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, buildingcoastal installations currently used as 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 structurehas 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,andthe 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 2ka BP, is inferred from the comparison against the latest predicted sea level curve for the Southern Tyrrhenian Sea, suggestingnew evaluations of the volcano-tectonic hazard for this area of the Aeolian islands.

Keywords: Aeolian Islands, sea level change, land subsidence, maritime archaeology

1. Introduction

Coastal settlements and ports constructed in antiquity along the coasts of the Mediterraneanprovide important insightsinto reconstructions of historical sea-level changes during past millennia (Flemming and Webb, 1986; Schmiedt, 1972; Lambeck et al., 2004a,b).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 archaeologicalsites such as villas, harbors, piers and fish tanks of Roman age, with geological data and geophysical modeling.Results allowed thetemporal and spatial reconstruction of the values and trends of therelative sea level changes and vertical land movementsat specific sites (Anzidei et al., 2011a,b; Lambeck et al., 2004b;Mourtzas, 2012; Paskoff et al., 1981).

Recent studies have shown that the relative sea level changes observed along thecoasts of the Mediterranean Sea depends on the sum of eustatic, glacio-hydro-isostatic andtectonic(including volcanic)signals, according to the following equation (Lambeck and Purcell, 2005):

$$\Delta\zeta_{rsl}(\varphi,t) = \Delta\zeta_{esl}(t) + \Delta\zeta_{I}(\varphi,t) + \Delta\zeta_{T}(\varphi,t)$$
(1)

Where, $\Delta\zeta_{rsl}(\varphi,t)$ 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$\Delta\zeta_{esl}(t)$; the second term $\Delta\zeta_{I}(\varphi,t)$ is the glacio-hydro-isostatic contribution andthe last term $\Delta\zeta_{T}(\varphi,t)$ is the tectonic contribution (including volcanic and other disturbances) for active areas. The $\Delta\zeta_{esl}$ is mainly driven by climate changes and is time-dependent,while $\Delta\zeta_{I}$ and $\Delta\zeta_{T}$ are functions of positionφ 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 recentlypredicted and compared with direct observational data in deformingzones (Lambeck et al., 2011; Lambeck et al., 2010).Results provided new insights on the relationships between sea level change and vertical land motion, because most of maritime archaeological sitesare 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 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 waystoward Sicily and northern Africa(Bernabò-Brea and Cavalier, 1985; Bernabò Brea, 1985; Bound, 1992; Kapitan, 1958; 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. Weused this well preserved structure as an archaeological

indicator of the intervening relative sea level change and land subsidence occurredover 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 mainsectors (Falsaperla et al., 1999; De Astis et al., 2003):*a)*the extinct western sector characterized by CA (Calc-Alkaline) and HKCA (High PotassiumCalc-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 placed along a northwest-southeast trending tectonic lineament, namely the Tindari – Giardini-Letoianni 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 Palinuro seamounts. Volcanic activity started at800 ka (De Astis et al., 2003) and it is still persistent at Stromboli whereas episodic gas eruptions occur at Panarea (Esposito et al., 2006; Anzidei et al., 2005; 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 portion of the submarine stratovolcano 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 evidenced 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 concentrates 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 (Boschi et al., 1997; SGA, 1996; Esposito et al., 2006; Monecke et al., 2012).Besides the volcanic activity, the Aeolian islands arenowadays characterized by deep to shallow seismicityand ground deformations (Chiarabba et al., 2005; Guidoboni, 1994; Hollenstein et al., 2003; 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 surroundings 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 calcalkaline 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 Torrione Lithosome),* were emplaced at Panarea and surrounding islets during several discrete eruptive events that occurred between about 70 and 8 kaBP (Lucchi et al., 2003). Some other tephras of external provenance are intercalated within these 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 towardPunta 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 solifluxion 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 to the BF (Lucchi et al 2003, 2013).

4. Materials and methods

The submerged archaeological structure located in the most sheltered side ofPunta Levante (Fig.2a,b,c), was surveyed during repeated campaigns ofscuba diving prospecting, to provide a detailed map of the submerged archaeological site suitable for geophysical interpretation. Former surveystook place on September 1996 and June 1997, while additionaldata were collected onNovember 2001, May 2003 and in 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 andsingle and multibeam echo-sounding systems, the latter two coupled with Global Positioning System (DGPS) (Anzidei et al., 2000; 2005). A description of the survey featuresand the realization of the morphobathymetric mapsare 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 derives 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 archeological site partially prevented the realization ofmultibeam 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 a survey accuracy better than±0.05 m. Although this value includesall instrumental uncertaintiesand tidal correctionswe 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).

