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Evidence of vertical tectonic uplift at Briatico (Calabria, Italy) inferred from Roman age maritime archaeological indicators

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A R T I C L E I N F O

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A B S T R A C T

Calabria is one of the most complex geological regions of the Mediterranean basin, which experienced large earthquakes and uplift and is still undergoing active tectonics. Along its coasts are located archaeological sites that can be used as powerful indicators of the relative vertical movements between land and sea since their construction. This paper presents and discusses data on the relative sea-level change as estimated from maritime archaeological indicators of the last ~2.0 ka BP existing along the Tyrrhenian coast of Briatico. These sites still show the remnants of a Roman age fish tank and a submerged breakwater about 320 m long.

The palaeo sea level has been obtained measuring the functional elevation of the significant archaeological markers. Their elevation was compared against the latest predicted sea level curve for the Holocene along the Tyrrhenian coast of Calabria. As this coastal area is affected by significant and continuous vertical tectonic uplift during Pleistocene, the data show the counterbalance between coastal uplift and relative sea level change caused by the glacio-hydro-isostasy, acting since the construction of these archaeological sites. The sum of these movements determined an about null relative sea level change for this location. These data are in contrast with other part of the tectonically stable areas of the Mediterranean and provide evidence that crustal uplift continued in the last 1806 ± 50 y at a rate of 0.65 mm/y.

1. Introduction

Past sea levels are represented along the large part of the Earth's coasts from geomorphological indicators produced by the sea level stands during the interglacial periods. The Mediterranean coastlines during the Pleistocene were often displaced at various elevations, providing indications on sea level changes and tectonic activity (Pirazzoli, 1976). In Italy, this evidence can be found along most of the coasts, and particularly in southern Calabria, which is among one of the most seismic area of the Mediterranean (Antonioli et al., 2006, 2007; Ferranti et al., 2007; 2010). During the last decade, multidisciplinary surveys in coastal archaeological sites of the Mediterranean have allowed the estimation of the timing and trends of the vertical movements of the Earth's crust and the relative sea level changes since the late Holocene. Archaeological data as indicators of relative sea level change have been used since the 1970s (Flemming, 1969; Schmiedt, 1974; Flemming and Webb, 1986), to study the coasts of the Mediterranean settled by Romans or pre-roman civilizations that built villas, harbors, piers and fish tanks. Recently, the integration of altimetric observations obtained in these classes of archaeological sites, with geological data and geophysical modeling has allowed the temporal and spatial reconstruction of the size and trends of the movements (Lambeck et al., 2004b). Sea level change along the coasts of the Mediterranean depends on the sum of eustatic, glacio-hydro-isostatic and tectonics (Lambeck and Purcell, 2005). The first one is mainly driven by climate changes and is time-dependent, while the latter two can also change in space and may vary from location. The glacio-hydro-isostatic component has been recently predicted and compared with direct observational data in deforming zones, after the Last Glacial Maximum (LGM) (Lambeck et al., 2004b, 2011; Antonioli et al., 2007; Anzidei et al., 2011b).

As the coasts of the Mediterranean are particularly rich in archaeological sites, there is the opportunity to obtain significant data for this study from maritime structures that nowadays are often submerged or emerged, even up to several m below or above the present sea level (Schmiedt, 1974; Pirazzoli, 1976, 1996; Flemming and Webb, 1986; Anzidei et al., 2003, 2011a, 2011b; Tallarico et al., 2003; Lambeck et al., 2004a, 2004b; Fouache and Pavlopoulos, 2005; Antonioli et al., 2007; Desruelles et al., 2009; Brückner et al., 2010).

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The presence of these archaeological indicators, located along the Tyrrhenian coast of Calabria, between the mouth of Trainiti creek and Briatico, allow estimation of the relative sea level changes and the vertical motion of the land over the last 2 ka in this area. This paper discusses data from these sites and the comparison of their elevations with the predicted sea level curves, calibrated at 40 sites in Italy (Lambeck et al., 2011) and, with the long term tectonic rates inferred from the elevation of the Quaternary marine terraces that are uplifted up to hundreds of metres in this area.

2. Geology and tectonics

The Calabrian arc is made up by Mesozoic and Cenozoic metamorphic and sedimentary units. Above these units are deposits aged from Miocene to Holocene. The extensional tectonics that have driven the geodynamics of the Calabrian arc since the late Pliocene have produced high and low structures, NW-SE and NE-SE trending. The northern sector of the arc (Fig. 1) shows, from west to east, the high of Capo Vaticano, the Mesima basin and the Serre relief, all bordered by transversal faults (Bianca et al., 2011).

The tectonics of this region are induced by the large scale movements of the African and Eurasian plates, that have produced regional uplift originated by re-equilibrium of isostatic movements (Westaway, 1990), crustal thickening (Ghisetti, 1981), or the intrusion of an astenospheric hot body between the mantle and the crust (Miyauchi et al., 1994). Uplift and extension have been interpreted as a response to slab retreat underneath the Calabrian arc and subsequent astenospheric flow resulting from slab detachment (Westaway, 1993; Wortel and Spakman, 2000; Goes et al., 2004) or supported by astenosphere wedging beneath the decoupled crust (Locardi and Nicolich, 1988; Miyauchi et al., 1994; Gvirtzman and Nur, 1999; Doglioni et al., 2001). The consequence of the uplift in this region is the occurrence of Pliocene-Pleistocene marine sequences with terraces placed up to 1200 m above sea level (Ferranti et al., 2010 and references therein).

In the investigated area, between Vibo Valentia Marina and Briatico, the tectonic unit of Capo Vaticano is exposed (Tortorici et al., 2003). This is a structural NE-SW trending high, bordered toward the SE by the Mesima basin, two main NW-SE trending antithetic faults (Mileto fault), in SSW by the Coccorino and Nicotera faults with WNW-ESE trends, and toward N-NW by a fault system, down-lifted northward (Fig. 1). Tortorici et al. (2003) found in the area of Briatico a typical morphological aspect of a bridge zone, placed between two fault planes (Ghisetti, 1979).

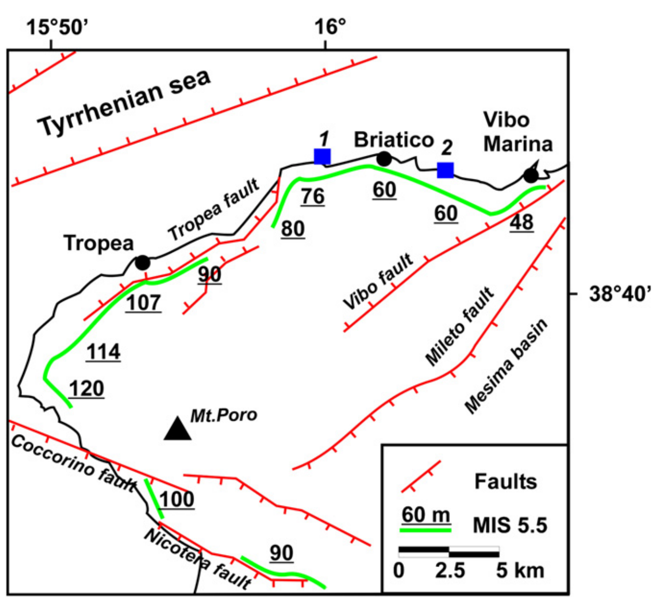

Fig. 1. The MIS 5.5 terrace (green line with elevation in meters) and the main faults at Capo Vaticano promontory (from Miyauchi et al., 1994). Numbered blue squares are 1) the location of the Scoglio Galera fish tank and 2) the pier at the mouth of Trainiti creek. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The current elevation of the Pleistocene marine terraces allowed estimation of the vertical tectonic rates in this area (Ferranti et al., 2006, 2010). These outcrops, which are approximately homogeneously distributed, show significant height differences (i.e. Salmoiraghi, 1884; Cosentino and Gliozzi, 1988; Carobene and Dai Prà, 1990; Anselmi et al., 1992; Miyauchi et al., 1994; Bordoni and Valensise, 1998; Bianca et al., 2011). Ferranti et al. (2006) speculated that the large uplift values recorded by the Calabria-Peloritano arc can be related to the general uplift of the lithosphere above a subducting plate.

