



Evidence of active subsidence at Basiluzzo island (Aeolian islands, southern Italy) inferred from a Roman age wharf



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ABSTRACT

The Aeolian Arc (Southern Tyrrhenian Sea, Italy) is one of the most active volcanic areas of the Mediterranean basin, affected by volcanic/hydrothermal and seismic activity. Ancient populations settled this region since historical times, building coastal installations which currently are valuable archaeological indicators of relative sea level changes and vertical land movements. In this study we show and discuss data on the relative sea level change estimated from a submerged wharf of Roman age dated between 50 B.C. and 50 A.D., located at Basiluzzo Island. This structure has been studied through marine surveys and archaeological interpretations and is presently located at a corrected depth of -4.10 ± 0.2 m. We explain this submergence by a cumulative effect of the relative sea level change caused by the regional glacio-hydro-isostatic signal, active since the end of the last glacial maximum, and the local volcano-tectonic land subsidence. Finally, a total subsidence rate of 2.05 ± 0.1 mm/yr⁻¹, with a volcano-tectonic contribution of 1.43 ± 0.1 mm/yr⁻¹ for the last 2 ka BP, is inferred from the comparison against the latest predicted sea level curve for the Southern Tyrrhenian Sea, suggesting new evaluations of the volcano-tectonic hazard for this area of the Aeolian islands.

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1. Introduction

Coastal settlements and ports constructed in antiquity along the coasts of the Mediterranean provide important insights into reconstructions of historical sea-level changes during past millennia (Schmiedt et al., 1972; Flemming and Webb, 1986; Lambeck et al., 2004a, 2004b). Despite the large number of archaeological remains in this region, only those that are well preserved can be used to obtain precise information on their former relationship to sea level (Auriemma and Solinas, 2009; Lambeck et al., 2010). During the last decade, new studies integrated altimetry observations in coastal archaeological sites such as villas, harbors, piers and fish tanks of Roman age, with geological data and geophysical modeling. Results allowed the temporal and spatial reconstruction of the values and trends of the relative sea level changes and vertical land movements at specific sites (Paskoff et al., 1981; Lambeck et al., 2004b; Anzidei et al., 2011a, b; Mourtzas, 2012).

Recent studies have shown that the relative sea level changes observed along the coasts of the Mediterranean Sea depends on the sum of eustatic, glacio-hydro-isostatic and tectonic (including

volcanic) signals, according to the following equation (Lambeck and Purcell, 2005):

$$\Delta\zeta_{rsi}(\varphi, t) = \Delta\zeta_{esi}(t) + \Delta\zeta_I(\varphi, t) + \Delta\zeta_T(\varphi, t) \quad (1)$$

Where, $\Delta\zeta_{rsi}(\varphi, t)$ is the observed change of sea surface relative to land at a location φ and time t , compared to its present position. The first term is the eustatic change $\Delta\zeta_{esi}(t)$; the second term $\Delta\zeta_I(\varphi, t)$ is the glacio-hydro-isostatic contribution and the last term $\Delta\zeta_T(\varphi, t)$ is the tectonic contribution (including volcanic and other disturbances) for active areas. The $\Delta\zeta_{esi}$ is mainly driven by climate changes and is time-dependent, while $\Delta\zeta_I$ and $\Delta\zeta_T$ are functions of position φ and time t , that can vary with location (φ).

The glacio-hydro-isostatic signal acting in the Mediterranean basin after the Last Glacial Maximum (LGM), has been recently predicted and compared with direct observational data in deforming zones (Lambeck et al., 2010, 2011). The results provided new insights on the relationships between sea level change and vertical land motion, because most maritime archaeological sites are currently submerged or emerged (Antonioli et al., 2007; Anzidei et al., 2013).

With the aim to estimate the vertical tectonic contribution to the observed relative sea level change in the volcanic arc of the

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Aeolian Islands, we investigated a submerged structure located at Basiluzzo Island. This small island, as well as the others of the Aeolian archipelago, has been settled since pre-historical times, and during the Roman time they become a crossroad of the maritime commercial ways toward Sicily and northern Africa (Kapitan, 1958; Bernabò-Brea and Cavalier, 1985; Bernabò Brea, 1985; Bound, 1992; Todesco, 1996; Zagami, 1993; <http://www.regione.sicilia.it/beniculturali/>).

Between 50 B.C. and 50 A.D., a large villa was built on Basiluzzo Island, supplied with a maritime structure located at Punta Levante. We used this well preserved structure as an archaeological indicator of the intervening relative sea level change and land subsidence over the last 2 ka, being submerged at an average depth of 3.20 ± 0.2 m. Here, we show and discuss surveys and results, in order to discriminate between the multiple responsible factors contributing to the observed relative sea level change.

2. Tectonic setting

The Aeolian Archipelago consists of seven major islands (Alicudi, Filicudi, Salina, Lipari, Panarea, Vulcano, and Stromboli) and some seamounts that form a Quaternary volcanic arc in the Southern Tyrrhenian Sea due to the opening of the back-arc Tyrrhenian basin. The volcanic arc extends for about 200 km along the inner side to the Peloritano-Calabrian orogenic belt and delimits the southern boundary of the Marsili basin (Barberi et al., 1973, 1974) (Fig. 1a).