Archeological data

The archaeological site(Fig.2)is foundedon the rocky seafloor,fitting its morphology. Ithas a trapezoidal shape and displays three mainwallswith an average depth of -3.20±0.2 m,up to 2.8 m wide, 2.5 m tick and 6 to 15 m long, enclosing a small basin (Fig. 2c,d,f,g,h).The latter has a depthup to –5.5 m andis partially silted by debris and rocks fallen from the nearby cliff. Within the basin an outcropping rock (CR1) is partially carvedand flattened at the top to be shapedat 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 isatabout -4 m.The northeastern and southeasternwalls display two openings of 1.9and 1.3 m of width andtheir bottom areat-4.50 and -4.70 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 footprint(WP1) of 0.4x0.4x1.5m of size, left by a no longer existing wooden pole(Fig.2c). Along the northwesternside of the basin an additional footprint left by a wooden pole mounted verticallyis placed (WP2)at 3.55 m of depth(Fig.2c).

5. Resultsand 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 neither aharbor nora 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 theharbor 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, foundin the wellknown fish tanks located along the coast of the Tyrrhenian Sea and in other parts of the Mediterranean basin (Auriemma and Solinas, 2009; Blackman, 1973; Schmiedt et al., 1972; Lambeck et al., 2004b; Lambeck et al., 2010; Pirazzoli, 1976). 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 tocontrol the exchange of water within the basin) (Fig.2c,d,f,g); *ii)*the *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 *aquatio*, 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 like seabass or mullets), in the fish tanks, albeit not all fish tanks had these constructional features (Schmiedt, 1972; Auriemma and Solinas, 2009).

Finally, we exclude the hypothesisof a small house, due to the raw constructional featuresnot similar to those described by the Latin author Vitruvio in his book*De Architectura*. Particularly, the submerged structure does not have a coverage in *opus reticolatum*along the walls (typical of subaerial buildings as the villa located in Basiluzzo, Fig.2a,e. See Adam, 2000),which are oflarge size (typical of harbors or fish tanks, see Felici, 1993, 1998, 2004 and Auriemma and Solinas, 2009).

The age of this wharf can be dated back between 50 B.C. and 50 A.D.as evident from the architectural features of the large Roman villa placed on the island,which is 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 theisland's coast with the lowest elevation, from which is easier to land. The remaining coast of Basiluzzois too deep and the cliffs aretoo steep for coastal installations.Furthermore, it is worth of notice that between the wharf and the cliff, at about 3 m below sea level, the remains of stones cemented to the bedrockare 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, onceused to access the impending villa through still partially existent stairs built along the cliff.

We also findsimilar constructional features that are typical of the Roman age ports built inthe Mediterranean, such as the footprints of wooden polesfor the constructional formwork of the walls (like WP2),the use of horizontal woodsused to facilitate moorings of ships at the quayside (like WP1), the narrow openings along the outer walls,the use of hydraulic mortar to build in maritime environmentand the carved seafloor (like in CR1 and CR2) to fit it for the 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 inmodern 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 harborslocated along the Tyrrhenian coast of Italy (Ventotene Island, Torre Astura, Miseno andBaia)and in other exemplary sites of the Mediterranean basin (Leptis Magna, in Libya, Cesarea Marittima in Israel, Marseille in Franceand in Lebanon) (Antonioli et al., 2007; Auriemma and Solinas, 2009; Blackman, 1973; Felici,1993, 1998; Franco, 1997; Hesnard, 2004; Lambeck et al., 2004b;McCann, 1987; Marriner et al., 2006; Morhange et al., 2001; Morhange et al., 2006; Schmiedt, 1972), 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 alwaysabove water level even duringhigh 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 theage of the archaeological structureand support geophysical interpretationswe 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,waslargely 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 made 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 constructions in marine environment (Adam, 2000; Felici, 1993; Franco, 1997). The limestone used in the mixture was shipped from peninsular Italy or Sicily, because this sedimentary rock is not present in none of the volcanic islands of the Aeolian archipelago. Concerning thepozzolana, this was likely shipped fromthe Roman city of Puteoli (the present Pozzuoli, near Naples, Italy),beingthe nearest and the most important extractivecenterin 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 et al. (2012),Morhange et al. (2001, 2006) and Evelpidiou et al, 2012, among others.

