Palaeogeography, Palaeoclimatology, Palaeoecology 463 (2016) 112–125

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Historical sea level changes and effects on the coasts of Sorrento Peninsula (Gulf of Naples): New constrains from recent geoarchaeological investigations

Pietro Aucelli [a], Aldo Cinque [b], Gaia Mattei [a],*, Gerardo Pappone [a]

[a] Dipartimento di Scienze e Tecnologie, Università degli Studi di Napoli Parthenope, Centro Direzionale Is C4, 80121 Napoli, Italy
[b] Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università di Napoli Federico II, Largo San Marcellino, 10, 80138 Napoli, Italy

ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form 26 September 2016
Accepted 28 September 2016
Available online 29 September 2016

Keywords:
Archaeological sea-level markers
Historical landscape reconstruction
Submerged geoarchaeological sites
Roman period
Vesuvius 79 CE eruption
Southern Italy

ABSTRACT

This paper describes the results of a multidisciplinary study of four geoarchaeological sites on the Sorrento Peninsula coast (Italy) where the submerged ruins of Roman buildings have enabled the ancient position of both the sea level and the coastline to be reconstructed. The results highlight that the sea level in Roman times, deduced from the submersion measurement of archaeological markers, did not exceed 1.2 m ± 0.30 m, except for Seiano whose submerged remains and surrounding area were heavily damaged by extreme events following the 79 CE Vesuvius eruption. The comparison of these results with the eustatic sea-level curve in Roman times together with the submersion of the tectonically stable site on the Tyrrhenian coast of Italy (Torre Astura, with a well-preserved Roman fishpond) demonstrate that the Sorrento Peninsula has been tectonically stable over the last two millennia. This behaviour started many thousands of years ago, not later than the last interglacial, while the nearby plain of Pompeii and probably the bottom of the adjacent Gulf of Naples have been subsiding at rates of 1 or more mm per year. In the same time span, two of the investigated coastal sectors (Capo di Sorrento and Punta Campanella) have not suffered any significant changes because their sea cliffs are cut in hard limestone. The tufa sea cliff of the Sorrento plain on the other hand, has been retreating by several metres. On the Marina di Equa (Seiano) alluvial coastal plain, which suffered the effects of the 79 CE eruption, the debris and hyperconcentrated flow produced a progradation of >200 m, which has been totally dismantled over three centuries.

1. Introduction

Several factors affect how coasts have evolved in the last two thousand years, however vertical ground movements play a fundamental role by interfering with global factors such as eustatic sea level changes associated with climate change (Vacchi et al., 2016; Church et al., 2013; Anzidei et al., 2011; Lambeck et al., 2011; Antonioli et al., 2009; Giorgi and Lionello, 2008; Rahmstorf, 2007; Antonioli et al., 2007; Lambeck et al., 2004b; Pirazzoli, 1997).

Tectonic and volcano-tectonic activity in particular, along with human activities directly influence the morphological evolution of the coastal environment. Regarding the Italian coastlines, it is essential to consider the ongoing evolution of the Apennine chain, which is a very young orogen, with particular focus on the Tyrrhenian flank where vertical ground movements are not negligible (Brancaccio et al., 1991; Cinque et al., 1993; Ferranti et al., 2006; Casciello et al., 2006; Milia et al., 2013).

The coast of the Campania region is one of the most diversified coastal systems in Italy, with alternating high and low coastal sectors, many of which have been greatly influenced by tectonic and volcanic processes (Brancaccio et al., 1991, 1995; Ferranti et al., 2006; Milia and Torrente, 2015). The Last Interglacial markers (Ferranti et al., 2010) indicates the substantial subsidence of this region due to faults, magma chamber withdrawal and soil compaction, with exceptional uplifts due to volcanic-tectonic processes.

The coasts of the Gulf of Naples (Fig. 1A) were mainly modified during the Late Quaternary, and since Roman times (Mattei, 2016) by the volcanic activity of Somma-Vesuvius, Phlegraean Fields and Ischia (Aiello et al., 2001; Milia et al., 2003). In fact, in the caldera centre of the Phlegrean Fields (Fig. 1A), several uplifts episodes have been associated with local volcanic-tectonic processes, although the submersion of several Roman archaeological sites in the Pozzuoli Gulf is the result of volcano-tectonic subsidence (Cinque et al., 1997; Morhange et al.,

* Corresponding author.
E-mail addresses: pietro.aucelli@uniparthenope.it (P. Aucelli), aldocinque@hotmail.it (A. Cinque), gaia.mattei@uniparthenope.it (G. Mattei), gerardo.pappone@uniparthenope.it (G. Pappone).

http://dx.doi.org/10.1016/j.palaeo.2016.09.022
0031-0182/

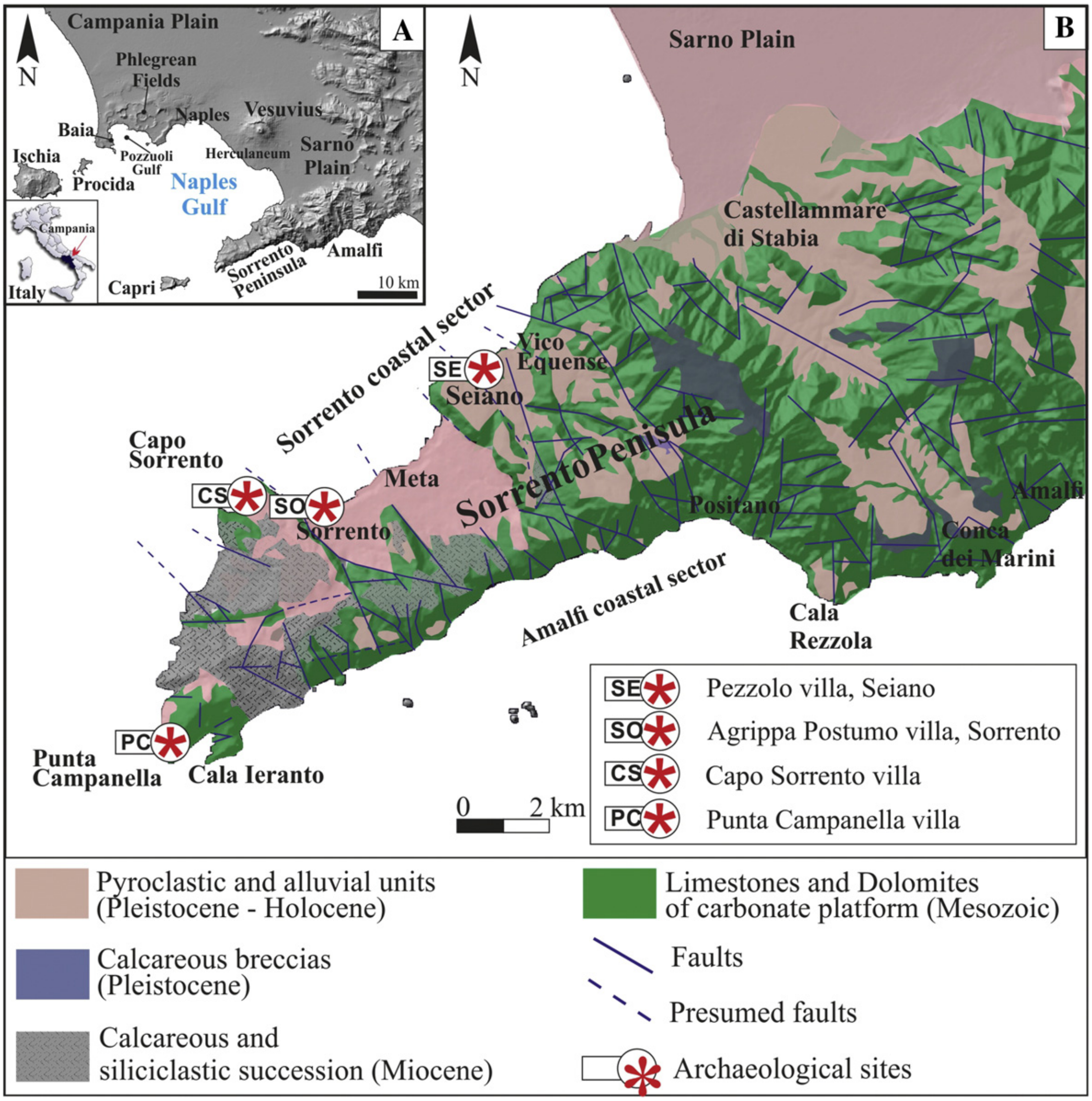

Fig. 1. A) Shadow relief of Campanian coasts between Phlegraean Fields and the Sorrento Peninsula; B) Geological map of study area (after Iannace et al., 2015) with positions of archaeological sites.

2006; Passaro et al., 2013). Moving southward, the coast of Naples (Fig. 1A) in the Late Holocene was affected by 1 mm/yr of subsidence, probably not related to volcanism. This mean subsidence rate was deduced from beachface deposit identification at a depth of −3 m b.s.l. during geo-archaeological excavations associated with public transport works (Cinque et al., 2011; Romano et al., 2013). On the other hand, the Vesuvius coastal sector was much influenced by Holocene volcanic activity, as demonstrated by vertical ground movements inferred from a geoarchaeological study of Herculaneum (Fig. 1A, Cinque and Irollo, 2008). Finally, a subsidence rate of 1.5 mm/yr was observed in the Sarno coastal plain (Fig. 1A), mainly due to soil compaction under the heavy pyroclastic sediment load (Cinque, 1991; Pescatore et al., 2001; Vogel and Maerker, 2010).