The archipelago displays a complex geological setting and the islands belong to three main sectors (Falsaperla et al., 1999; De Astis et al., 2003): a) the extinct western sector characterized by CA (Calc-Alkaline) and HKCA (High Potassium Calc-alkaline) magmas dated 1.3 to 0.05 Ma (Tranne et al., 2002b). It includes the islands of Alicudi, Filicudi and Sisifo Seamount, lying along a WNW–ESE right lateral fault system; b) the active central sector is formed by the NNW–SSE trending islands of Salina, Lipari and Vulcano. They are located along a northwest-southeast trending tectonic lineament, namely the Tindari – Giardini-Letoanni fault system, which extends in southern Sicily (Esposito et al., 2010; Serpelloni et al., 2010) (Fig. 1a). The volcanic activity started at ~400 ka BP and is still active at Lipari (the last eruption are dated at 580 AD) and Vulcano (last eruption in 1880–90 AD) (Tranne et al., 2002a), with magmas of CA, HKCA, and shoshonitic affinity. c) the active eastern sector, which includes Panarea and Stromboli islands and the Lamentini, Alcione and Pal-inuro seamounts. Volcanic activity started at ~800 ka (De Astis et al., 2003) and is still persistent at Stromboli whereas episodic gas eruptions occur at Panarea (Anzidei et al., 2005; Esposito et al., 2006; Monecke et al., 2012). This sector, which is located along a NE–SW trending extensional fault system (Gabbianelli et al., 1993; De Astis et al., 2003), includes the emergent part of the submarine strato-volcano of Panarea, which is higher than 2000 m and 20 km wide (Gabbianelli et al., 1990; Gamberi et al., 1997) and comprises the islets of Basiluzzo, Dattilo, Panarelli, Lisca Bianca, Bottaro, Lisca Nera and Le Formiche (Fig. 1b).

Geological and geo-chronological studies revealed the existence of two main volcanic stages in the Aeolian Archipelago: the older stage developed in Pleistocene time when the islands of Alicudi, Filicudi, part of Panarea and Salina and the northwest side of Lipari were produced. During the more recent stage (late Pleistocene–Holocene), the islands of Salina, Lipari, and Panarea were entirely formed and the magmatic activity concentrated in the still active volcanoes of Vulcano and Stromboli (Beccaluva et al., 1985; Gillot, 1987).

Frequent volcanic eruptions and seismic events were reported both in the main islands and offshore during the last 2000 years (SGA, 1996; Boschi et al., 1997; Esposito et al., 2006; Monecke et al., 2012). Besides the volcanic activity, the Aeolian islands are nowadays characterized by deep to shallow seismicity and ground deformation (Guidoboni, 1994; Hollenstein et al., 2003; Chiarabba et al., 2005; Serpelloni et al., 2005, 2010, 2013; Esposito et al., 2010). Particularly, gravimetric data revealed the existence of a positive local gravimetric anomaly between Basiluzzo and Panarea Island (Gabbianelli et al., 1990, 1993; Cocchi et al., 2008).

3. Basiluzzo Island

The island of Basiluzzo belongs to the Panarea volcanic complex, which also includes Panarea Island and the surrounding islets of Dattilo, Panarelli, Lisca Bianca, Bottaro, and Lisca Nera (Fig. 1b). Volcanic activity at Panarea complex started about 150 ka BP (Calanchi et al., 1999). It is mainly characterized by the emplacement of lava domes, plugs, and lava flows, which are high-K calc-alkaline andesites to dacite and rhyolites (Calanchi et al., 1999, 2002), while pyroclastic deposits are subordinate. According to Lucchi et al. (2003), the eruptive history is divided into six successive eruptive epochs with periods of volcanic activity separated by quiescence stages. During the last 100 ka, volcanic activity was characterized by the emplacement of the endogenous dome of Basiluzzo (54 ± 8 ka) and of two pumiceous pyroclastic layers. Widespread pyroclastic deposits of external provenance (Punta Torriente Lithosome) were emplaced at Panarea and surrounding islets during several discrete eruptive events that occurred between about 70 and 8 ka BP (Lucchi et al., 2003). Some other tephros of external provenance are intercalated within these