Miyauchi et al. (1994) observed along the Tyrrhenian coast of southern Calabria twelve orders of Pleistocene terraces up to 1350 m above sea level. Among the areas where uplift is greater (Monte Poro, Le Serre and Aspromonte), the zone of Capo Vaticano promontory shows a large differential uplift. Here, the Tyrrhenian terrace of MIS 5.5 is at about 50 m above sea level near Vibo Valentia. At Capo Vaticano, it is up to 120 m above sea level, a difference of about 70 m (Fig. 2), in contrast with the recent ages published by Tortorici et al. (2003) who found an elevation even up to 285 m in this area.

Fig. 2 shows the seismicity of the Calabrian region according to the database of the Seismic Network of Calabria University. In black are plotted the events with $m_L \geq 2.5$ and focal depth to 50 km in the period 1981–2011 (Barberi et al., 2004). Red void squares indicate macroseismic epicentres of historical earthquakes in Calabria with $I_0 \geq$ VIII MCS from CPTI catalogue (CPTI Working Group, 2004). The inset shows a compilation of fault plane solutions for earthquakes shallower than 50 km in the Calabrian area and $m_L \geq 2.8$, obtained by the combination of: a) the EMMA database by Vannucci et al. (2004); b) the Global and Italian CMT Catalogs (http://www.globalcmt.org/; Pondrelli et al., 2006); c) original computations performed in the framework of the SyNaRMa Interreg IIIB Project (Guerra, 2007) using the FPFIT algorithm by Reasenberg and Oppenheimer (1985); d) specific papers published more recently (e.g. D'Amico et al., 2010; D'Amico et al., 2011).

In historical times, the city of Vibo Valentia was destroyed by the catastrophic earthquake ($m = 7.0$, $I_0 =$ XI MCS) of September 8th, 1905. The location of the source of this shock, and consequently the identification of the major tectonic structure from which it was generated, is still debated since Mercalli (1906) and Baratta (1906). Several authors have studied more recently or are presently studying the problem, by using different approaches (e.g. Piatanesi and Tinti, 2002; CPTI Working Group, 2004; Michelini et al., 2005; Loreto et al., 2011), but a sound solution has not yet been reached.

The Capo Vaticano promontory and its surrounding sea are characterized by a very low level of surface seismicity (Chiarabba et al., 2005). On the basis of the knowledge of the historical seismicity and of the instrumental data for the last decades, the existence of coseismic differential displacements between different domains inside the Monte Poro complex in historical times can be excluded.

3. Materials and method

Between Vibo Valentia marina, at the mouth of the Trainiti creek and the village of Briatico, are located two archaeological structures of Roman age (Fig. 1). The first is represented by a breakwater built at the mouth of Trainiti creek near Porto Salvo village (Fig. 3a, b). The second is a fish tank, excavated on the Scoglio Galera, a small rocky islet near the small village of Santa Irene (Briatico) (Figs. 4a and 5a, b). With the goal to estimate the vertical motion of the

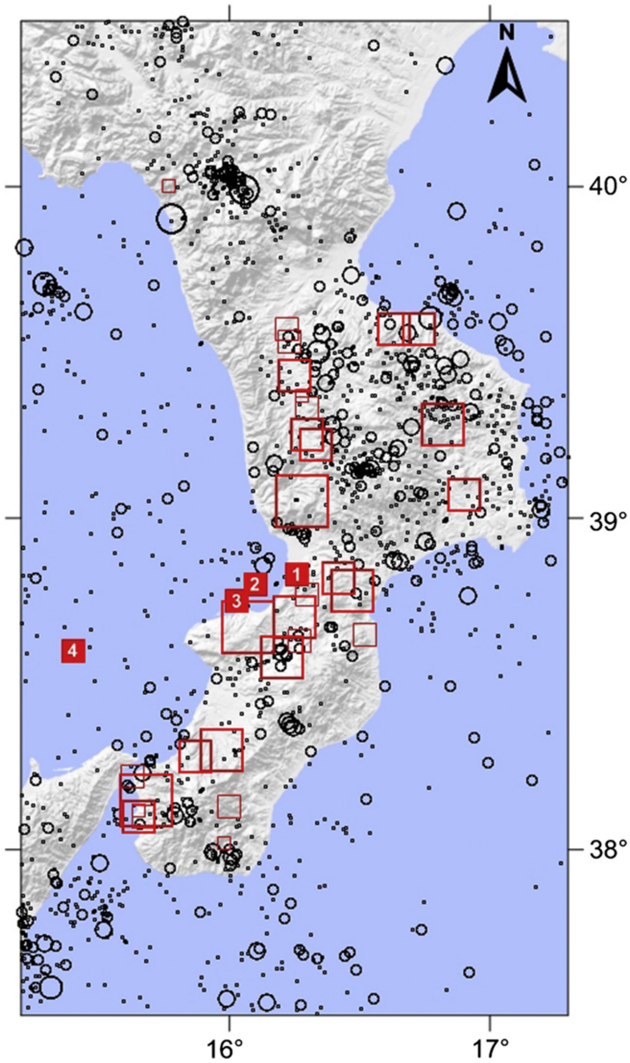

Fig. 2. Seismicity of Calabria. See text for description. Red squares are the epicentres of the historical earthquake (size is proportional to Magnitude). The locations of the 1905 earthquake are from: 1 = Rizzo (1907), 2 = Riuscetti and Schick (1974); 3 = Camassi and Stucchi (1997), 4 = Michelini et al. (2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

land and the relative sea level changes along this coast, these archaeological sites were analyzed, taking into account their former use and the functional elevations, following the guidelines described in Lambeck et al. (2004b).

To account for tides that can affect the measurements of the elevation of the archaeological markers, observational data have been reduced for tide values at the time of surveys, using tidal data from the nearest tide gauge stations of ISPRA (http://www.mareografico.it/). The time series of the near tide gauge data of Reggio Calabria was analyzed to estimate the sea level trend and the tidal range for this area. To account for the long term vertical land movements, the elevation of the inner margin of the marine terrace of MIS 5.5 (Miyauchi et al., 1994) was used. The normal elevation of the MIS 5.5 is 7 m for tectonically stable areas, but in the vicinity of the Scoglio Galera it is at 65 m above sea level, thus indicating a marked uplift of this area (Miyauchi et al., 1994; Ferranti et al., 2010 and references therein).

Data included a terrestrial and marine topographic survey. The latter was performed by a single beam survey, across the pier and around the fish tank of Scoglio Galera, to get an overview of the morphology of the seafloor, to help in interpretation (Fig. 4).

3.1. Bathymetric and topographic surveys

Bathymetric and topographic data were collected during two distinct surveys, using the Differential Global Positioning System technique (DGPS). Data allowed producing an accurate bathymetric and topographic map of the investigated area. This method is normally used to perform rapid and accurate bathymetric surveys in very shallow waters where conventional surveys performed from large boats cannot be carried out (Anzidei, 2000).

The topography of Scoglio Galera was obtained using two DGPS Trimble 4000ssi receivers equipped with radio modems and collecting data at 1 s sampling rate (Fig. 4). The reference station was located on a benchmark previously established on the islet while the rover was moved along defined paths. Bathymetry was obtained using two DGPS receivers: one located on the Scoglio Galera while the second was installed on a small boat and connected to an echo sounder and navigation software running on a portable Personal Computer (Fig. 4). The GPS antenna of the rover receiver and the echo sounder transducer were mounted at the ends of a rigid pole, which was installed on the right side of the boat. The latter was sailing at a constant speed of 2 knots during surveys. Positioning data were collected by GPS Novatel receivers equipped with an Omnistar correction system, while depth measurements used an Odom echo sounder (standard accuracy of 0.5% $\pm$ 1 cm). All data were collected at 1 s sampling rate. At the beginning of the survey a calibration of the transducer was performed, and sound speed values were estimated and applied during data analysis. Tidal corrections were neglected due to the small values of tide amplitudes during surveys ($\leq$15 cm) and depths were measured with respect to the instantaneous sea level. During data analysis, the noise due to pitch and roll of the boat were removed to correct the observations.