In this paper we present new data on the relative sea-level change in the historical time along the coast of the Sorrento Peninsula promontory (Lattari Mts.) overlooking the Gulf of Naples, using submerged archaeological markers such as docks, piers, quays, and fishponds (Fig. 1B).

This coastal territory has been influenced in the last 2000 years by local forces (Cinque et al., 2000) such as volcanic events and sea level changes. The interaction between these endogenous and exogenous factors, which differ in duration and intensity, have produced both continuous coastal changes such as those related to sediment budget and abrupt changes related to huge alluvial events and Somma-Vesuvius eruptions. The eruption that had the greatest impact on this coast was the famous Plinean Vesuvius eruption of 79 CE (Sigurdsson et al., 1982; Santacroce et al., 2008; Cinque and Robustelli, 2009).

The human impact in the Roman period along the coasts of the Sorrento Peninsula, is documented by the many seaside villas that were built with a density that is only comparable with those in Capri and Baia (Fig. 1A). These villas, which were built around the 1st century AD, were restored and rebuilt up until the 3rd century AD, because of the effect of the eruption of Vesuvius in 79 CE that drastically changed the morphology of this area.

Studying the many ruins of seaside villas in the area, both spatial and chronological constrains can be obtained regarding the coastal changes occurring since Roman times. Maritime annexes of these villas, such as small harbours and fishponds, are the focus of the study, as they are good indicators of sea level rises (SLRs). In fact, because of the small tidal range (±0.30 m, Vacchi et al., 2016), they provide significant information on the relative sea-level changes over the last two millennia,

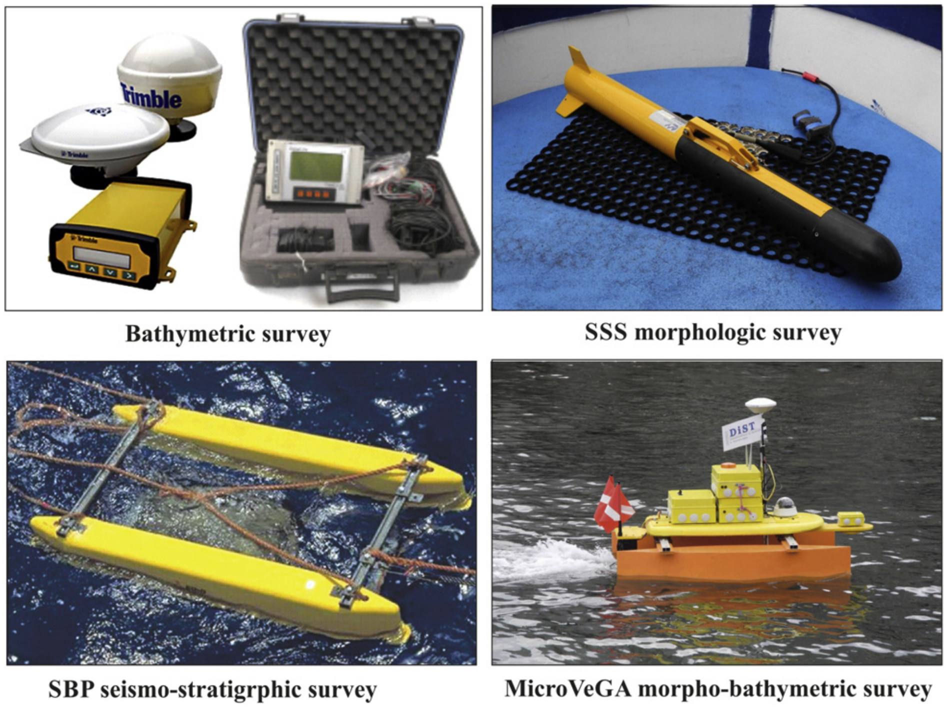

Fig. 2. Integrated geoarchaeological marine methods used in this research.

thanks to a precisely defined relationship to the sea level at the time of construction (Flemming, 1969; Schmiedt and Caputo, 1972; Flemming and Webb, 1986; Lambeck et al., 2004a; Antonioli et al., 2007; Auriemma and Solinas, 2009).

The aim of this multidisciplinary research was to reconstruct the Roman landscape in four geo-archaeological sites in the northern sector of the Sorrento Peninsula (Fig. 1B), together with the coastal changes due to the relative sea level rise in Roman times.

2. Historical setting

The area of the ancient *Surrentum* covers the entire Sorrento Peninsula. In the beginning of the 5th century. B.C. *Surrentum* was briefly under Etruscan domination and the after being occupied by the Oscas in around 420 BCE, it was a Greek colony, as documented by an inscription in Doric dialect dated from the 4th century. B.C., found on the statue of Artemis in the city (Mingazzini, 1946).

The vestiges of the Greek *Surrentum* include various graves and remains of statues (5th cen. BC – 1st cen. BC). The only visible remains of the pre-Roman city consist of two doors and a stretch of wall along the ancient Greek city walls. Another important finding is a paved road leading to the famous temple of Athena at Punta Campanella, of which only a few votive objects have been found. The Roman town preserved the original Greek plan, with the streets intersecting at right angles and the Roman Agora is positioned in the same place as the Greek market.

Surrentum was very probably part of Nucerine League, together with *Stabiae*, *Pompeii* and *Herculaneum*. After the Social War (91–88 BCE), *Surrentum* had Roman citizenship, as documented by a city hall or colony. Many villas of wealthy Romans were built between the I cen. B.C. and I A.C. In fact, the remains of the Roman period are abundant along the Sorrento Peninsula coasts. The most impressive imperial villas are: the villa of Agrippa Posthumus (located where the Hotel delle Sirene currently stands and the adjoining area); the Capo di Sorrento villa (Bagni della Regina Giovanna - Baths of Queen Joan); the villa of Punta di Massa (referred to by Statius, the Roman poet, of which almost nothing remains); the villa at Punta Campanella (probably a pied-a-terre of the emperor and for those who went to Capri) and other smaller villas, scattered along the coast of the Gulf of Naples. These villas are strikingly beautiful. According to the Greek historian Strabo “the crater is completely dotted by towns we called, as well as villas and gardens, and these and those, lying between them one after the other, offer the appearance of a single city”.

3. Geological and geomorphological setting

The Sorrento Peninsula is a WSW–ENE elongated horst and lowered to the west, which separates two semigrabens, the Gulf of Naples in the Campania Plain to the North, and the Gulf of Salerno in Sele Plain to the south (Cinque and Robustelli, 2009; Pappone et al., 2010, 2011; D'Argenio et al., 2012; Iannace et al., 2015).

The structural framework is characterized by NW dipping homoclinal blocks which are dissected by faults with NW–SE, NE–SW and E–W trends (Brancaccio et al., 1991; Carannante et al., 2000).

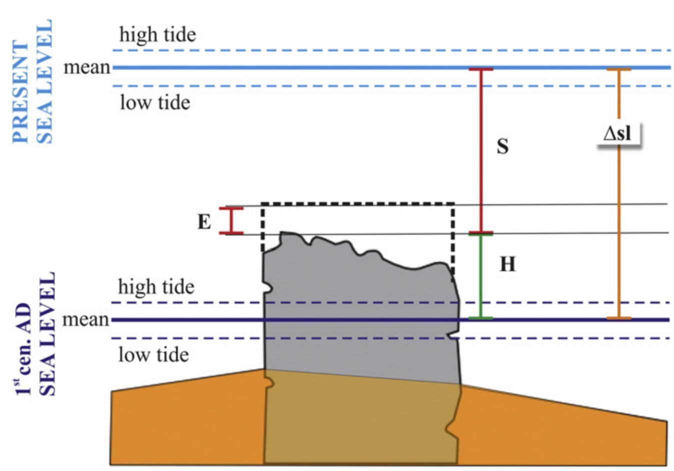

Fig. 3. Parameters used for the evaluation of the Roman sea level: S submersion of the archaeological marker; E hypothetical amount of erosion; H functional height of archaeological marker, amount of emersion during the usage period.