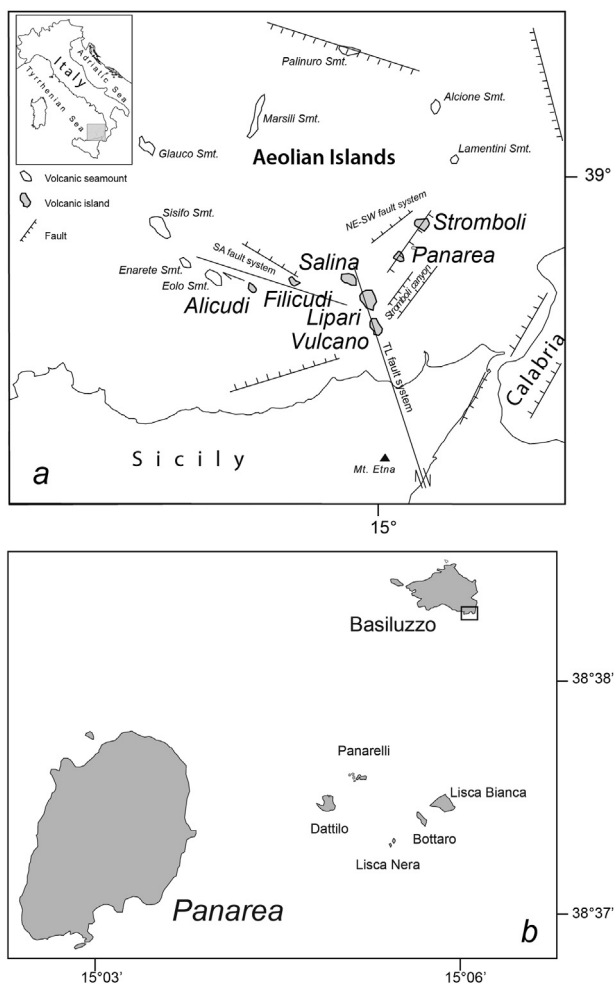


Fig. 1. a) Tectonic sketch of the Aeolian island; b) the Panarea archipelago. The square is the location of the Roman Age wharf located at Basiluzzo island.

pyroclastic deposits and provide significant chronologic and stratigraphic constraints.

Basiluzzo Island displays steep and indented coasts and its highest peak is 165 m a.s.l. Its surface displays anthropic terraces that lower gently to Southeast toward Punta Levante, which is the lowest elevated part of the island (33 m a.s.l.) (Fig. 2a).

The northern side, between Punta Zangona and Punta Monaco Santo, displays Aeolian geomorphological forms (tafoni), whereas solifluction largely affects the surface of the island. Three lithostratigraphic units were identified (Calanchi et al., 1999): the Basiluzzo Formation (BF), Pianoconte Formation (PF), and Mauro Formation (MF). BF consists of an endogenous lava dome of rhyolitic composition, while PF and MF are massive ash tuffs with CA basaltic-andesite to andesite composition superimposed on the BF (Lucchi et al., 2003, Lucchi, 2013).

4. Materials and methods

The submerged archaeological structure located in the most sheltered side of Punta Levante (Fig. 2a,b,c), was surveyed during repeated campaigns of scuba diving prospecting, to provide a detailed map of the submerged archaeological site suitable for geophysical interpretation. Surveys occurred in September 1996 and June 1997, while additional data were collected in November 2001, May 2003, and June 2011. We also included in this study available data from bathymetric surveys carried out in 1997, 2002, 2003, and 2005. The latter three were performed during the 2002–2003 Panarea gas eruption (Anzidei et al., 2005).

4.1. Survey data

Topographic data have been collected through marine surveys performed by scuba diving and single and multibeam echosounding systems, the latter two coupled with Global Positioning System (DGPS) (Anzidei, 2000, Anzidei et al., 2005). Descriptions of the survey features and development of the morphobathymetric maps are exhaustively reported in Anzidei (2000), Anzidei et al. (2005), Esposito et al. (2006), and Monecke et al. (2012). The integrated high resolution Digital Terrain and Marine Model is derived from the combination of aerial photogrammetry, LIDAR, and bathymetric data (Fabris et al., 2010). These data allowed us to map the ground surface and the seafloor bathymetry surrounding Basiluzzo Island at a resolution better than 1 m. Unfortunately, the shallow depth of the seafloor in the area of the submerged archaeological site partially prevented the realization of multibeam surveys. Therefore, elevations were mainly determined through direct measurements carried out by depth meters and levelling rods, also coupled with GPS, during repeated scuba diving investigations. Positions and depths of 73 points collected were used to extract an accurate map of this archaeological site (Fig. 2c,d).

Due to a lack of tidal stations in the investigated area until 2011, the depth data collected in 1996, 1997 and 2001, have been calibrated for tides using an a-priori (forecast) model valid for the Tyrrhenian Sea, with an estimated accuracy of ± 0.10 m (Istituto Idrografico della Marina, 1996, 1997, 2001). After 1996, a new regional tidal network in Italy was established (www.mareografico.it). Therefore, to improve the accuracy of our data, surveys were repeated in 2011 when tidal data from the nearest station located at Stromboli were available (tidal amplitudes at Stromboli are ± 0.2 m in the average). Finally, we used the 2011 epoch surveys as reference, obtaining survey accuracy better than ± 0.05 m. Although this value includes all instrumental uncertainties and tidal corrections, we prefer to apply a safer uncertainty of ± 0.2 m to our data to

include eventual additional unrecognized sources of errors from the archaeological site (Table 1).