Geophysical modelling explainedthe observed changes withthe 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 mostlystable during the last centuries (Church et al., 2010) but is recently experiencing an accelerating rise,estimatedat 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 to 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 and apart from the glacio-hydro-isostatic signal, it is often associated with active tectonics or volcanism(Lambeck et al., 2004b; Anzidei et al., 2013; Flemming and Webb, 1986; Villy et al., 2002; Antonioli et al., 2007; Morhange et al., 2001, 2006; Cinque et al., 2011; Evelpidiou et al., 2012). This implies that over long periods (up to3000 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 partpresently located at -3.20±0.2 m, once local instabilities due to ground tilt or gravity slides, are excluded.

This value is obtained assuminga minimum functional elevationof 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 isfor June 17, 2011, time 11:00-12:00 GMT. Data from www.mareografico.it).

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

Although the discrimination between the volcano-tectonics and the glacio-hydro-isostatic signalsfrom the observed RSLCis 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., 2044b; Antonioli et al., 2007;

Anzidei et al., 2011b, 2013)(Fig. 4). In our analysis, we included the recent eustatic sea level rise,estimatedat ~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 is 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 tothe tectonic contribution, withanaverage 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(~30% of the total observed RSLC) and volcano-tectonic dynamics (~70% of the observed RSLC), both active since its construction. This dynamic can be addressedto 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 evidenced a structural lineament in the submerged summit of Panarea volcano, i.e. a fault scarp northeast-southwest trending, running west of BasiluzzoIsland(Anzidei et al, 2005).

Finally, the subsidence trend inferred from the archaeological site isin 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 evidence 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} in the 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 Basiluzzowe cannot exclude that before and after the beginningof 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 2ka 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 2ka.

7. Conclusion

The archaeological datacollected at BasiluzzoIsland 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-tectonics 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 that may have affected Basiluzzo Island, as for 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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FIGURE CAPTIONS

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

Fig.2 Composite panel showing the studied site: a) aerial photo of Basiluzzo. The redopen 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 redsquare 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 (in brown); e) the remains of the Roman villa located on the top of the island with walls built in *opus reticolatum* and pavements with mosaics; f) view of the walls and the basin withthe two openingsA1 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 theinner side of thebasin with the walls builton the rocky seafloor.The walls were made by rhyolite fixed by hydraulic mortar. See text for details.

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

Fig.4Plot 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±0.05m(RSLCt) belowthe predicted sea level at 2 ka BP (RSLCp). Sris the observed subsidence at rate 2.05±0.1 mm/yr^{-1}, while Tr is therate 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).

Table Caption

Tab.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.