The final accuracy of each planar coordinate collected along the routes was $\pm$30 cm. Seafloor coordinates and depths were computed and converted in an ASCII file suitable to be managed by numerical and graphic software. Data were collected along $\sim$8 nautical miles and were used to construct several cross sections and a Marine Digital Terrain Model of the sea bottom. Bathymetric data were also combined with the topographic data provided by the terrestrial GPS survey on the islet and with the available digital aerial images, providing valuable information on the overall morphology of the area. Fig. 3b show the area of the pier at the mouth of Trainiti and Fig. 4 is the plot of the MDTM for the Scoglio Galera. The Marine Digital Terrain Models and the Digital Terrain Models were computed by the triangulation interpolation method.

3.2. Piers at the mouth of the Trainiti creek

This archaeological site consists of a submerged structure, approximately rectangular in shape, about 320 m long and 40 m wide (Fig. 3a, b). It extends NW-SE (330° N), oblique with respect to the coastline to which is connected. Another smaller wing was previously found by Mariottini (2001), but it was not found during these investigations. Both wings formed a typical harbor entrance named *faucies*, by their position suitable to protect an inner harbor. These structures can be interpreted as offshore breakwaters pertaining to a large harbor, likely belonging to the ancient port of *Hipponion/Valentia*, which presently is completely buried by coastal sediments (Schmiedt, 1966).

The structure was built with large blocks of concrete that contain several fragments of amphorae dated to Roman age (2 ka BP). The constructional features of the main wing show at least three

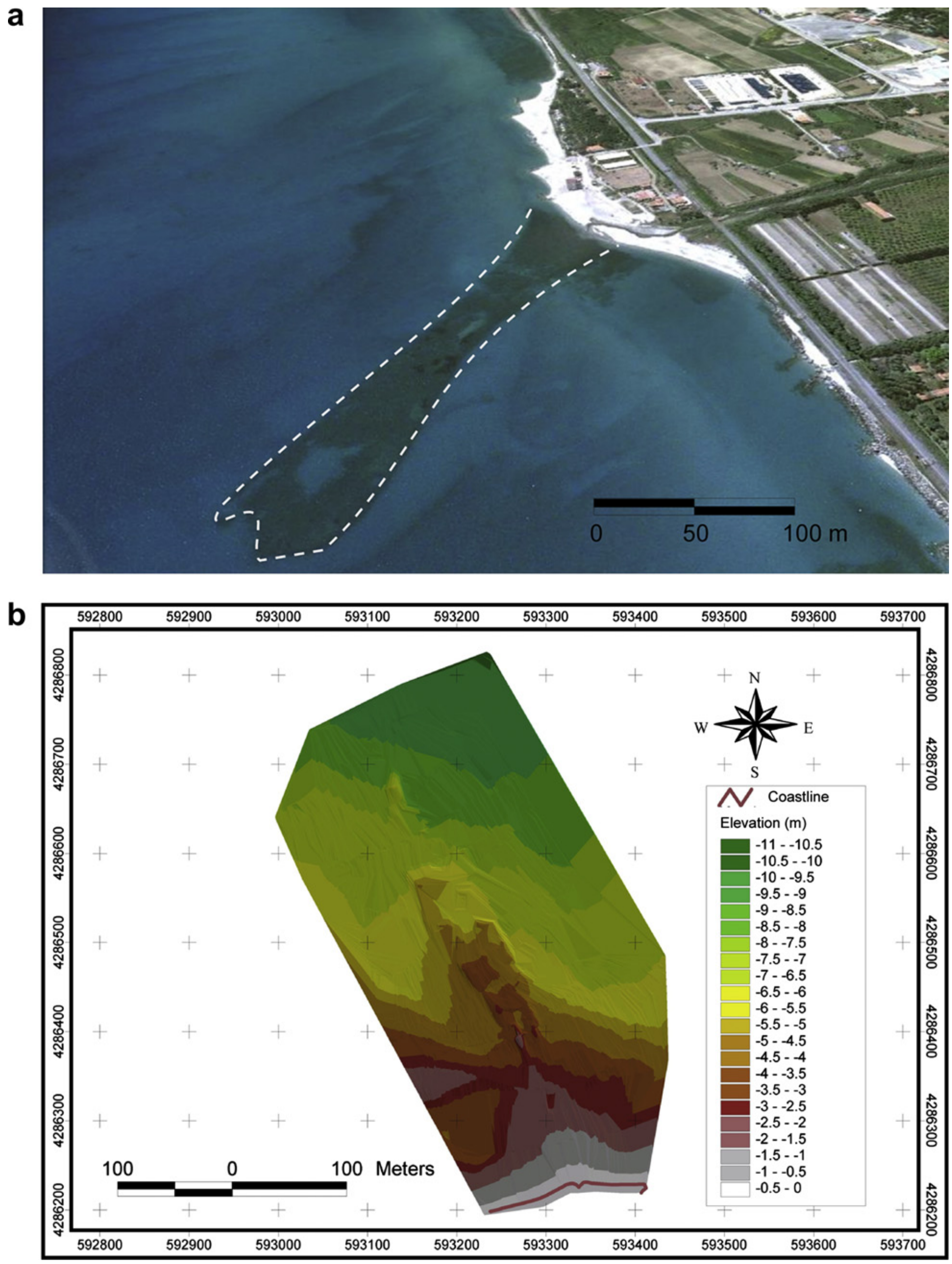

Fig. 3. a) Aerial view of the pier at the mouth of Trainini creek (image from Google Earth, http://www.earth.google.com); b) bathymetric map across the pier (see color scale for depth values), c) cross section of the seafloor across the pier. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

homogenous building sectors of: i) strongly cemented material containing abundant fragments of archaeological remains, ii) dissolved material, with poor archaeological remains and finally, iii) breakwater material, with elements partially built but without archaeological material.

The surface of the structure is rough, and its base follows the irregular topography of the seafloor, which is tilted toward offshore. It begins from the shore at an elevation of -1 m and extends offshore up to -9 m at its end. The surface of this structure was likely covered by pavements, now destroyed. Similar structures are found in other areas of the Mediterranean settled since Roman or pre-roman times, such as at Tharros, in Sardinia (Melis, 1998).

Previous geomorphological and palaeogeographical studies determined that this area suffered from significant changes of the coastline, which have caused the modification of the coastal plain that evolved toward a coastal environment with marshes and lagoons, separated by the sea from sand dunes (Lacquaniti, 1952; Cucarzi et al., 1995). Hence, this transitional zone underwent continuous flooding and silting caused by the Trainiti and S. Anna creeks (Medici and Principi, 1939; D'Alessandro et al., 1987). The progradation of the coastline and its timing is confirmed by Cucarzi et al. (1995) from the migration toward north of several phases of human settlements.

The old topographic maps of the Italian Istituto Geografico Militare (IGMI) show some ruins that could match the ancient harbor structures as reported in XVIII century by Priest Fiore. The description made by G. Schmiedt (1966) is the same as left by Fiore in 1680, when the harbour was *"destroyed under the order by the Roman pope to give to the barbarians a poorhouse"* and that this harbour was *"built with cut stones from the ancient inhabitants of*

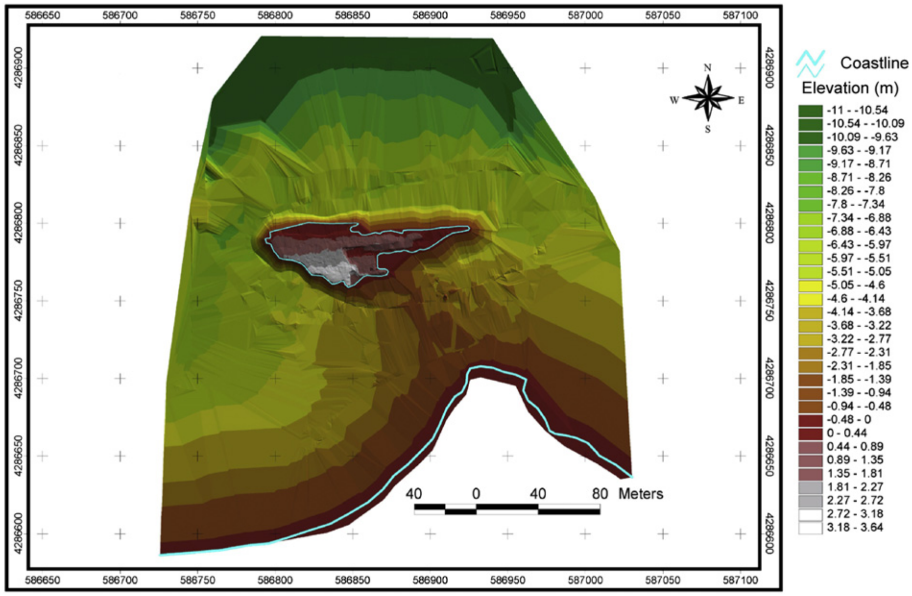

Fig. 4. Bathymetry and topography of Scoglio Galera (see color scale for depth values). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Hipponion, in a shape similar to a bended arm", in a time when most of its parts could still be seen.