4.2. Archeological data

The archaeological site (Fig. 2) is founded on the rocky seafloor, fitting its morphology. It has a trapezoidal shape and displays three main walls with an average depth of -3.20 ± 0.2 m, to 2.8 m wide, 2.5 m thick and 6–15 m long, enclosing a small basin (Fig. 2c, d, f, g, h). The latter has a depth to -5.5 m and is partially silted by debris and rocks fallen from the nearby cliff. Within the basin, an outcropping rock (CR1) is partially carved and flattened at the top, shaped at the same depth of the upper surface of the walls (Fig. 2c, d, f). An additional flattened rock (CR2) is located along the external side of the basin, between the northeastern wall and the coastline (Fig. 2c, d, f). Its top is at about -4 m. The northeastern and southeastern walls display two openings of 1.9 and 1.3 m width and their bases are at -4.5 m above sea level and -7 m below sea level, respectively (A1 and A2 in Fig. 2c, d, f, g, h). The top of the southeast corner of the wall shows a rectangular mark (WP1) of $0.4 \times 0.4 \times 1.5$ m of size, left by a no longer existing wooden pole (Fig. 2c). Along the northwestern side of the basin, an additional mark left by a wooden pole mounted vertically is located (WP2) at 3.55 m depth (Fig. 2c).

5. Results and interpretations

The investigated submerged archaeological structure was formerly interpreted by Bound (1992) as a small harbor, and more recently, as a fish tank by Castagnino (1994). On the basis of our surveys, we can exclude both the previous hypothesis because from its size and features, the structure cannot be considered as either a harbor or a fish tank. We also exclude the hypothesis of a small building constructed along the coast. Therefore, we interpret this structure as a small wharf with the function to serve the villa, in agreement with Bernabò-Brea (1985).

The key points for which we exclude the harbor hypothesis are: *i*) the two openings (A1 and A2) located along the external walls are too narrow to cross even with small boats, having a width between 1 and 1.5 m (Fig. 2c,d), *ii*) the inner basin is too small to host boats and the seafloor is too shallow for mooring, preventing boats to float safely without crashing with their keels on the rocky seafloor (Medas, 2003; Pomey, 2003; Auriemma and Solinas, 2009) (Fig. 2c, d). We also exclude the fish tank hypothesis because this structure lacks the typical features of these tidally controlled installations, found in the well-known fish tanks located along the coast of the Tyrrhenian Sea and in other parts of the Mediterranean basin (Schmiedt et al., 1972; Blackman, 1973; Pirazzoli, 1976; Lambeck et al., 2004b; Auriemma and Solinas, 2009; Lambeck et al., 2010). Particularly, *i*) the openings along the walls are lacking of channel systems, or even part of them (channel systems normally include sluice gates, thresholds and posts used to control the exchange of water within the basin) (Fig. 2c, d, f, g); *ii*) a *crepido*, a narrow sidewalk normally built along the inner side of the basin, is missing; *iii*) the raw constructional feature with missing pavements (or their eventual imprints) over the walls or in the basin. In addition, the lack of fresh water in the island also excluded the existence of the *aquatia*, as described by Latin authors Columella and Varro. This technique consisted in mixing marine and fresh water to attract particular species of fish (such as sea bass or mullets), in the fish tanks, although not all fish tanks had these constructional features (Schmiedt et al., 1972; Auriemma and Solinas, 2009).

Finally, we exclude the hypothesis of a small house, as the constructional features are not similar to those described by the