Figure
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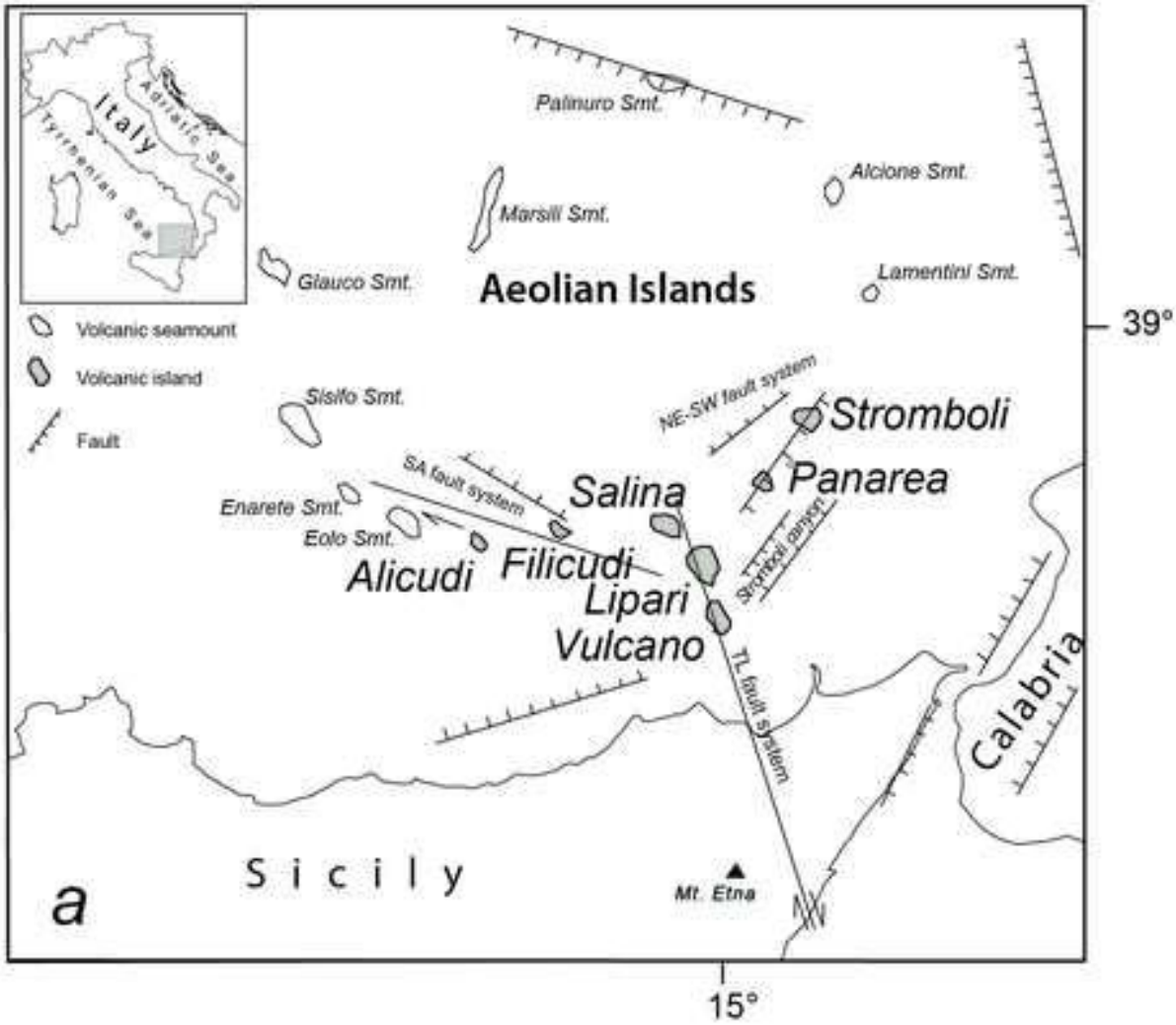

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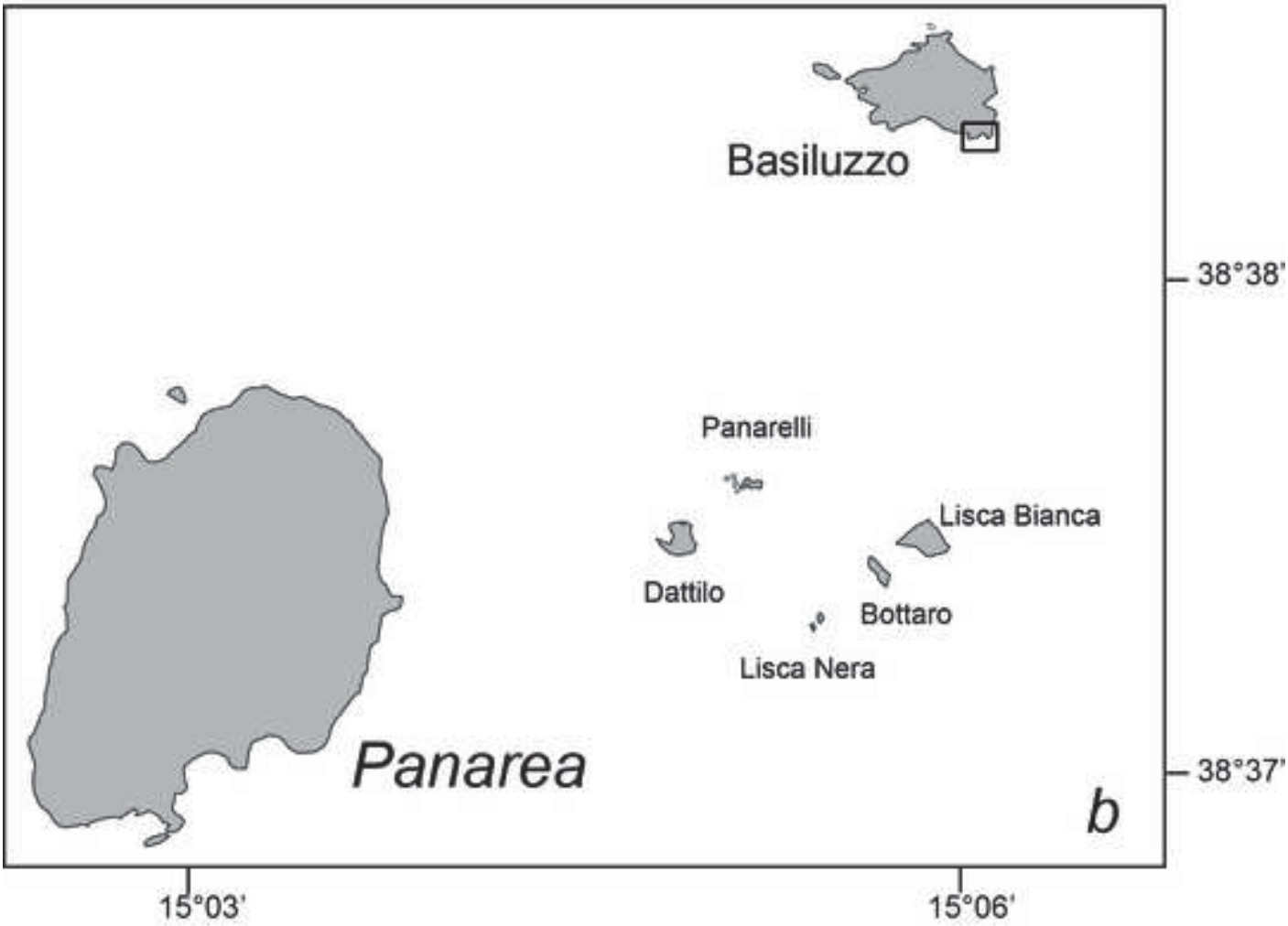