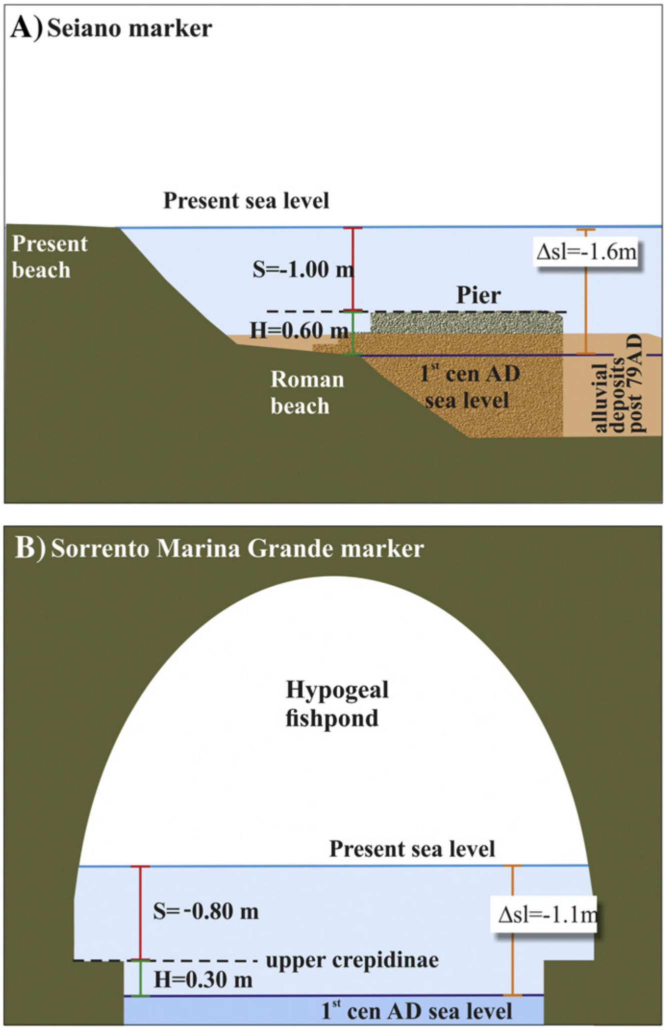

Fig. 4. Evaluation of sea level rise (Δsl) in the last 2 ky using submersion measurements (S) and corrections with respect to the functional height (H) in A) Pezzolo villa at Seiano; B) Agrippa Posthumus villa at Sorrento Marina Grande.

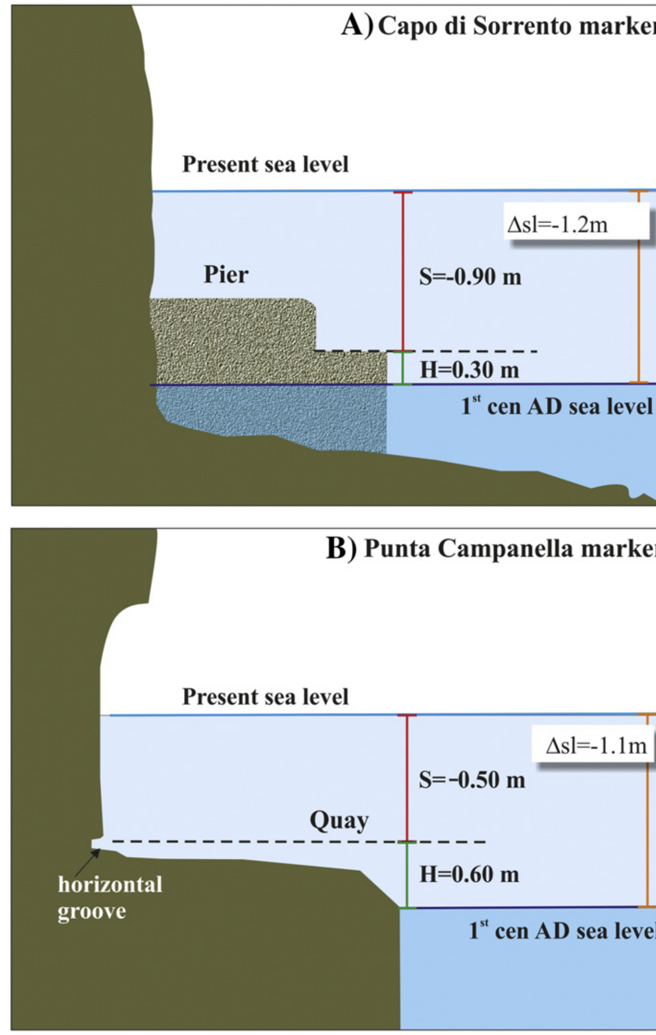

Fig. 5. Evaluation of sea level rise (Δsl) in the last 2 ky using submersion measurements (S) and corrections with respect to the functional height (H) in A) Roman villa at Capo di Sorrento; B) Roman villa at Punta Campanella.

The structural setting is the result of Late Miocene–Pliocene compressive tectonics and of the subsequent Plio-Quaternary transcurrent and extensional tectonics (Brancaccio et al., 1991; Cinque and Romano, 1990; Iannace et al., 2015).

Mesozoic carbonate platform limestones and subordinated dolostones of Upper Cretaceous succession crops out in the Sorrento Peninsula promontory and were overlain by a transgressive Miocene succession and, locally, overlain by Pleistocene calcareous breccias and Pleistocene–Holocene pyroclastic rocks (Fig. 1B).

The whole promontory is also carpeted by a pyroclastic unit emitted by Somma Vesuvius and the volcanoes of the Phlegraean Fields, with a thickness varying between a few centimetres and >10 m (Iannace et al., 2015). The most important eruption producing these deposits during the Holocene, was the Vesuvius eruption of 79 CE The 79 CE pyroclastic unit rests directly on the Mesozoic rocks or on eruption units of Middle-Late Pleistocene. Therefore, between 18 ky ago and 79 CE the Lattari Mts. did not receive any significant fallout deposits, because during this time span, the Vesuvius Plinian eruptions were dispersed in other directions (NE to E; Santacroce et al., 2008, Cinque and Robustelli, 2009).

During the 79 CE eruption, the Lattari ridge was completely mantled by loose pyroclastic deposits, with a thickness of between 1 and 2.5 m of pumice and ash (Sigurdsson et al., 1982; Santacroce et al., 2008; Cinque and Robustelli, 2009). This cover has been almost totally removed from the steepest hill slopes of the Lattari Mts. by mass wasting and fluvial denudation; whereas, on less inclined hill slopes some parts of the cover have been preserved. Some traces of this eruption are still preserved within the archaeological remains of Roman villas such as those at Pezzolo villa (Seiano) and Capo di Sorrento villa (see below).

3.1. The sea level marks left by the last interglacial maximum

The Sorrento Peninsula coasts preserve good traces of palaeo-sea levels, for example along the southern coast of the Peninsula, where the raised Middle Pleistocene marine terraces, such as Cala Rezzola (Fig. 1B), at elevations from 40 to 15 m (Cinque and Romano, 1990),

Table 1
Measurements and corrections of the submersion of archaeological markers in the four archaeo-sites of Sorrento Peninsula.

Site	Marker	Submersion (S)	Functional height (H)	Ancient sea level (Δsl)
Seiano	Pier	−1.00	0.60	−1.60 ± 0.50
Sorrento	Fishpond	−0.80	0.30	−1.10 ± 0.30
Capo di Sorrento	Pier	−0.90	0.30	−1.20 ± 0.30
Punta Campanella	Quay (horizontal groove)	−0.50	0.60	−1.10 ± 0.30

