunamis and displaced epiphytic foraminifera rich layers. A comparative study between transport modeling of sediments during storms and tsunamis could also be a useful tool to better discriminate these phenomena in shallow-shelf areas.

Final Considerations

Coastal tsunami hazard evaluations include modeling of expected inundations and their frequency in time at a specific site. Therefore, a detailed knowledge of the distribution of past, inundated areas and their timing is critical. The Augusta Bay area represents a unique case study because it allows a comparison between geological (both inland and offshore) and historical records. We obtained 3 different Average Tsunami Recurrence Interval values [250-400 yrs from historical data, 600-700 yrs from inland studies (De Martini et al., 2010) and 330-370 yrs from offshore findings (Smedile et al., 2011)] that may ask for few short considerations, potentially relevant to environmental risk management and Civil Protection applications, taking into account that the Augusta Bay area is a major national industrial and military site.

Historical data, although generally too limited in time and space to be used as the sole reference to forecast the effects and frequency of future tsunami events, are very useful in giving directions for the selection of the best tsunami research area and for a first estimate of peculiar tsunami parameters like run-up height or inundation distance.

The in-land research for tsunami deposits is for sure able to detect evidence for large tsunamis but medium-small size events could be easily missed. In fact, it suffers the difficulties related to the intense human activity along the coastline as well as to superficial erosional processes that may remove tsunami signatures/deposits and the related record is usually far to be complete.

Finally the marine environment resulted clearly to be the best performing for the identification and dating of tsunami signatures, even if we believe that only a combination of the 3 approaches discussed above may furnish robust results also in areas densely populated.

We hope that our study could give new perspectives in the paleotsunami research and for the development of innovative approaches, which could be tested and applied in several other Mediterranean sites prone to tsunami hazard.

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