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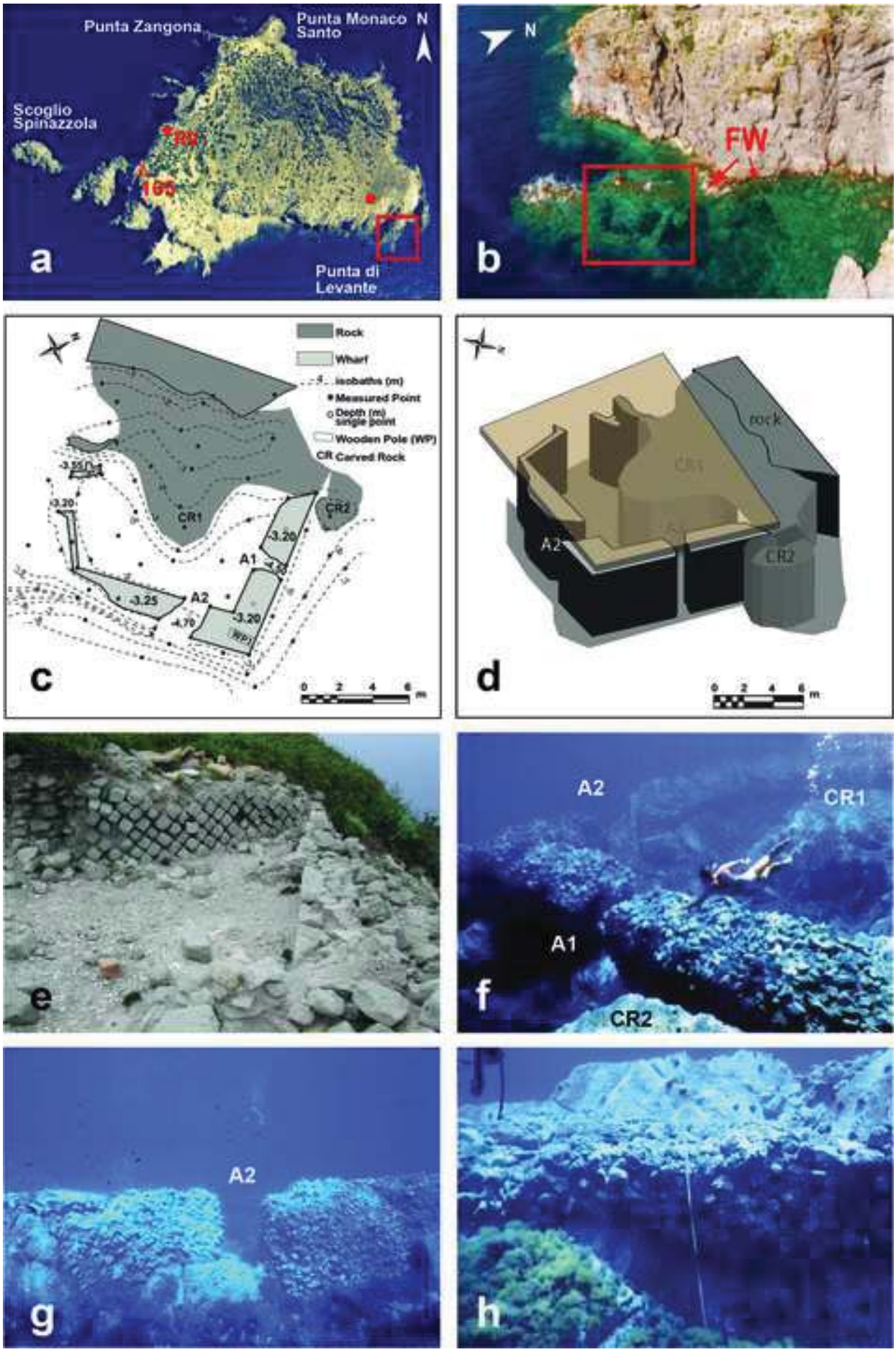