Schmiedt (1966) cites previous descriptions *"Even today in the low and calm tide can be observed large remains of a big construction composed by very large blocks with arches and pillars of concrete and even the moorings to tie ships"* and *"the Harbour of Hipponium was placed in the bay in front of the castle of Bivona, at that time partly in a lagoon and connected with sea; near the shore of the lagoon there were large squared pillars built with bricks, distributed in regular intervals, that were outcropping from the sand and likely holding arcades circling the whole harbor"*.

Schmiedt himself (1966) observes that *"on the shore, in the same zone indicated by the aerial photographs, are present structures built with bricks that seem to be ancient,... it is not an hazard to collocate the ancient basin of the harbour of Hipponium in the bay where a lagoon was existent in the previous century"*.

All these information support the hypothesis that during the Roman time the current coastal plain was the site of the ancient port. The submerged structures, in particular those placed at the mouth of Trainiti creek, are likely part of the ancient Harbour which had two entrances: the first at the mouth of Trainiti creek, and the second in the eastern side of the lagoon. The underwater structure can be interpreted as a system to facilitate the outflow of the debris transported by creeks that exit in the basin, preventing its progressive infilling.

3.3. Scoglio Galera

Scoglio Galera is located near the village of Briatico, about 100 m distant from the coast. It is ~120 m long and ~40 m wide, extending east-west (Figs. 4 and 5a, b). This small islet was known from historical tradition to be used by Arabs to jail the Christians, sinking them in the pools.

Recently, marine archaeologists classified this site as a fish tank and a fish processing plant (Mariottini, 2001). The islet was excavated and cut at its surface, thanks to the softness of the biomarlstone and limestone of Miocene age (Fig. 5c).

Along the NNW side of the islet, which is the most exposed to the sea, the remnant of a wall and traces of the formworks used for the concrete, are still present. The fish tank consists of four nearby pools, E-W aligned, that follow the natural morphology of the islet (Fig. 5c, d, e). The pools have a total length of about 28 m and a constant width of 2.5 m. The two main pools are subdivided into minor pools and their inner walls show some holes at ~1 m above sea level, that were likely used to host horizontal wooden beams and a roof. The pools are crossed by two main channels, A and B, which link the inner basin with the open sea (Fig. 5b, e). The latter is protected and suitable for the moorings of ships. In particular, channel B crosses the islets by a tunnel. Two additional minor channels, C and D, connect the pools 2 and 3 with the inner basin. The pools are all connected by channels and separated by partition sects (Fig. 5c, d).

All the channels show the signs of the grooves used to operate the sluice gates, similar to those found in the fish tanks along the Tyrrhenian coasts of central Italy and other localities (Lambeck et al., 2004b; Anzidei et al., 2011b). These were used to provide an effective water exchange in the basin but without letting the fish escape. The inner side of the basin shows i) the crepidini, narrow sidewalks used to walk around the pools without getting wet, ii) the surface of a dock, and iii) ten bollards of different size, all rock cut in the islet. The inner side of the pools show a present day notch about 40 cm high and 30–60 cm deep. Its lower part shows an organic platform typical of environments at high hydrodynamics, which is in agreement with the amplitude of the local tides (Fig. 5c, d, e).

The underwater part of the islet, particularly inside the mooring basin, shows a selective erosion process, acting in coincidence with the different level of local stratigraphy, separated each other by 40 cm (Fig. 5f). The surface of the islet shows an additional squared small pool of ~1.5 × 1.5 m in width, crossed by a channel without sluice gates.

The geology of Scoglio Galera belongs to the outer limits of the youngest marine terrace of Upper Pleistocene (Miyauchi et al., 1994) that is exposed between 0 and 30 m above sea level. It consists of littoral deposits formed by alternating clastic facies with variable size of strongly cemented conglomerates, sands and bio-limestone. The thickness of the strata ranges from 20 to 250 cm and those aligned N 260°–290° are tilted 10°–15° toward NNE. The thickness of the bio-limestones is about 200 cm in the islet.

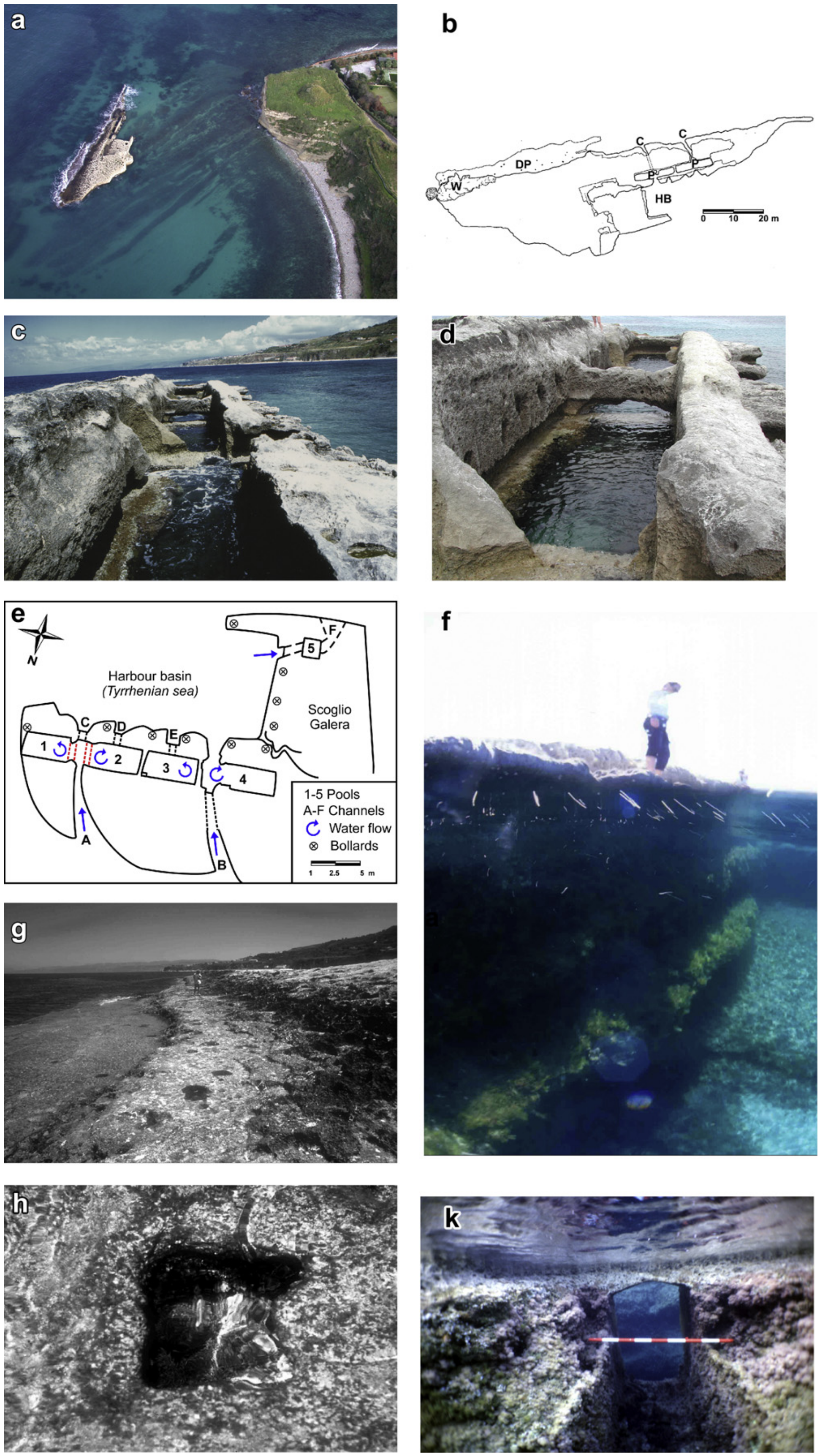

Fig. 5. a) Aerial view of the Scoglio Galera and b) its topographic map (modified from Mariottini, 2001) c) the pools of the fish tanks and d) their partition sects and the erosion notch. Below the sects run the channels that link the nearby pools. e) Particular of the Scoglio Galera: Black dots are the bollards excavated in the rock; pools are numbered 1–5; the main (A, B) and secondary (C,D,E,F) channels, are also reported in the map. f) An underwater view of the islet from inside the harbor basin. These notches are caused by selective

As the strata are all tilted NNE, the islet has an asymmetric morphology. Its southern part is indented and with a vertical coastline up to 3 m high, while the northern part shows a linear trend and is gently tilted NNE.