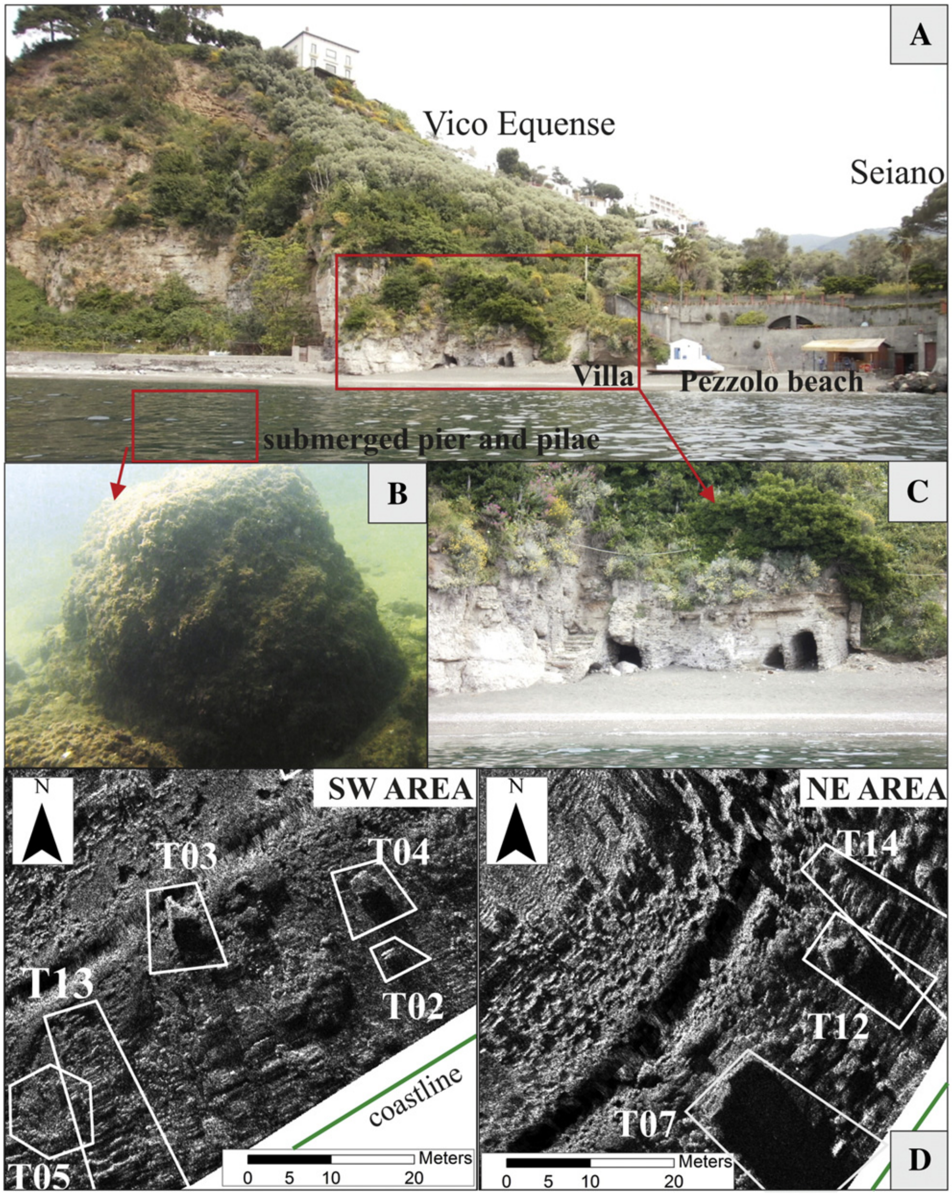

Fig. 6. A) Photo overview of Pezzolo villa archaeological site; B) Underwater photo of a pila comprising the submerged harbour; C) Zoom of ruins on the beach; D) SSS archaeological targets of SW and NE survey area.

suggest that the last phase of block-faulting affecting the Peninsula dates back to this period. A subsequent period of uniform tectonic uplift, acting at a low rate, can be recognized by the O.I.S. 7 shoreline at a constant elevation of about + 10 m a.s.l. (Cinque and Romano, 1990; Riccio et al., 2001).

In the Amalfi coastal sector (Fig. 1B), much evidence of ancient shorelines at about 8 m asl have been recognized permitting to evaluate the paleo-sea-level during Stage 5 (Brancaccio et al., 1978; Cinque and Romano, 1990; Romano, 1992; Ferranti et al., 2006). This paleo-sea level was dated by measuring the $^{230}Th/^{238}U$ activity ratio in coral fossil samples (Brancaccio et al., 1978) in two sites (Conca dei Marini and Cala Ieranto, Fig. 2). The mean age calculated for the samples from Conca dei Marini was 129,000 years, while the Cala di Ieranto, was aged at 128,000 years (Brancaccio et al., 1978). Both correspond, within the limits of analytical error and the limit of one OIS 5 gloacio-eutatic highs (Shackleton et al., 2003). In these sites, traces of marine notch at 7–8 m a.s.l. are also present, which were correlated by the authors (Brancaccio et al., 1978) with the sea level at the time of dating. This level almost coincides with the well-known glacio-eustatic position reached by the sea level during the *optimum* of the last interglacial, substage 5e (Riccio et al., 2001; Shackleton et al., 2003).

Riccio et al. (2001) highlighted the presence of another sea level stand which occurred during substage 5e, at − 1.5 m below the Eutyrrhenian level + 8 m. This level was preceded by a rise and followed by a lowering of the sea level. The particular morphology of the marine notches used as sea level markers, suggests a slightly fluctuating sea level between + 6 and + 7.5 m. They also highlight the presence of younger highstands which can be chronologically referred to the minor climatic fluctuations of Stage 5.

The first evidence of a sea level-stand is at + 3.5/4 m a. s. l. This event occurred after the + 8 m Eutyrrhenian peak, probably during the last part of substage 5e or later (in any case before Stage 4 because these shorelines are covered by the Last Glacial slope breccia), and was characterized by a considerable duration.

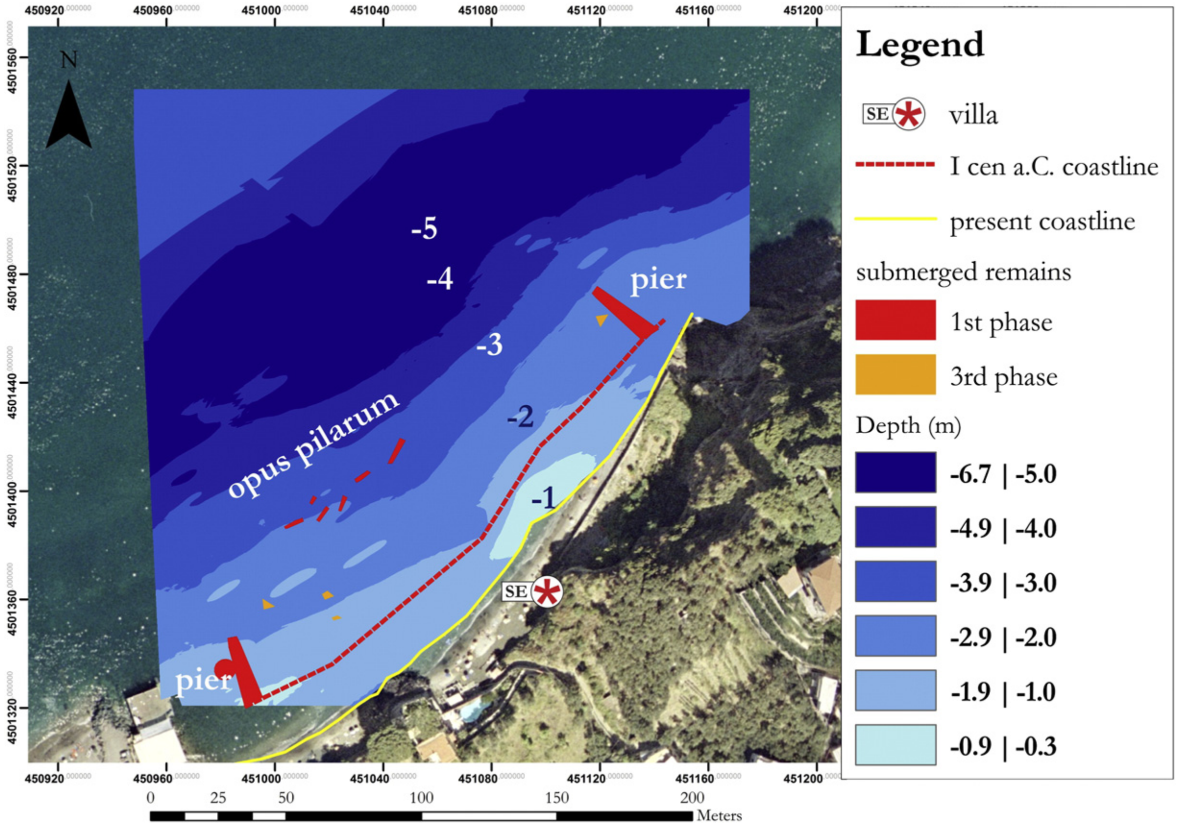

Fig. 7. Coastline evolution in Seiano 1st cen AD coastline position (red dashed line) and present coastline (yellow line).

Evidence of the second sea level, between +1.5 and +2 m a. s. l., could also be classified chronologically as falling into Stage 5, after the Eutyrrhenian peak, and before Stage 4 (also in this case because the sea level markers cut the biogenic Cladocora body and are covered by slope breccia deposited during the Upper Pleistocene cold periods). A comparison with other studies (Hearty, 1986; Ulzega and Hearty, 1986; Vacher and Hearty, 1989; Mush et al., 1994; Lundberg and Ford, 1990) would seem to indicate that this level is at substage 5a.

The presence of multiple traces of sea level stand along the southern coast of the Sorrento Peninsula, demonstrated that several high-stand peaks characterized the sea level in the last interglacial.

These levels (Riccio et al., 2001) almost coincide with the well-known glacio-eustatic position reached by the sea level during the *optimum* of the last interglacial (Lambeck and Chappell, 2001; Vacchi et al., 2016).

In fact, during this last interglacial period several authors have demonstrated that the global sea-level was higher than the modern one (Shackleton and Opdyke, 1973; Waelbroeck et al., 2002; Siddall et al., 2003). However the related sea-level curves along the Mediterranean coasts result in a height difference of several meters (Lambeck and Chappell, 2001; Potter and Lambeck, 2004). The average sea level during the MIS 5.5 (6 ± 3 m) can be inferred by coastal measurements in Sardinia as the best eustatic reference for the central Mediterranean (Lambeck et al., 2004a; Ferranti et al., 2006; Ferranti et al., 2010; Vacchi et al., 2016).

Comparing the aforementioned eustatic values with the present elevation of marks left by the O.I.S. 5.5 high stand (6 to 8 m above sea level), it can be concluded that the Sorrento Peninsula has remained substantially stable over the last 130,000 yrs (as proposed by Brancaccio et al., 1978; Cinque, 1986; Cinque and Romano, 1990; Riccio et al., 2001; Ferranti et al., 2006). However, the match between the measured elevation of coastal traces and the corresponding eustatic sea-level is not perfect, with a difference of about 1–2 m.