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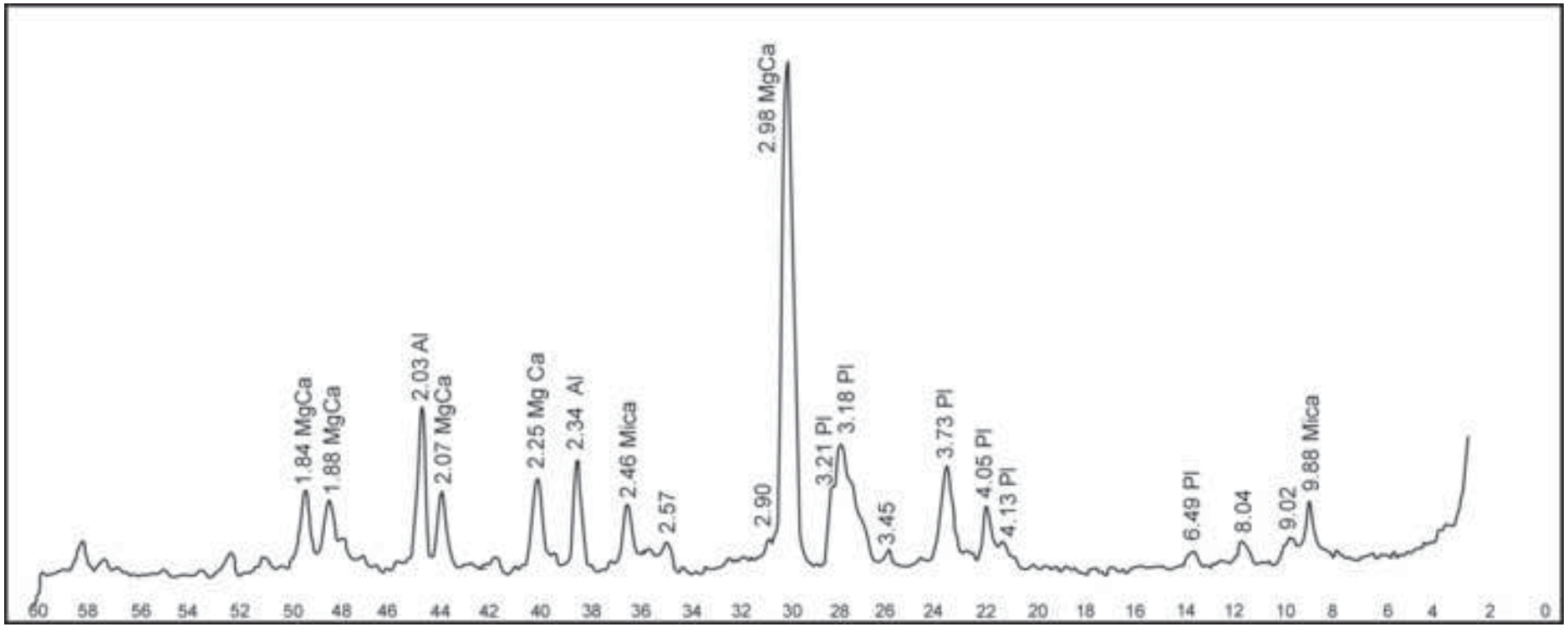