Along the southern border, inside the pools and in the mooring basin, a present day erosion notch 30–60 cm wide and 50–100 cm high, is present (Fig. 5c, d). The northern border displays an abrasion platform up to 6 m wide, characterized by *Dendropoma petreum*. These gastropods usually live in the lower intertidal environment (Antonioli et al., 1999).

The northern border shows also relics of a marine terrace ~60–80 cm above sea level, at the same level of the walking surface (crepidine) that runs along the mooring basin. The crepidine was partially excavated on the surface of the marine terrace.

The cross section (Fig. 6) shows the cliff running along the northern coast of the islet whose bottom ends in the seafloor at a depth of 6–7 m. The elevation of the intertidal abrasion shows a level of 7–8 cm of *Dendropoma petreum* (Antonioli et al., 1999) which is in agreement with the current sea level. This platform includes several squared holes, excavated in the islet to support the wooden poles that made up the reinforcements of high concrete walls, built to protect the islet from the waves. The platform ends with a small scarp 80 cm high, over which were developed a small terrace 3.5 m wide (Fig. 5g). The latter ends with an additional small scarp, and its surface shows other squared holes where parts of the walls are still remaining. Although this may appear as natural terrace, it appears to have been excavated to adapt the surface of the islet to the wall foundations. Along the opposite side of the islet the seafloor is up to 4–5 m deep and shows an erosion-smoothed marine notch. The present day erosion notch has a size a few cm larger than the tidal range.

4. Results

The goal of this paper is to provide quantitative data on the relative sea level changes during the late Holocene and of the vertical land movements in an area of high tectonic deformation rate. For this purpose, direct measurements of archaeological and geomorphological markers connected to sea level were used. To correlate the archaeological structures to sea level at the time of their construction, the functional elevations of the observed architectural features are defined as significant parameters to estimate the local relative sea level change. These are specific parts of an archaeological site which were constructed at specific elevations for functional purposes, defining the minimum elevation above high tide (Lambeck et al., 2004a, 2004b).

4.1. Trainiti creek

Surveys have determined that the depth of the main pier ranges between −1 and −9 m from its attachment along the coast towards the offshore (Fig. 3b). This structure, a breakwater or an outer pier, was built to ensure that at least 1 m remained emerged in the part close to the shore, to function properly and to guarantee good protection to the harbor basin, which today is silted (Lena, 1989; Mariottini, 2001). Excluding any large vertical movement, this structure was intentionally built at these depths to create an artificial barrier against waves and currents. The bathymetry support this hypothesis, as the pier is tilted toward offshore, following the surface of the seafloor. The latter is gently deepening, and does not show any relevant first order morphological signatures. In absence of precise constructional and morphological elements in the shallow part of the pier, precise estimation of the intervening relative sea level changes since the time of its construction cannot be determined, mainly due to a lack of more precise information on the harbor, that today is completely buried under the recent sediments of the coastal plain (Schmiedt, 1966).

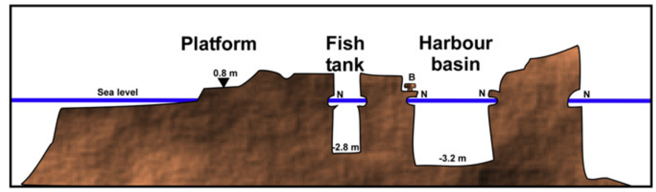

Fig. 6. Sketch of a cross section of Scoglio Galera (not in scale) with i) present day abrasion platform placed at the same elevation of the ii) present day erosion notches placed inside the pools, iii) mooring basin, iv) bollard and crepidine. All the analyzed archaeological and geomorphological markers are in agreement with an unchanged relative sea level since 1806 ± 60 years BP.

4.2. Scoglio Galera

The fish tank of Scoglio Galera shows significant features that allow the precise estimation of past sea level positions in this area. In particular, as also reported in Lambeck et al. (2004b), from the elevation of the channels used for water exchange within the basin, it is possible to determine the relative sea level change since its construction at this site. Latin writers, as Columella (De Re Rustica XVII), suggest for basin constructions a depth up to 2.7 metri ...*in pedes novem defondiatur piscina*… even depending from the fish species to breed. Moreover, the pools were protected from waves ...*'Mox praeiaciuntur in gyrum moles, ita ut conplectantur sinu suo et tamen excedant stagni modum...* In the fish tank of Scoglio Galera, the pools show average depths of 2.8 m, while channels for water exchange of the inner basin show maximum depths of 1.9 m, with elevations compatible for a good functioning of the pools driven by the typical tides of the Mediterranean Sea, normally ~50 cm high. Therefore the pools and the channels of the fish tank are tidally controlled, even today.

To date the fish tank, whose age was still unknown, a piece of wooden pole found in one of the squared holes along the northern side of the islet was dated (Fig. 5h). ^{14}C AMS analysis dated this sample as Roman age, precisely at 1806 ± 50 BP (calibrated age, Calib 4, Stuiver et al., 1998).

5. Discussion

The sea level curve estimated by Lambeck et al. (2011) (that models the crustal response to the glacio-hydro-isostatic signal) predicts a sea level change for this location of −113 cm since the last 1806 ± 50 years, at a mean rate of −0.63 mm/y (Fig. 7). Observations have estimated that the relative sea level has changed only 7 cm since the construction of the archaeological site (Table 1). Therefore, the recent tectonic uplift inferred from the fish tank exceeds by ~0.18 mm/y the previous estimates of Miyauchi et al. (1994) obtained from the elevation of the MIS 5.5 marine terrace,

erosion processes occurring along the different levels of the geological unit. g) The abrasion platform with the *Dendropoma petreum* which is drilled with several squared holes used to host wooden poles. A relic of wood allowed us to date by ^{14}C AMS this site at 1806 ± 60 years BP. h) One of the holes for the wooden poles of 20 × 20 cm size. k) One of the channels used for water exchange in the pools. Their functional elevations still correspond to those at the time of the construction of the fish tank. The openings of the channels were originally closed by fixed gates to avoid the escape of fish.

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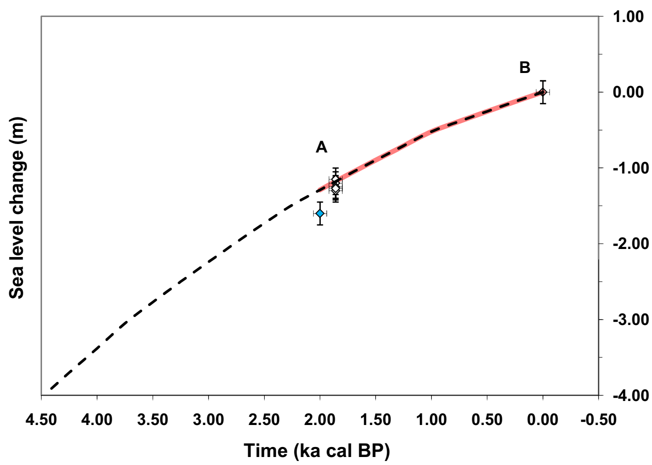

Fig. 7. Plot of the predicted sea level curve (from Lambeck et al., 2011) compared with the elevation of the archaeological markers of the fish tank (diamonds with error bars for age and elevation). The archaeological indicators remained at the same elevation with respect to local sea level since 1860 ± 60 ka BP. The data at the top right of the curve show the current mean elevation value of the markers, as listed in Table 1, still matching the local sea level.

which infers an uplift rate of 0.47 mm/y at Briatico. Bianca et al. (2011) found the MIS 5.5 terrace at 216 m of elevation, in contrast to the value of about 60 m reported in Miyauchi et al. (1994) (Fig. 1), thus inferring a long term uplift rate up to 1.74 mm/y. As this value is in large contrast with the previous measurements of Miyauchi et al. (1994), who dated this terrace through the *Strombus B.*, the latter is preferred for comparison here.