One of the aims of this paper is to add some younger control points to verify the recent tectonic behaviour of the Sorrento Peninsula and, most importantly, to establish whether the substantial stability, presumed in previous studies from an average of two points (130 kys and today), is a continuous trend or the result of alternating lifting and subsidence movements.

4. Methods

4.1. Geoarchaeological surveys

The integrated geoarchaeological surveys of the four coastal sites were carried out using specific geophysical techniques for each area (Giordano, 2010).

In the first studied site, Marina di Seiano, a marine geophysical survey was carried out of the underwater extension (maritime annexes) of the Pezzolo villa. A morpho-bathymetric survey using a single-beam echo sounder (SBES) and a side scan sonar (SSS) was carried out. A seismo-stratigraphic survey was then performed by means of a sub-bottom profiler (SBP) system to investigate the sub-bottom and any artifacts buried beneath sediments.

In the other coastal archaeo-sites, where the archaeological remains were only submerged by a few centimetres, we used an unmanned surface vessel (USV, MicroVeGA in Fig. 2) created specifically for surveys in very shallow waters (Giordano et al., 2015). Where the GPS signal was absent, as in the case of the *crepidinae* inside the hypogea fishpond in Sorrento, direct measurements by means of graduated stadia were carried out in relation to the submerged findings.

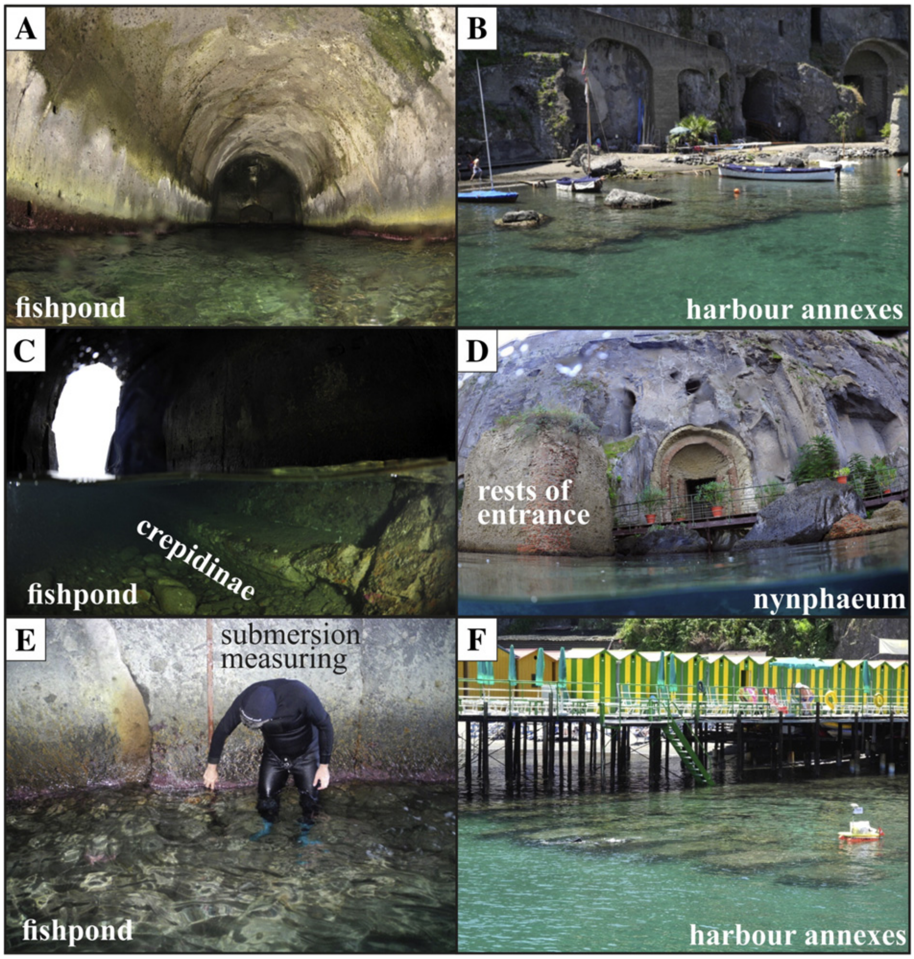

Fig. 8. Photos of archaeological structures in Sorrento Marina Grande: A) Fishpond entrance; B) Harbour annexes now submerged; C) Underwater photo of crepidinae; D) Nymphaeum entrance; E) Measurement of crepidinae submersion; F) Harbour annexes nowadays submerged.

4.2. Marine survey instruments

A seismo-stratigraphic survey is very useful to detect thin stratifications below the seabed as well as structures or artifacts buried by marine sediments. An EG&G Uniboom electromagnetic system and D-Seismic acquisition system (Mattei and Giordano, 2015) were used for this purpose. The resulting positional accuracies were ± 0.60 m (horizontal) and approximately ± 0.25 m (vertical). This is a high-resolution system and discriminates faces in the order of 0.25–0.30 m.

The Side Scan Sonar morphological system, on the other hand, performs the acoustic mapping of the seabed. This system identifies the remains lying on the seabed and the geo-morphological characterization of the substrate (Giordano, 1995). A GeoAcoustics dual-frequency (114/410 kHz) SSS system (MOD259) was used. The positional accuracy was ± 0.60 m. The SSS sonographs were interpreted and relevant targets were identified.

The bathymetric system is an Ohmex single beam echo-sounder optimized for shallow water which measures the depth with a centimetre precision. We used this system to measure the depth of archaeological remains. A Trimble DSM 232 GPS and an Ohmex SonarLite Single Beam Echo Sounder (SBES) were used, providing a positional accuracy of ± 0.6 m and depth accuracy of ± 0.025 m (route mean square, RMS). The depths referred to the vertical datum of mean sea level (MSL).

The MicroVeGA drone is an Open Project conceived, designed and built to operate in very shallow waters, where it is difficult for a traditional boat to manoeuvre. It was engineered by the DIST research group at the University of Naples and is designed to carry out morpho-bathymetric surveys in critical areas, especially in the presence of submerged archaeological structures (Giordano et al., 2016). The drone is a small and ultra-light catamaran (1.35 m length, 0.85 m width and 20 kg payload), with a few draught centimetres, and is therefore suitable for performing surveys up to the shoreline (Fig. 2). It is equipped with; two differential GPS systems; a single beam echo sounder; an integrated system for attitude control; an obstacle-detection system; and a video acquisition system (both above and below sea level). The data is stored on board in RAW format by a computerized system and is broadcast to the base station by a data link system in real time.

4.3. Correction of measurements

The submersion measurement of an archaeological marker (index point of the ancient sea level) is influenced by several factors; therefore, a specific methodology was used to correct the measurements.

In order to obtain the submersion with respect to the mean sea level (S), we corrected the measurement of the depth below sea level (Q) at which the archaeological structures were found with respect to the tide and the atmospheric pressure.

Measurements were corrected by the formula of Leoni and Dai Pra (1997):

$$S = Q + h_i + \Delta h_p \qquad (1)$$

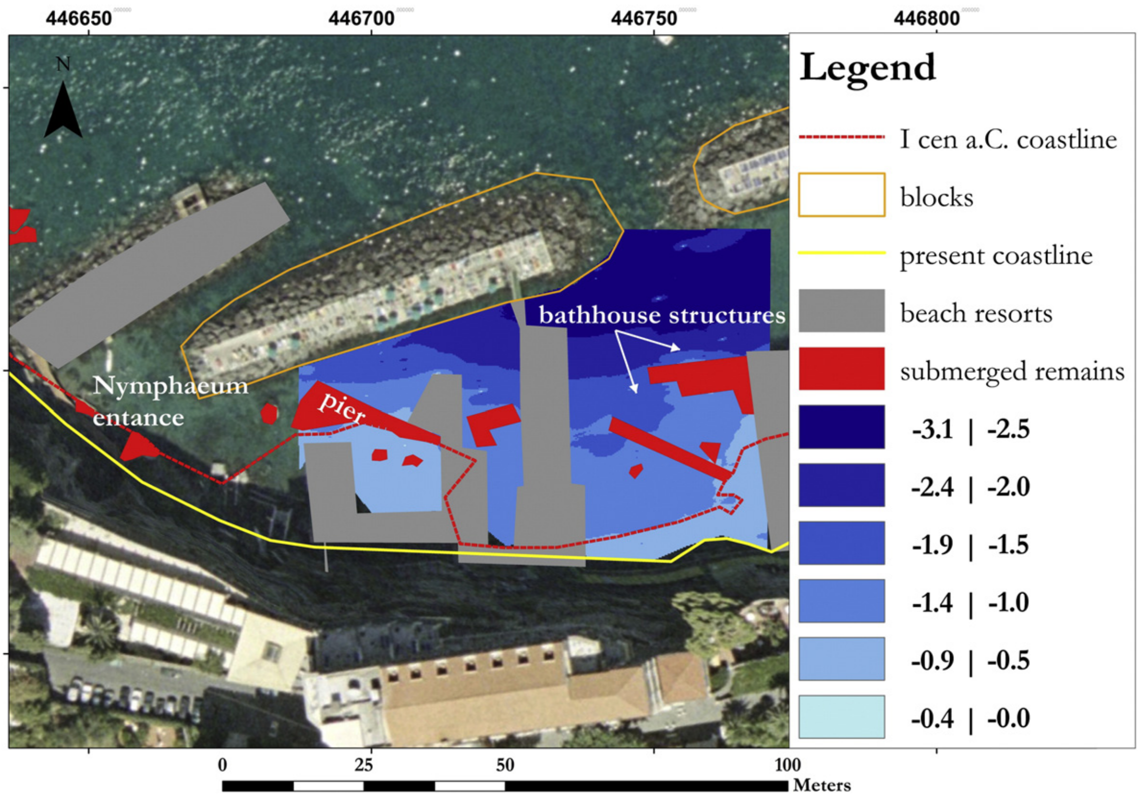

Fig. 9. Coastline evolution in Sorrento Marina Grande: 1st century BC. coastline (red dashed line) and present coastline (yellow line).

where, h_i is the tidal level at the time of measurement and Δh_p is the sea level barometric correction. Tidal height (h_i) was calculated by linear interpolation between the tide records of the two nearest ports (Naples and Salerno).