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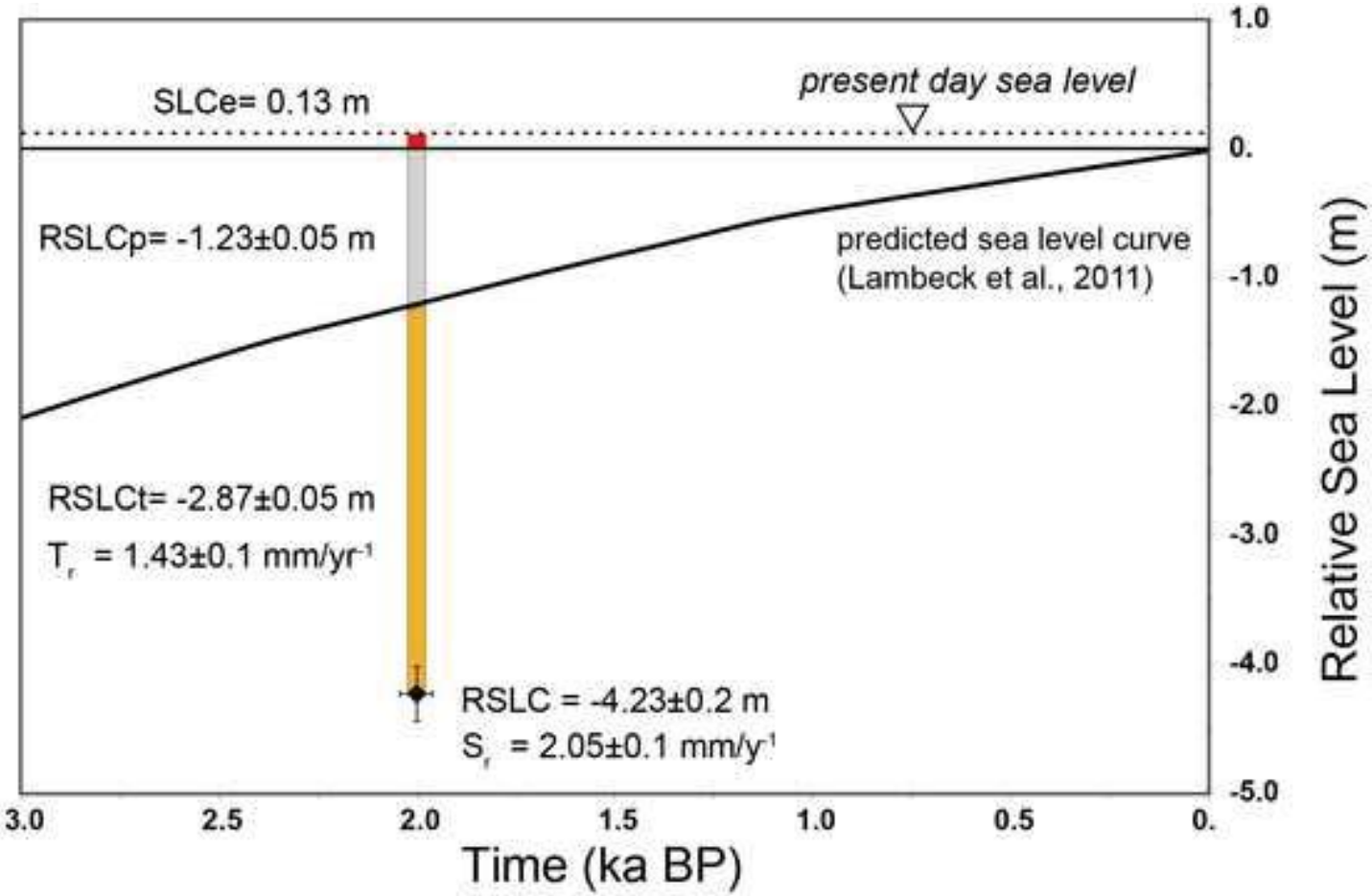

Table 1

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