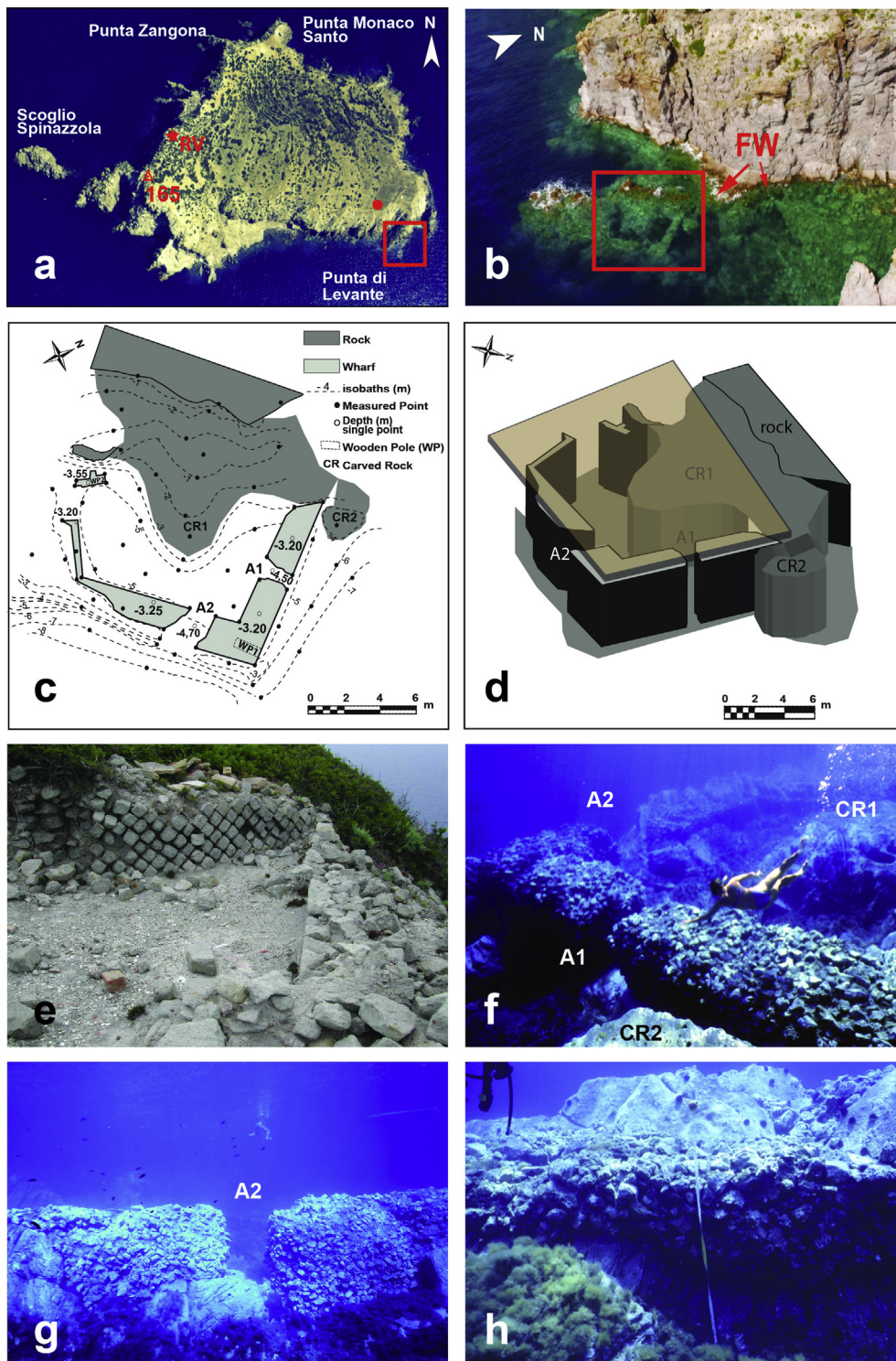


Fig. 2. Composite panel showing the studied site: a) aerial photo of Basiluzzo. The open triangle is the GPS benchmark (BA3D station, as reported in [Esposito et al., 2010](#)) of the local geodetic network; RV is the location of the Roman villa while the square shows the area of Punta di Levante, where the wharf is located; b) aerial photo of Punta Levante bay with the submerged wharf. FW is the position of the sidewalk at the bottom of the cliff; c) topographic map of the wharf. CR1 and CR2 are the two carved rocks. A1 and A2 are the two main openings along the external walls. WP1 and WP2 are the imprints of the wooden poles. Black dots are the position of the topographic points measured during the submarine investigations or extracted from the single beam bathymetric survey ([Anzidei, 2000](#)); d) 3-D rendering of the wharf with the two openings A1 and A2, the carved rocks CR1 and CR2 and the hypothetical reconstruction of the wooden platform; e) the remains of the wharf located on the top of the island with walls built in *opus reticulatum* and pavements with mosaics; f) view of the walls and the basin with the two openings A1 and A2 and the carved rocks CR1 and CR2; g) view of the northeastern wall of the wharf with the opening A2; h) particular of the inner side of the basin with the walls built on the rocky seafloor. The walls were made by rhyolite fixed by hydraulic mortar. See text for details.

Latin author Vitruvius in his book *De Architectura*. Particularly, the submerged structure does not have a coverage in *opus reticulatum* along the walls (typical of subaerial buildings as the villa located in Basiluzzo, Fig. 2a, e; see Adam, 2000), which are of large size (typical of harbors or fish tanks, see Felici, 1993, 1998, 2004; Auriemma and Solinas, 2009).

The age of this wharf can be dated between 50 B.C. and 50 A.D., as evident from the architectural features of the large Roman villa placed on the island, similar to other coeval buildings and coastal installations built in the Mediterranean (Schmiedt et al., 1972; Slim et al., 2004; Auriemma and Solinas, 2009). The Romans built this wharf at Punta Levante because it is the island's coast with the lowest elevation, from which it is easier to land. The remaining coast of Basiluzzo is too deep and the cliffs are too steep for coastal installations. Furthermore, between the wharf and the cliff, at about 3 m below sea level, the remains of stones cemented to the bedrock are present (Fig. 2b, shown with FW). We hypothesize that these are the remnants of the narrow sidewalk built to connect the wharf to the nearby shore of Punta Levante, once used to access the villa through still partially existing stairs built along the cliff.

We also find similar constructional features that are typical of the Roman age ports built in the Mediterranean, such as the imprints of wooden poles for the constructional formwork of the walls (WP2), the use of horizontal timber used to facilitate moorings of ships at the quayside (WP1), the narrow openings along the outer walls, the use of hydraulic mortar to build in the maritime environment, and the carved seafloor (CR1 and CR2) to fit it for coastal construction, as observed in other Roman harbors of the Tyrrhenian Sea (Felici, 1993, 1998) (Fig. 2c). The two narrow openings (A1 and A2, Fig. 2c, d, f, g) likely had the function of reducing the force of the incoming sea waves breaking on the structure. Similar features are frequently present in modern piers and harbors (Franco, 1997).