Besides the long term geological data, recent geodetic observations are available in Calabria which show the present day uplift of this region. The tide gauge of Reggio Calabria has recorded a sea level trend of 0.28 mm/y during the time span 1999–2007 (Fig. 8). Although the duration of the sea level recordings for this station is still too short to provide a robust estimation, this value can be considered a preliminary indication that should correspond to a deficit of ~0.8 mm/y in the sea level increase with respect to tectonically stable coastlines of Italy. This result is in agreement with Braitenberg et al. (2011). Moreover, the available GPS data show a variable uplifting trend for southern Calabria (Devoti et al., 2010). Therefore, the rate of crustal uplift inferred from the marine archaeological site of Scoglio Galera provides the evidence of a continuous uplift, whose trend is in agreement with the recent instrumental observations. The archaeological data fills a gap between geological and instrumental data, providing new estimations on the tectonic trend of this region during historical times.

In Table 1, the predicted and observed data of sea level change are shown and compared against the tectonic signal, using the predicted sea level curve of Lambeck et al., 2011 for this location (Fig. 7). The vertical uplift rate is based on the elevation of the Quaternary terraces of MIS 5.5 (124 ka, elevated at 65 m according to Miyauchi et al. (1994)) (Fig. 1) and a uniform uplift since the last 1806 ± 50 yr BP, which is the age of the archaeological site, is assumed.

Column L of Table 1 contains the average value of f the relative sea level change inferred from the archaeological site, estimated at −106 cm for the last 1806 ± 50 y (radiocarbon age of the wooden pole). In column K of the same table, the predicted sea level curve for the last 1806 y gives a value of −113 cm.

The difference of only 7 cm between predicted and observed data results from the sum of the opposite movements of uplift and subsidence that counterbalance each other. This estimation includes the uncertainties from the model and field observation. This result is in good agreement with the tectonic rate inferred by

Table 1
(A) marker number; (B) type of marker: T is Trainiti Pier and SG is Scoglio Galera; (C) Age based on historical documentation at site 1 and also on radiocarbon dating for site 2; (D) and (E) are the WGS84 coordinates of the sites; (F) and (G) are the upper and lower limiting values of the significant markers; (H) relative sea level change based on the functional elevations of the markers; (K) predicted sea levels at 2 ka for this location according to Lambeck et al., 2011. (L) Difference between predicted and observed sea level. (M) is the geological vertical rate based on the elevation of the Quaternary terraces of MIS 5.5 (124 ka, elevated at ~60 m according to Miyauchi et al. (1994)). (N) is the uplift rate inferred from the archaeological site assuming a uniform tectonic uplift since the last 1806 ± 50 BP, time of construction of the archaeological site. A functional elevation of 0.20 m is assumed. Elevation data are the average values of multiple measurements collected at the best preserved parts of the structures. All elevation data are corrected for tides and atmospheric pressure using the tidal data from the Reggio Calabria and Palinuro stations of ISPRA (http://www.mareografico.it/). The maximum tidal range for this coast is 0.60 m. The estimates include observational uncertainties.

A	B	C	D	E	F	G	H	K	L	M	N
N.	Site and Type of marker	Age (ka)	Lat N	Lon E	UL (cm)	LL (cm)	Obs. RSLC (cm)	Pred. SLC (cm)	Pred. − Obs. SLC (cm)	Geo. Tect. rate (mm/y)	Arch. Tect. rate (mm/y)
1	T Pier	2 ± 0.1	38°43′18″	16°04′22″	−1	−9	–	−129 (at 2000 BP)	–	0.47	–
2 a	SG Channel B	1.86 ± 0.05	38°43′31″	15°59′57″	30	−70	20	−113 (at 1806 yr BP)	−93		0.60
2 b	SG Channel E				40	−68	14		−99		0.61
2 c	SG Channel D				40	−73	16.5		−96.5		0.60
2 d	SG Bollards				–	50	0		−113		0.69
2 e	Dock surface				50	–	0		−113		0.69
2 f	SG notch				40	0	0		−113		0.69
					Mean 46.7	Mean −26.8	Mean 7.21	Mean 0.63 mm/y in 1806 ± 50 y	Mean −106	Uplift is 85 cm in 1806 ± 50 y	Mean 0.65 mm/y in 1806 ± 50 y

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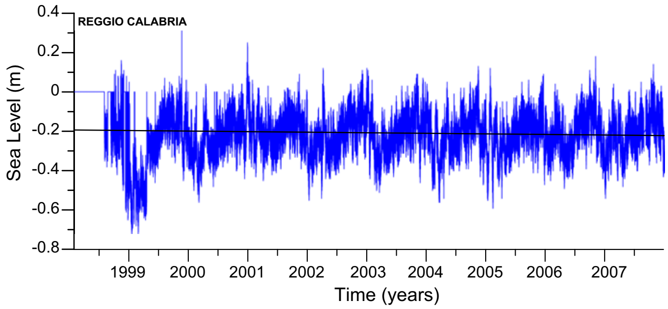

Fig. 8. Plot of the tide gauge recordings at Reggio Calabria station from 1999 to 2007. Data show a sea level trend at 0.28 ± 0.1 mm/y (linear fit shown by the black line). The maximum tidal range is 0.63 m for this location, in agreement with the height of the erosion notch at Scoglio Galera.

the elevation of the terraces of MIS 5.5, located at 60 m above sea level, that infer a vertical uplift of 0.47 mm/y (Miyauchi et al., 1994), that caused a displacement of about 85 cm since the last 1806 ± 50 years at the studied site. This estimate, which differs by 21 cm from the present study's results, could result from the measurements of the MIS 5.5 elevation in this region, which shows large spatial variability. Finally, the flat surface at 80 cm above sea level on the northern side and in the harbor of Scoglio Galera, is interpreted as entropic (Fig. 5g).

6. Conclusions

The timing of the relative sea level changes along the Tyrrhenian coast of Calabria, at Briatico, can be inferred from the elevation of the Quaternary marine terrace and the coastal archaeological sites of roman age. As the pier located at the mouth of Trainiti creek does not provide any precise data, the only available indicator along this coast is the Scoglio Galera. Analysis used: i) functional elevations of channels used for water exchange within the pools; ii) functional elevation of crepidine and bollards; iii) elevation of the erosion notch in the pools, correlated with the Dendropoma platform placed along the northern side of the islet, and iv) the elevation of the marine terrace of the upper Holocene, excavated at 80 cm above sea level along the northern side of the islet.

As the age of the fish tank is 1806 ± 50 cal BP, the present day erosion notch in the inner side of the pools formed only after the fish tank was excavated. This geomorphological indicator, strictly related to the recent sea level, developed during this time, reaching a size related to the mean tidal range for this location, as estimated from tidal data (Fig. 8). Excluding any uplifting coseismic displacement, these observations imply that the fish tank, since the time of its construction, underwent continuous uplift with the same value of the subsidence signal caused by the glacio-hydro-isostasy. The erosion notches formed in this tectonic environment and developed under a constant tidal range amplitude, since the relative sea level remained steadily at the same relative level while it was continuously rising together with the Earth's crust (Fig. 7). The pools do not show any morphological evidence of submerged erosion notches, supporting the hypothesis that relative sea level has not changed since their construction.

Assuming a constant rate of uplift since the late Quaternary, including the last 1806 years, then the current elevation of the Scoglio Galera is due to the glacio-hydro-isostatic signal that counterbalances the tectonic signal. Therefore, the uplifting rate for this location can be estimated at ~0.65 mm/y for the last 1806 ± 50 BP.

The present day biological marker, the *Dendropoma* platform, is in agreement with these observations as well as with the tidal notch along the inner side of the pools of the fish tank. These markers developed in an environment characterized by a relative null vertical motion, and consequently are at the same elevation. This balance also includes the recent eustatic increase of 13 cm, as estimated for the Mediterranean by Lambeck et al. (2004b), Anzidei et al. (2011a, 2011b).