The functional height above or below sea level of the investigated archaeological target (Auriemma and Solinas, 2009; Morhange and Marriner, 2015) is important as it defines the minimum elevation of the structure above the highest local tides at the time of its construction. We estimated the specific functional height of each archaeological target taking into account the type of structure and its function, as described in the next section.

This kind of information always involves some uncertainty and the archaeological proxies used are sometimes badly preserved. The estimations given here for the sea level of the 1st cen A.C. are thus accompanied by an error margin which varies depending on local conditions, such as tidal range, and an additional measurement uncertainty depending on the kind and conditions of the markers used.

This approach enabled us to estimate the Roman sea level with respect to the investigated archaeo-markers (index points), thereby obtaining the relative sea level change (Δsl) (Fig. 3).

The relative sea level rise, Δsl in Eq. 2, was calculated taking into account:

S submersion of the archaeological marker, calculated by measuring the depth of the marker's upper part (less eroded);

E additional error due to the uncertainty regarding the conservation state of the archaeological ruins;

H functional height of the archaeological marker, evaluated by of the archaeological interpretation according to Auriemma and Solinas (2009);

$$\Delta sl = ((S - E) - H) \qquad (2)$$

The relative sea level rise has a variation range, as in Eq. 3, related to the three parameters (S, E and H), which defines the range of measurement error.

$$S - H_{max} < \Delta sl < (S - E_{max}) - H_{min} \qquad (3)$$

4.4. Archaeological markers of sea level rise

The northern sector of the Sorrento Peninsula preserves many Roman remains. Four archaeo-sites were selected as these were the best conserved and/or had the most reliable archaeological sea level markers which we used as index points.

The archaeological markers used were: a submerged pier, in Seiano and Capo di Sorrento sites, a hypogeal fishpond carved into the Sorrento tufa sea cliff, and a quay carved into the limestone sea cliff at the Punta Campanella site.

To study the sea level variation in Roman times, the best type of marker is the fishpond, which was used between the 1st century BC and the 1st century AD, according to Plinius and Varro (Lambeck et al., 2004a; Auriemma and Solinas, 2009). For the Sorrento fishpond, the upper *crepidinae* running along the inner basin, was analysed (Fig. 4B). As this part always had to be above the water level in order to guarantee maintenance, the submersion measurement was corrected with respect to the value of high tide in this area (0.30 m).

The harbour structures have a greater margin of error, both due to the state of preservation and the limited knowledge of the ancient heights - only hypothesized - compared to the ancient sea level (Auriemma and Solinas, 2009). The highest parts of two piers, at Seiano (Fig. 4A) and Capo di Sorrento (Fig. 5A) coastal sites and a quay (Fig. 5B), at Punta Campanella site, were used as index points. The correction in relation to the functional height in these cases took into account that

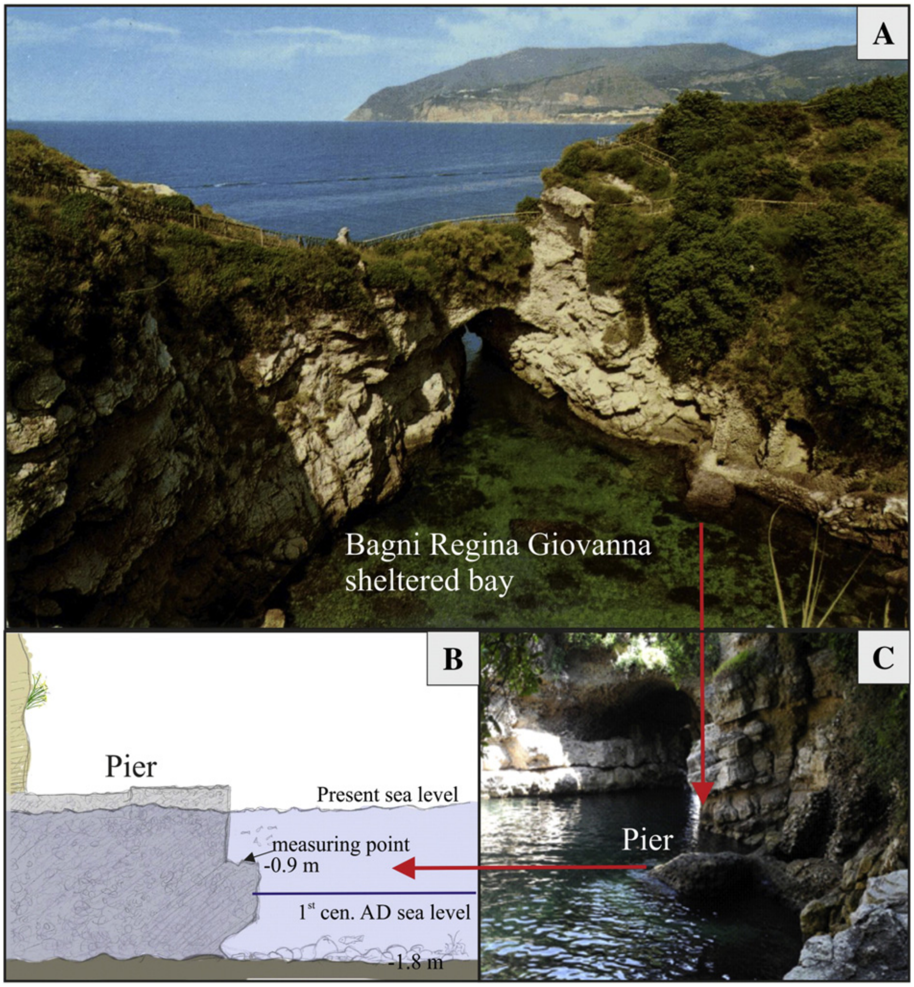

Fig. 10. A) Bagni Regina Giovanna sheltered bay; b) Reconstruction of the Capo di Sorrento submerged pier with submersion measures; C) Remains of the pier.

these landings were small, belonging to a residential unit where small boats would dock. These maritime annexes are very sensitive to low and high tides, in fact these structures were positioned on a very shallow seabed and rose from the ancient sea level by about 0.60 m (Janni, 1996; Auriemma and Solinas, 2009).

In the case of Seiano, the pier was partially buried by alluvial sediments post 79 CE and thus a typical functional height (0.60 m, Auriemma and Solinas, 2009) of a small pier was considered (Fig. 4A, Table 1).

In the Capo di Sorrento site, the seafloor depth was 1.8 m and the submersion of the pier at the top was 0.90 m. Based on the assumption that some wooden structure was probably built on this pier, a functional height of 0.30 m or less was presumed (Fig. 5A, Table 1). In fact, a minimum ancient depth of 0.60 m must be considered, in order to permit the landing of small boats in the inner basin.

In the case of Punta Campanella, a horizontal groove (Fig. 5B), probably used as a guide for a wooden superstructure was located 0.10 m above the quay, carved into the limestone cliff. Consequently, the submersion of the quay (−0.60 m) was added to this value (0.10 m) before considering the functional height (0.60 m).

5. Results

5.1. Pezzolo villa

The first site is the Pezzolo pocket beach in Marina di Seiano, where a patrician villa (Mingazzini, 1946), was built at the mouth of the Rivo d'Arco (Fig. 6A, B). The ruins belong to three different building phases. The villa was first built at the beginning of the 1st cen. BC which was then damaged by the Vesuvius eruption in 79 CE and almost totally buried by the subsequent alluvial events which aggraded the coastal plain with meters of debris flow and hyperconcentrated flow deposits (reworked pyroclastics of the same eruption) also leading to the coastline advancing considerably (Cinque and Robustelli, 2009). The villa was then re-built on top of the alluvial deposits during the 2nd century AD, (suggesting that the alluvial crisis had finished). The third building phase, probably in the 3rd century, took place when the site became once again unstable, however for a different reason. The retreat of the sea cliff was destroying the coastal alluvial body and the resulting sea cliff came close to the villa itself. This meant that structures had to be reinforced, such as an inclined tunnel as a new sat down from the house to the beach and robust walls against the sea cliff.