The existence of typical architectural elements, such as bollards, mooring rings, stairs, wooden poles, found in the still well preserved Roman age military and commercial harbors located along the Tyrrhenian coast of Italy (Ventotene Island, Torre Astura, Miseno, and Baia) and in other exemplary sites of the Mediterranean basin (Leptis Magna, in Libya, Caesarea Maritima in Israel, Marseille in France, and in Lebanon) (Schmiedt et al., 1972; Blackman, 1973; McCann, 1987; Felici, 1993, 1998; Franco, 1997; Morhange et al., 2001, 2006; Hesnard, 2004; Lambeck et al., 2004b; Marriner et al., 2006; Antonioli et al., 2007; Auriemma and Solinas, 2009), suggest for this wharf a minimum functional elevation of 1 ± 0.2 m above the mean sea level at the time of its construction, so that its surface remained always above water level even during high tides. Based on these features, we hypothesize that the wharf was covered by a wooden platform fixed over the walls and CR1, facilitating landing and loading of goods (Fig. 2d).

To better constrain the age of the archaeological structure and support geophysical interpretations, we collected and analyzed a sample of mortar extracted from the top of the wharf's walls. The petrographic analysis showed that the chemical composition of the sample consists in a mixture composed by a binder (limestone and volcanic rocks) and an aggregate (pozzolana, known also as pozzolanic ash) (Fig. 3). This kind of mixture, named hydraulic mortar, was largely used only after the first century B.C. by the Romans (Felici, 1993, 1998, 2004) to build maritime structures, because it is characterized by enhanced mechanical and chemical properties with respect to the conventional concrete used for the construction of terrestrial buildings (similar association in the skeleton but different for the groundmass) (McCann, 1987; Mertens et al., 2009). The main property of the pozzolana is its composition of siliceous or siliceous and aluminous material, which reacts with calcium hydroxide in the presence of water, thus creating the hydraulic mortar when mixed with limestone. This mixture is very

resistant to mechanical erosion and chemical dissolution, and is particularly suitable for construction in marine environments (Felici, 1993; Franco, 1997; Adam, 2000). The limestone used in the mixture was shipped from peninsular Italy or Sicily, because this sedimentary rock is not present in the volcanic islands of the Aeolian archipelago. Pozzolana was likely shipped from the Roman city of Puteoli (the present Pozzuoli, near Naples, Italy), the nearest and the most important extractive center in the Mediterranean area (Felici, 1993, 1998, 2004).

6. Discussion

The archaeological evidence of Relative Sea Level Changes (RSLC) in the Mediterranean Sea have been described in several publications since the pioneering studies of Schmiedt et al. (1972), Pirazzoli (1976) and, more recently, by Lambeck et al. (2004b), Anzidei et al. (2011a,b), Mourtzas (2012), Morhange et al. (2001, 2006) and Evelpidou et al., 2012, among others.

Geophysical modelling explained the observed changes with the glacio-hydro-isostatic signal, active since the end of LGM (Lambeck and Purcell, 2005; Lambeck et al., 2004a, 2004b; 2010, 2011), and the global sea level rise. The latter has been mostly stable during the last centuries (Church et al., 2010) but is recently experiencing an accelerating rise, estimated at ~ 1.8 mm/yr⁻¹ during the last 120 years in the Mediterranean (Woppelmann and Marcos, 2012; Anzidei et al., 2014), which is also associated with climate change (Rahmstorf, 2007). Geological and archaeological data collected in several Roman fish tanks distributed along the coastlines of the Mediterranean basin show that sea level rise since the Roman age is dependent on location. Apart from the glacio-hydro-isostatic signal, it is often associated with active tectonics or volcanism (Flemming and Webb, 1986; Morhange et al., 2001, 2006; Villy et al., 2002; Lambeck et al., 2004b; Antonioli et al., 2007; Cinque et al., 2011; Evelpidou et al., 2012; Anzidei et al., 2013). This implies that over long periods (up to 3000 years) and in absence of other evidence, we cannot determine the contribution of single deformational events, but only the total deformation averaged on the time inferred, starting from the construction of the archaeological site, under the assumption of constant velocities and trends for the investigated tectonic or volcanic region.

From our data, we estimated a mean RSLC of -4.23 ± 0.2 m (Table 1), since the construction of the wharf at 2 ± 0.05 ka B.P. with its upper part presently located at -3.2 ± 0.2 m, once local instabilities due to ground tilt or gravity slides, are excluded. This value is obtained assuming a minimum functional elevation of 1.0 ± 0.2 m (Felici, 1993; Auriemma and Solinas, 2009) and applying a tidal correction of -0.03 m to depth measurements during surveys, using the nearby tidal station of Stromboli (reference survey of June 17, 2011, time 11:00–12:00 GMT. Data from www.mareografico.it).