On the base of these data, the archaeological markers at Scoglio Galera did not record coseismic significant displacements along the vertical, including the December 8th, 1905 Ms = 7 earthquake, which is the largest in this region in the last centuries, in agreement with the dislocation model proposed by Piatanesi and Tinti (2002). However, coseismic movements may have occurred before the construction of the fish tank.

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References

Antonioli, F., Chemello, R., Improta, S., Riggio, S., 1999. The Dendropoma (Mollusca Gastropoda, Vermetidae) intertidal reef formations and their paleoclimatological use. Marine Geology 161, 155–170.
Antonioli, F., Ferranti, L., Lambeck, K., Kershaw, S., Verrubbi, V., Dai Pra, G., 2006. Late Pleistocene to Holocene record of changing uplift rates in southern Calabria and eastern Sicily (southern Italy, Central Mediterranean Sea). Tectonophys 422, 23–40.
Antonioli, F., Anzidei, M., Lambeck, K., Auriemma, R., Gaddi, D., Furlani, S., Orru, P., Solinas, E., Gaspari, A., Karinja, S., Kovacic, V., Surace, L., 2007. Sea level change during Holocene from Sardinia and northeastern Adriatic (Central Mediterranean sea) from archaeological and geomorphological data. Quaternary Science Reviews 26, 2463–2486.
Anzidei, M., 2000. Rapid bathymetric surveys in marine volcanic areas: a case study in Panarea area. Physics and Chemistry of the Earth 25 (1), 77–80.
Anzidei, M., Lambeck, K., Antonioli, F., Baldi, P., Benini, A., Esposito, A., Nobili, A., Surace, L., 2003. Sea level change from Roman time up to the present in Central Mediterranean. In: Mastronuzzi, G., Sansò, P. (Eds.), Puglia 2003-Final conference. Quaternary Coastal Morphology and Sea Level Changes, IGCP 437 Project, Otranto/Taranto - Puglia (Italy) 22–28 September 2003, pp. 27–39.
Anzidei, M., Antonioli, F., Lambeck, K., Benini, A., Soussi, M., Lakhdar, R., 2011a. New insights on the relative sea level change during Holocene along the coasts of Tunisia and western Libya from archaeological and geomorphological markers. Quaternary International 232, 5–12.
Anzidei, M., Antonioli, F., Benini, A., Lambeck, K., Sivan, D., Serpelloni, E., Stocchi, P., 2011b. Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. Quaternary International 232, 13–20.
Anselmi, B., Dai Prà, G., Galletti, M., Myauchy, T., 1992. Età dei depositi a Strombus bubonius di Vibo Valentia Marina (Italia meridionale). Il Quaternario 6, 139–144.
Baratta, M., 1906. Il grande terremoto calabro dell'8 settembre 1905. Atti della Societá Toscana di Scienze Naturali, Pisa, Memorie 22, 57–80.
Barberi, G., Cosentino, M.T., Gervasi, A., Guerra, I., Neri, G., Orecchio, B., 2004. Crustal seismic tomography in the calabrian arc region, south Italy. Physics of the Earth and Planetary Interiors 147, 297–314.
Bianca, M., Catalano, S., De Guidi, G., Gueli, A.M., Monaco, C., Ristuccia, G.M., Stella, G., Tortorici, G., Tortorici, L., Troja, S.O., 2011. Luminescence chronology of Pleistocene marine terraces of Capo Vaticano peninsula (Calabria, southern Italy). Quaternary International 232, 114–121.
Bordoni, P., Valensise, G., 1998. Deformation of the 125 Ka marine terrace in Italy: tectonic implications. In: Stewart, I.S., Vita-Finzi, C. (Eds.), Coastal Tectonics. Geol. Soc. London, Spec. Publ., vol. 146, pp. 71–110.
Braitenberg, C., Mariani, P., Tunini, L., Grillo, B., Nagy, I., 2011. Vertical crustal motions from differential tide gauge observations and satellite altimetry in southern Italy. Journal of Geodynamics 51, 233–244.
Brückner, H., Kelterbaum, D., Marunchak, O., Porotov, A., Vött, A., 2010. The Holocene sea level story since 7500 BP – Lessons from the Eastern Mediterranean, the Black and the Azov Seas. Quaternary International 225 (2), 160–179.
Camassi, R., Stucchi, M., 1997. NT4.1: un catalogo parametrico di terremoti di area italiana al di sopra della soglia di danno. http://emidius.mi.ingv.it/NT/.
Carobene, L., Dai Prà, G., 1990. Genesis, chronology and tectonics of the quaternary marine terraces of the Tyrrhenian coast of northern Calabria. Il Quaternario 3 (2), 75–94.
Cosentino, D., Gliozzi, E., 1988. Considerazioni sulla velocità di sollevamento dei depositi eutirreniani dell'Italia meridionale e della Sicilia. Memorie della Società Geologica Italiana 41, 127–143.
Chiarabba, C., Jovane, L., Di Stefano, R., 2005. A new view of Italian seismicity using 20 years of instrumental recordings. Tectonophysics 395, 251–268.