The marine geophysical survey off Pezzolo villa ruins provided substantial morphological information regarding the submerged archaeological remains occurring in the area, on the geomorphology of the bottom, and the stratigraphy of the 20 m sub-bottom.

As a result, the GIS overlay of all the geoarchaeological datasets confirmed the presence of a Roman harbour related to the Pezzolo villa and enabled the spatial distribution of the related maritime annexes to be identified (Aucelli et al., 2016).

Fig. 6D illustrates the archaeological targets localized by SSS interpretations. A close inspection (Fig. 6B) confirmed the presence of two piers (T13 and T14 in Fig. 6D) and several defence structures (*pilae*) (T03, T12, T2, T4 in Fig. 6D). The seismic profiles (Sangree and

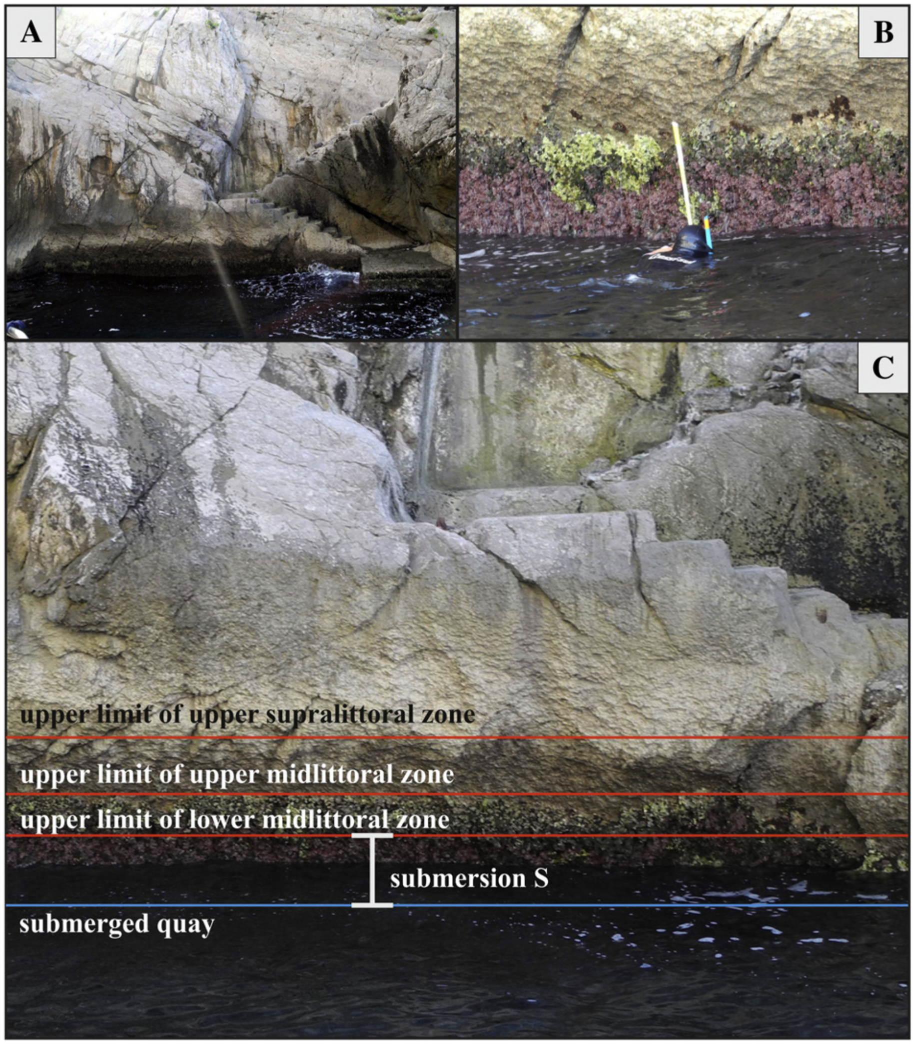

Fig. 11. The western landing of Punta Campanella: A) Western landing of Roman villa; B) submersion measurement of the Roman quay; C) limits of littoral zones.

Widmier, 1978; Giordano, 2010) highlighted the superficial layer of 0.8 ms (about of 1.2 m) burying, or partially burying, several archaeological structures. This acoustic facies was interpreted as alluvial deposits post 79 CE which buried the Roman villa and prograded the coastline by some hundred metres.

However, the submersion of the harbour annexes to the villa, localized by our geoarchaeological investigations (Aucelli et al., 2016), revealed that the sea level rise on this site was up to 1.60 ± 0.50 m. This measurement was obtained using the submersion value of the upper part of T13 target (the least eroded pier) as an archaeological marker

Table 2
Sea level rise parameters evaluated at the four sites.

Parameters	Archaeological sites			
	Seiano	Sorrento	Capo di Sorrento	Punta Campanella
S	−1.00 m	0.80 m	0.90 m	0.50 m
E	>0 m	0–0.05 m	>0 m	0–0.05 m
H	0.6 0 m	0.30 m	0.30 m	0.60 m
Δsl	−1.60 ± 0.50 m	1.10 ± 0.30 m	1.20 ± 0.30 m	1.10 ± 0.30 m
Substrate	Soft sediments	Tuff welded hard	Limestone	Limestone

of SLR, adding the functional height typical of a small Roman pier (Auriemma and Solinas, 2009). The uncertainty of this measurement is due to the poor conditions of the archaeological remains, partially destroyed by the alluvial events.

By overlaying the bathymetric and archaeological data, the position of the coastline at the moment of the villa construction in the1st cen AD was obtained (Fig. 7).

5.2. Sorrento Marina Grande

The Agrippa Posthumus villa, in Sorrento Marina Grande (Mingazzini, 1946; Russo, 2006), is an imperial Roman villa of considerable size, including a domus above the local sea cliff and a seaside sector composed of elements sculptured in the cliff forming tuff, as well as two nymphaea (Fig. 8D) and a large fishpond (Fig. 8A, B, C) plus harbour annexes and also pavilions, bridges and terraces made in wood (Fig. 9B and F).

The ruins of the harbour annexes, which today are submerged and partially eroded, consist of a series of concrete blocks.

In this site, we carried out a morpho-bathymetric survey, by means of a MicroVeGA drone in the nearshore area between 0 and 3 m of depth, in order to measure the archaeological marker submersion and to reconstruct the seabed morphology.

The recent evolution of this coastal sector has been influenced both by human actions and by the glacio-isostatic sea level rise. Here the submersion measure of the upper *crepidinae* in the fishpond (−0.80 m) led to an evaluation of 1.1 ± 0.30 m if the sea level rise occurring in the last 2000 years, while the geophysical and geomorphological investigations led to the reconstruction of the 1st century BC coastline. The change in coastline position and shape are shown in Fig. 9.

5.3. Capo di Sorrento villa

The imperial villa of Capo di Sorrento is located on a steep rocky coast, with limestone sea cliffs.

This villa was built in the 1st cen. AD. and was partially rebuilt after the 79 CE eruption, because the pumice deposits buried the floors (Russo, 2006). The villa included three landings, one within a very sheltered small bay Bagni Regina Giovanna, Fig. 11A) and two outside of it. The outside landings were destroyed by the waves, while the internal landing is still recognizable. In fact, immediately after entering the sheltered bay, now there is a partially destroyed pier (Fig. 10C).

The archaeological marker used to reconstruct the Roman sea level was the top of a partially-eroded pier measured at the point of minimum erosion (Fig. 10B). The measurement taken on this site was 1.20 ± 0.30 m. There has been no visible erosional retreat in the last 2000 years.

5.4. Punta Campanella Villa

The fourth site is the imperial villa of Punta Campanella which was erected by Augustus as the bridgehead to the Isle of Capri (Mingazzini, 1946). This villa had two landing places. The eastern landing has been partially destroyed, the western one is still perfectly preserved and nestles into the limestone cliff (Fig. 11A). We studied this landing structure using a direct survey with graduated stadia (Fig. 11B). We measured the top of the quay. Considering a functional height at 0.60 above water (Auriemma and Solinas, 2009), a sea level at 1.10 ± 0.30 m can be inferred.

The methodology used to calculate the submersion of the quay in this site is particular because of there is usually a strong undertow. In fact, we used the upper limit of the lower mid-littoral zone as the mean sea level at the time of measuring (Giaccone et al., 1993), and calculated the distance between this limit and the underwater quay as the value of submersion S (Fig. 11C).

6. Discussion

The measurements carried out in the four sites of the Sorrento Peninsula provided an evaluation of the sea level rise since the first century BC but also enabled us to reconstruct the planar modifications of the coastline. The first study site, the Pezzolo villa in the pocket beaches of Marina di Seiano, has an evolutionary history that is closely linked to the eruption of Vesuvius in 79 CE and the flooding associated with it. The geoarchaeological study of the site led to the positioning of the villa harbour which is now submerged (Aucelli et al., 2016). Also, the integration of geophysical and archaeological data highlighted the coastline position and the sea level rise in the last 2000 years, totalling 1.60 ± 0.50 m. By comparing this measure with the predicted sea-level curve of Lambeck et al., 2011, the difference of 0.50 m is probably due both to the poor conditions of the identified piers (which were partially destroyed by flooding) and to the compaction of loose sediments constituting their foundation (Aucelli et al., 2016).