As the elevation of the Roman wharf of Basiluzzo is deeper with respect to other contemporary maritime archaeological sites located along the tectonically stable Tyrrhenian coast of Italy (Lambeck et al., 2004b; Evelpidou et al., 2012) (besides those located along the uplifting coast of Calabria, as described in Anzidei et al., 2013; in the subsiding area of the Phlaegrean Fields as reported in Lambeck et al., 2010), therefore a local volcano-tectonic contribution for land subsidence, capable to cause the exceeding relative sea level change, must be invoked.

Although the discrimination between the volcano-tectonics and the glacio-hydro-isostatic signals from the observed RSLC is a challenging task, we have tentatively attempted to separate these contributions to obtain the vertical tectonic rates of deformation of this active region, as previously done for other areas of the Mediterranean (Lambeck et al., 2004b; Antonioli et al., 2007; Anzidei

Table 1
Data for Basiluzzo wharf, located at geographical coordinates Lat 38°39'38.54"N and Lon 15°7'2.72"E; A) Mean depth of the top of the walls; B) Minimum functional elevation; C) Tidal correction; D) Relative Sea Level Change (RSLC) after tidal correction; E) Eustatic Sea Level Change (SLCe) (Lambeck et al., 2004b); F) Residual Relative Sea Level Change (RSLCr) after removal of the recent eustatic part; G) Relative Sea Level Change prediction (RSLCp) at 2ka (from Lambeck et al., 2011); H) Tectonic contribution to the observed RSLC (from residual minus modeled data); I) Land subsidence rate inferred from the predicted glacio-hydro-isostatic model; K) Land subsidence rate (sum of tectonic and glacio-hydro-isostatic signals); L) Tectonic subsidence rate.

A	B	C	D	E	F	G	H	I	K	L
Depth (m)	Functional elevation (m)	Tide (m)	RSLC (m)	SLCe (m)	RSLCr (RSLC-SLCe) (m)	RSLCp (m)	RSLCt (m)	Sp (mm/yr ⁻¹)	Sr (mm/yr ⁻¹)	Tr (mm/yr ⁻¹)
-3.20 ± 0.2	1.0 ± 0.2	-0.03	4.23 ± 0.2	0.13	4.10 ± 0.2	1.23	2.87 ± 0.2	-0.61	-2.05 ± 0.1	-1.43 ± 0.1

et al., 2011b, 2013)(Fig. 4). In our analysis, we included the recent eustatic sea level rise, estimated at ~ 0.13 m in the Mediterranean Sea during the last 100 ± 50 years (Lambeck et al., 2004b; Anzidei et al., 2011b). After the eustatic part has been removed, a total RSLC of 4.10 ± 0.2 m for this structure was obtained, with a mean subsidence rate (Sr) at 2.05 ± 0.1 mm/yr⁻¹ since its construction. Because the glacio-hydro-isostatic contribution to the RSLC observed for this location is predicted at -1.23 m at 2 ka BP, with a rate at -0.61 mm/yr⁻¹(Sp), (Lambeck et al., 2011), by subtracting this part to the total RSLC, the residual signal of 2.87 ± 0.2 m corresponds to the tectonic contribution, with an average tectonic-volcanic subsidence rate (Tr) at -1.43 ± 0.1 mm/yr⁻¹.

Therefore, the present position of the wharf is due to the combined effect of relative sea level rise caused by the glacio-hydro-isostatic contribution acting after the LGM ($\sim 30\%$ of the total observed RSLC) and volcano-tectonic dynamics ($\sim 70\%$ of the observed RSLC), both active since its construction. This dynamic can be related to the still ongoing post-volcanic activity, linked with the hydrothermal-geothermal system and the volcano-tectonic structures running northeast-southwest and northwest-southeast in this sector of the Aeolian Islands (Anzidei et al., 2005; Esposito et al., 2006; Monecke et al., 2012). Recent studies revealed a structural lineament in the submerged summit of Panarea volcano, a northeast-southwest trending fault scarp, west of Basiluzzo Island (Anzidei et al., 2005).

Finally, the subsidence trend inferred from the archaeological site is in agreement with recent geodetic GPS data collected at the benchmark located at Basiluzzo, that show an active subsidence at -4.7 ± 1.5 mm/yr⁻¹ in the time span 1995–2007 (Esposito et al., 2010). This result is consistent with regional GPS solutions, that indicate a subsiding trend active at the scale of the Aeolian archipelago with values at about -3 mm/yr⁻¹ (Serpelloni et al., 2013), but with higher rates across Vulcano and Lipari islands, at -7.4 ± 0.8 mm/yr⁻¹ on average (Mattia et al., 2008).

Both short (instrumental) and middle term (archaeological) subsiding trends are in contrast with the long term geological data,

that infer a continuous but not constant in time, sustained uplifting trend since the last interglacial at Panarea archipelago (Lucchi et al., 2007). Therefore, we interpreted the subsidence deformation pattern as the result not of a transitory, volcano-related component but as a regional signal in the framework of the southern Tyrrhenian geodynamics, in agreement with Serpelloni et al. (2013).