CPTI-Working Group, 2004. Catalogo Parametrico dei Terremoti Italiani. Ver. 2004 (CPTI04). INGV, Bologna. http://emidius.mi.ingv.it/CPTI04/.
Cucarzi, M., Iannelli, M.T., Rivolta, A., 1995. The coastal site of Bivona. Its detection and its environmental changes through geoarchaeological explorations. In: Egypts, T.G.S.O. (Ed.), Proceedings of International Conference "Geosciences and Archaeology in the Mediterranean Countries", Cairo 28–30 November 1993, pp. 149–168.
Columella, De Re Rustica, XVII. 50 BC.
D'Alessandro, L., Raffi, R., Catizzone, A., 1987. Il litorale del Golfo di S. Eufemia (Calabria): indagini sulle variazioni della spiaggia nell'ultimo secolo. Ministero Pubbl. Istruz., Prog. Naz. "Dinamica e Tutela delle Coste", Roma.
D'Amico, S., Orecchio, B., Presti, D., Zhu, L., Herrmann, R., Neri, G., 2010. Broadband waveform inversion of moderate earthquakes in the Messina Straits, southern Italy. Physics of the Earth and Planetary Interiors 179, 97–106.
D'Amico, S., Orecchio, B., Presti, D., Gervasi, A., Zhu, L., Guerra, I., Neri, G., Herrmann, R., 2011. Testing the stability of moment tensor solutions for small earthquakes in the Calabro-Peloritan arc region (southern Italy). Bollettino di Geofisica Teorica ed Applicata 52 (2), 283–298.
Desruelles, S., Fouache, E., Ciner, A., Dalongeville, R., Pavlopoulos, K., Kosun, E., Coquinot, Y., Potdevin, J.L., 2009. Beachrocks and sea level changes since Middle Holocene: comparison between the insular group of Mykonos-Delos-Rhenia (Cyclades, Greece) and the southern coast of Turkey. Global and Planetary Change. ISSN: 0921-8181 66 (1–2). ISSN: 0921-8181, 19–33. doi:10.1016/j.gloplacha.2008.07.009. Quaternary sea level changes: records and processes.
Devoti, R., Pietrantonio, G., Pisani, A., Riguzzi, F., Serpelloni, E., 2010. Present day kinematics of Italy. In: Beltrando, M., Peccerillo, A., Mattei, M., Conticelli, S., Doglioni, C. (Eds.), The Geology of Italy: Tectonics and Life along Plate Margins. J. Virtual Explorer, Electronic Edition. ISSN: 1441-8142, vol. 36. doi:10.3809/jvirtex.2010.00237. paper 2.
Doglioni, C., Innocenti, F., Mariotti, G., 2001. Why Mt Etna? Terra Nova 13, 25–31.
Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrù, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of the last interglacial sea level highstand along the coast of Italy: tectonic implications. Quaternary International 145–146, 30–54.
Ferranti, L., Monaco, C., Antonioli, F., Maschio, L., Kershaw, S., Verrubbi, V., 2007. The contribution of regional uplift and coseismic slip to the vertical crustal motion in the Messina Straits, Southern Italy: evidence from raised late Holocene shorelines. Journal of Geophysical Research 112, B06401. doi:10.1029/2006JB004473.
Ferranti, L., Antonioli, F., Anzidei, M., Monaco, C., Stocchi, P., 2010. The timescale and spatial extent of vertical tectonic motions in Italy: insights from relative sea-level changes studies. Journal of the Virtual Explorer 36 (Paper 30). http://virtualexplorer.com.au/.
Flemming, N.C., 1969. Archaeological evidence for eustatic changes of sea level and earth movements in the Western Mediterranean in the last 2000 years. Special Paper – Geological Society of America 109, 1–125 pp.
Flemming, N.C., Webb, C.O., 1986. Tectonic and eustatic coastal changes during the last 10,000 years derived from archaeological data. Zeitschrift für Geomorphologie, N.F. (Suppl. 62), 1–29.
Fouache, E., Pavlopoulos, K. (Eds.), 2005. Sea Level Changes in Eastern Mediterranean during Holocene. Indicators and Human Impacts. Zeitschrift für Geomorphologie, Supplementbände, vol. 137, p. 193.
Ghisetti, F., 1979. Evoluzione neotettonica dei principali sistemi di faglie della Calabria centrale. Bollettino della Societá Geologica Italiana 98, 387–430.
Ghisetti, F., 1981. L'evoluzione strutturale del bacino plio-pleistocenico di Reggio Calabria nel quadro geodinamico dell'arco Calabro. Bollettino della Societa Geologica Italiana 100, 433–466.
Goes, S., Giardini, D., Jenny, S., Hollenstein, C., Kahle, H.G., Geiger, A., 2004. A recent tectonic reorganization in the south-central Mediterranean. Earth and Planetary Science Letters 226, 335–345.
Gvirtzman, Z., Nur, A., 1999. The formation of Mount Etna as the consequence of slab rollback. Nature 401, 782–785.
Guerra, I., 2007. Earthquakes in Calabria Databases. SyNaRMa Interreg IIIB Project ARCHIMED (2000–2006), Technical Report. Physics Dept., Calabria University.
Lacquaniti, L., 1952. Variazioni di linee di spiaggia nei golfi di S. Eufemia e Gioia (Calabria Tirrenica). Atti XV Congresso Nazionale della Società Geologica Italiana 1, 278–283. I.T.E.R., Torino.
Lambeck, K., Antonioli, F., Purcell, A., Silenzi, S., 2004a. Sea level change along the Italian coast for the past 10,000 yrs. Quaternary Science Revue 23, 1567–1598.
Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., Esposito, E., 2004b. Sea level in Roman time in the Central Mediterranean and implications for modern sea level rise. Earth and Planetary Science Letters 224, 563–575.
Lambeck, K., Purcell, A., 2005. Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. Quaternary Science Reviews 24, 1969–1988.
Lambeck, K., Antonioli, F., Anzidei, M., Ferranti, L., Leoni, G., Scicchitano, G., Silenzi, S., 2011. Sea level change along Italian coast during Holocene and a proiection for the future. Journal of Quaternary International 232.
Lena, G., 1989. Vibo Valentia. Geografia e morfologia della fascia costiera e l'impianto del porto antico. Annali della Scuola Normale Superiore di Pisa 19 (2), 583–607. Pisa.
Locardi, E., Nicolich, R., 1988. Geodinamica del Tirreno e dell'Appennino Centro-Meridionale: la nuova carta della Moho. Memorie della Società Geologica Italiana 41, 121–140.
Loreto, M.F., Zgur, F., Pettenati, F., Facchin, L., Fracassi, U., Tomini, I., 2011. Active tectonics and potential seismogenic behavior of newly imaged structures in the Gulf of Santa Eufemia (southern Italy). EGU 2011, Vienna (Austria), 4–8 April, vol. 13.
Mariottini, S., 2001. Volontariato e archeologia subacquea: esperienze di ricerca in Calabria. In: Lezioni Fabio Faccenna. Edipuglia, Bari.
Medici, G., Principi, P., 1939. Le bonifiche di S. Eufemia e Rosarno. Zanichelli, Bologna.
Melis, S., 1998. Variation des rivages aux environs de la ville de Nora (Sardaigne Sud-Ouest – Italie) d'apres les données géoarchéologiques. In: Vertmeuller, F., De Dapper, M. (Eds.), Géoarchéologiques des Paysage de l'antiquité classique, pp. 127–135.
Mercalli, G., 1906. Alcuni risultati ottenuti dallo studio del terremoto calabrese dell'8 settembre 1905, vol. 36. Acc. Pontaniana, Napoli. 1–9.
Michelini, A., Lomax, A., Nardi, A., Rossi, A., Palombo, B., Bono, A., 2005. A modern re-examination of the locations of the 1905 Calabria and the 1908 Messina Straits earthquakes. Geophysical Research Abstracts 7, 07909. European Geosciences Union.
Miyauchi, T., Dai Pra, G., Sylos Labini, S., 1994. Geocronology of Pleistocene marine terraces and regional tectonics in the Tyrrhenian coast of southern Calabria, Italy. Il Quaternario 7 (1), 17–34.
Piatanesi, A., Tinti, S., 2002. Numerical modelling of the September 8, 1905 Calabrian (southern Italy) tsunami. Geophysical Journal International 150, 271–284.
Pirazzoli, P.A., 1976. Sea level variations in the northwest Mediterranean during Roman times. Science 194, 519–521.
Pirazzoli, P.A., 1996. Sea-level Changes- the Last 20,000 Years. Wiley, Chichester.
Pondrelli, S., Salimbeni, S., Ekström, G., Morelli, A., Gasperini, P., Vannucci, G., 2006. The Italian CMT dataset from 1977 to the present. Physics of the Earth and Planetary Interiors 159 (3–4), 286–303.
Reasenberg, P.A., Oppenheimer, D., 1985. FPFIT, FPPLOT and FPPAGE: FORTRAN computer programs for calculating and displaying earthquakes fault plane solutions. U.S. Geological Survey. Open File Rep., 85–739.
Riuscetti, M., Schick, R., 1974. Earthquakes and tectonics in southern Italy. Bollettino di Geofisica Teorica ed Applicata 17, 59–75.
Rizzo, G.B., 1907. Contributo allo studio del terremoto della Calabria del giorno 8 settembre 1905. Atti della Accademia Peloritana dei Pericolanti 22 (1), 3–86.
Salmoiraghi, F., 1884. Terrazzi quaternari sul litorale tirrenico della Calabria Citra. Bollettino del R. Comitato Geologico d'Italia XVII, 281–316.
Schmiedt, G., 1966. Antichi porti d'Italia. I porti delle colonie greche. L'Universo XLVI, 253–296.
Schmiedt, G., 1974. Il livello antico del mar Tirreno. Testimonianze da Resti Archeologici. E. Olschki, Firenze, pp. 323.
Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., Van der Plicht, J., Spurk, M., 1998. Intcal 98 radiocarbon age calibration, 24, 000–0 cal BP. Radiocarbon 40 (3), 1041–1083.
Tallarico, A., Dragoni, M., Anzidei, M., Esposito, A., 2003. Modeling long-term ground deformation due to the cooling of a magma chamber: case of Basiluzzo island, Aeolian Islands, Italy. Journal of Geophysical Research 108 (B12), 2568. doi:10.1029/2002JB002376.
Tortorici, G., Bianca, M., de Guidi, G., Monaco, C., Tortorici, L., 2003. Fault activity and marine terracing in the Capo Vaticano area (southern Calabria) during the Middle-Late Quaternary. Quaternary International 101–102, 269–278.
Vannucci, G., Pondrelli, S., Argnani, A., Morelli, A., Gasperini, P., Boschi, E., 2004. An atlas of Mediterranean seismicity. Annals of Geophysics 47, 1. Suppl. with CDR.
Westaway, R., 1990. Present-day kinematics of the plate boundary zone between Africa and Europe, from the Azores to the Aegean. Earth and Planetary Science Letters 96, 393–406.
Westaway, R., 1993. Quaternary uplift of southern Italy. Journal of Geophysical Research 98, 21741–21772.
Wortel, M.J.R., Spakman, W., 2000. Subduction and slab detachment in the Mediterranean-Carpathian region. Science 290, 1910–1917.

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