Although archaeological and GPS data indicate that subsidence is the predominant signal for the last 2 Ka in this area, for Basiluzzo we cannot exclude that before and after the beginning of the Roman settlement and the construction of the wharf, this island may have also experienced continuous or episodic uplift, possibly alternated with subsidence. This behavior has been observed for this area during the 2002–2003 submarine exhalative crisis, from GPS data (Esposito et al., 2010) and during the last ~ 2 ka from archaeological observations in the active volcanic area of Campi Flegrei (southern Italy), (Dvorak and Mastrolorenzo, 1991; Morhange et al., 2006; Todesco et al., 2014) and likely in other areas of the Mediterranean (Stiros et al., 2005). As far as we know, the area surrounding Basiluzzo experienced relevant seismicity and submarine volcanic eruptions in the past, as reported by the historical authors Livius (XXXIX, 56), Strabo (VI, 2, 88), and Plinius (N.H. II, 88). Finally, our result improves the previous estimation of subsidence rate given by Tallarico et al. (2003), at -1.87 mm/yr⁻¹ for the last 2 ka.

7. Conclusion

The archaeological data collected at Basiluzzo Island add new constraints for the intervening relative sea level changes and vertical land motion of the Panarea archipelago, since the last 2 ka BP. Subsidence is the dominating signal at -2.05 ± 0.1 mm/yr⁻¹, thus leading to the current submergence of the Roman wharf. This subsidence is driven by the sum of glacio-hydro-isostasy (-0.65 mm/yr⁻¹) and volcano-tectonic signals (-1.43 ± 0.1 mm/yr⁻¹). The latter possibly include the contribution of unknown episodic uplifting events related with seismic or volcanic activity

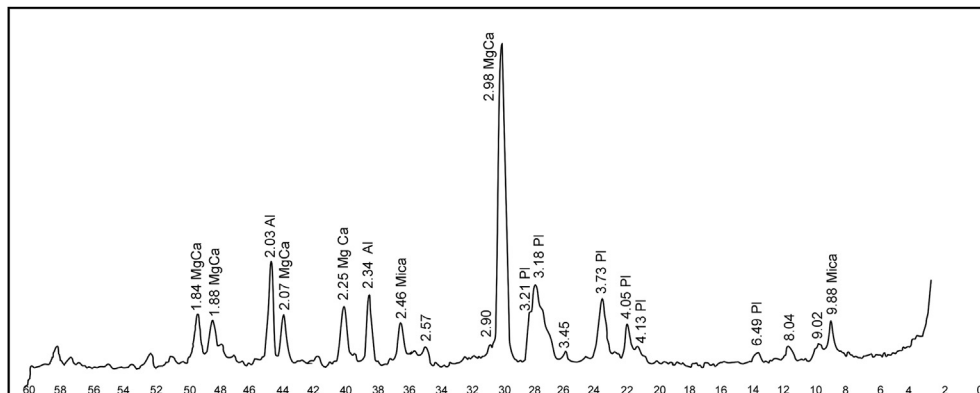


Fig. 3. Diffractogram of a rock sample with hydraulic mortar collected from the eastern wall of the wharf, at an elevation of -4.0 m.

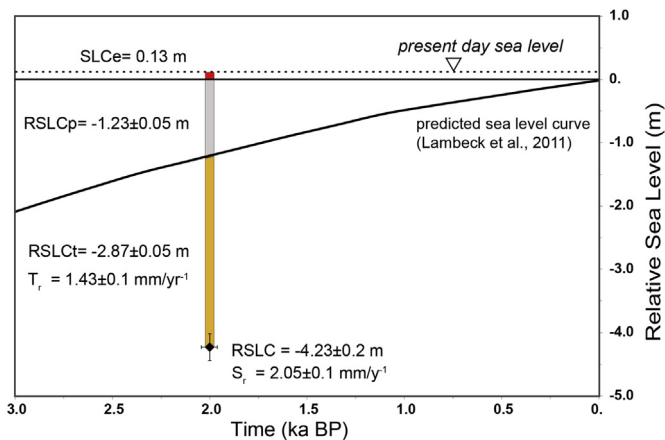


Fig. 4. Plot of the predicted sea level curve (from Lambeck et al., 2011) compared against the elevation of the Roman age wharf at Basiluzzo, dated at 2000 ± 50 years BP (diamond with error bars for age and elevation). The position of the archaeological indicator falls at -4.23 ± 0.2 m (RSLC) and at -2.87 ± 0.05 m (RSLCt) below the predicted sea level at 2 ka BP (RSLCp). S_r is the observed subsidence at rate 2.05 ± 0.1 mm/yr $^{-1}$, while T_r is the rate of the estimated tectonic contribution to the observed subsidence, at 1.43 ± 0.1 mm/yr $^{-1}$. SLCE is the recent eustatic change as estimated by Lambeck et al. (2004b).

that may have affected Basiluzzo Island, such as the 2002 gas eruption. In the last two decades, GPS data retrieved in this area have shown an acceleration of subsidence rates with respect to that inferred from the Roman wharf in the last 2ka. Our results suggest the need of further investigations and a new evaluation of the volcano-tectonic hazard of this sector of the Aeolian Islands.

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