The second site studied was the Imperial villa of Agrippa Posthumus in Marina Grande in Sorrento, built on top and into the tufa sea cliff. Maritime facilities include a Nymphaea and a fishpond system, as well as a number of facilities now submerged such as piers and docks. The recent evolution of this site has been influenced both by human actions and by the glacial-isostatic rising of the sea level. The integration of archaeological data, the morpho-bathymetric surveys and the submersion measuring at the top of the upper *crepidinae* in the fishpond, have enabled the I cen. a.C. coastline to be reconstructed and to evaluate the sea level rise in the last 2000 years as 1.10 ± 0.30 m, according to the modelled values (Lambeck et al., 2011). Finally, through the geoarchaeological study, the retreat of the coastal cliff was evaluated; in fact the distance between the partially destroyed Nymphaea entrance and the present-day sea cliff, highlights a retreat rate of 7.5 mm/year (about 15 m in total).

The other two sites of Capo di Sorrento and Punta Campanella are located on a steep rocky coast with limestone cliff, with an inappreciable retreat in the last 2000 years.

The Imperial Villa of Capo di Sorrento was partially destroyed by the eruption of 79 CE and the eruptive products covered its floors. Thus the *domus* was rebuilt on top of these ruins. The measurements at the top of the pier of the small landing within the protected bay of Capo di Sorrento highlighted a sea level rise in this site of 1.20 ± 0.30 m. The difference between the predicted sea-level value of Lambeck et al. (2011) and the measurement is about of 0.10 m, probably due to the poor conditions of the identified piers, which have been partially destroyed.

In the Punta Campanella Imperial villa, the investigation focused on the western harbour characterized by a perfectly preserved quay nestled into the limestone sea cliff. Here, the submersion of the top was measured and corrected with respect to the functional height, highlighting a sea level rise over the past 2000 years of 1.10 ± 0.30 m, which matched perfectly with the theoretical model here used (Lambeck et al., 2011).

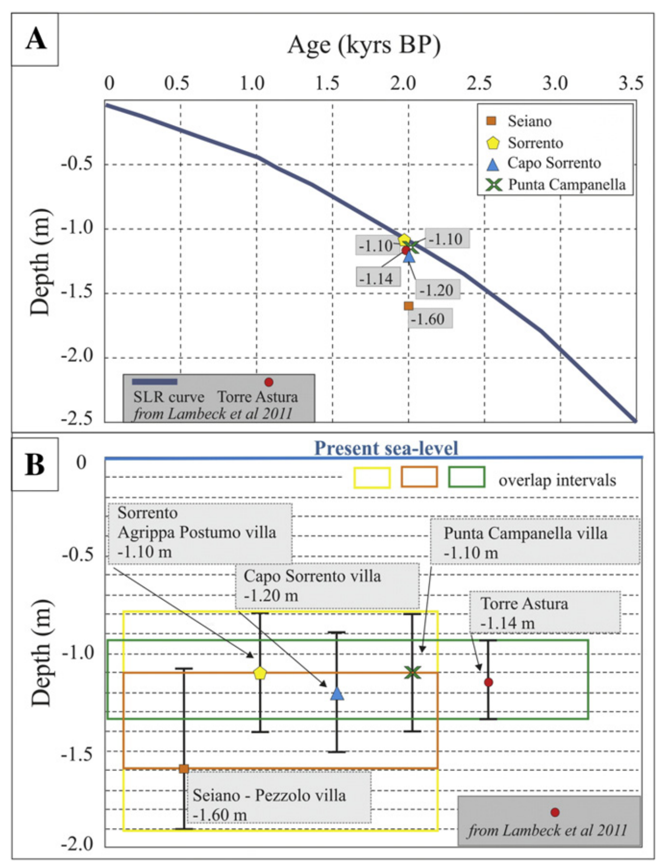

Fig. 12. A) Submersion measurements of the sites compared to the curve of predicted altitude in the last 2.5 ky (blue line, Lambeck et al., 2011 modified) of the Torre Astura tectonically stable site and the measured submersion value in this site (Lambeck et al., 2004a, 2004b; Lambeck et al., 2011); B) Submersion measures of the Sorrento Peninsula sites with an error bar, taking into account the uncertainty of the measurements.

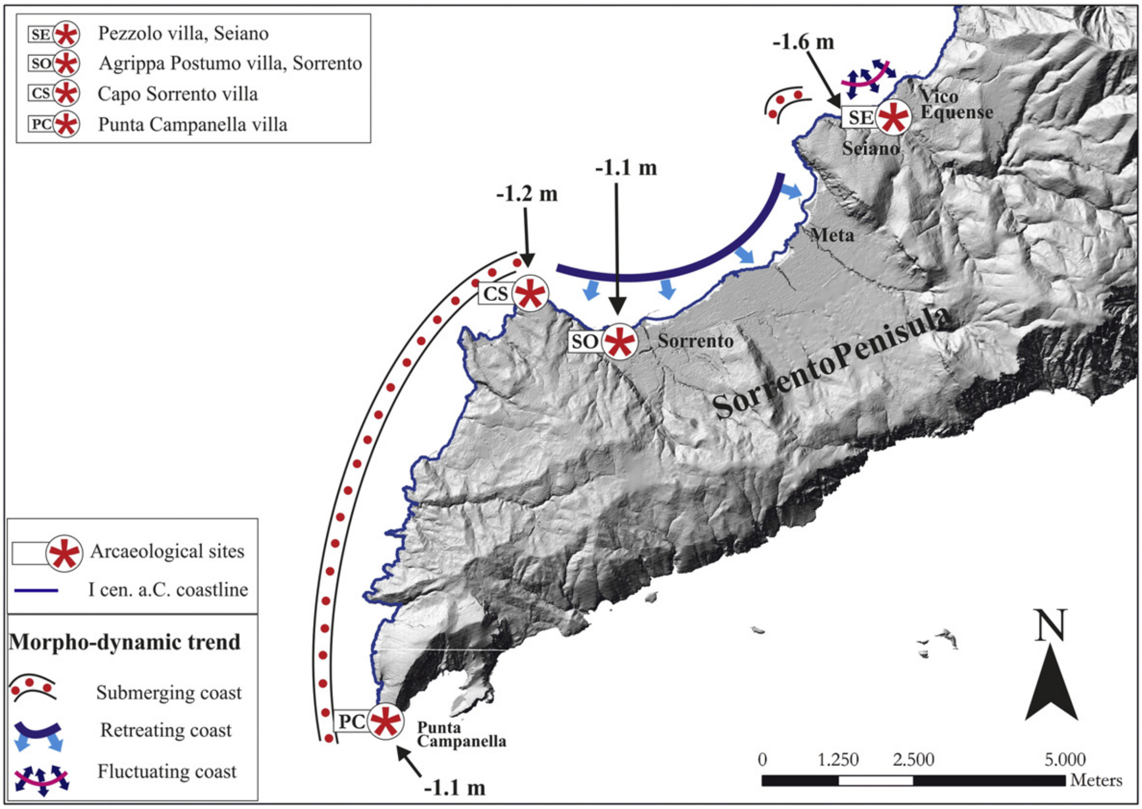

Fig. 13. Morpho-dynamic trends of the northern sector of Sorrento Peninsula coastline over the last 2000 years.

The measurements taken at four geoarchaeological sites of the Sorrento Peninsula give different values for the relative sea level rise occurring there since the 1st century AD (Table 2).

Each measurement involves an uncertainty due to both the state of preservation of the measured archaeological proxy and uncertainties regarding its original elevation (Auriemma and Solinas, 2009).

As shown in Fig. 12, a comparison of all the measurements taken (Fig. 12B) and a comparison with a tectonically stable site of the Tyrrhenian coast of Italy (Torre Astura, with a well preserved Roman fishpond, Lambeck et al., 2004a, 2011) and with the eustatic model of Lambeck et al. (2011) (Fig. 12A), highlights that those deriving from the best preserved ruins (Sorrento fishpond and Punta Campanella quay) match almost perfectly the value obtained at Torre Astura, especially if the tidal fluctuation of ± 0.30 m is considered.

As to the fluctuation of the coastline over the last 2000 years, there are a few meters of cliff retreat at Sorrento, an inappreciable change on the plunging cliff in hard limestone of Punta Campanella end Capo di Sorrento and, finally, great fluctuations at Seiano site, where the coastal dynamics were greatly influenced by the alluvial events following the eruption in 79 CE (Fig. 13).

7. Conclusions

The geoarchaeological study of the northern sector of the Sorrento Peninsula, in the Gulf of Naples, made it possible to reconstruct and interpret the historical coastal landscape, in terms of the interaction between endogenous and exogenous factors, such as volcanic eruptions, floods, coastal erosion, and the human settlement of coast.

The historical evolution of this coastal sector has been influenced by sea level rises due to the glacio-hydro-isostatic effect (sensu Lambeck et al., 2011) and wave erosion, which have led to the submersion and retreat of the coast. Locally, this trend has been influenced by pyroclastic fallout related to the 79 CE eruption of Vesuvius (Fig. 13).

While along the limestone high coasts the submersion has not produced significant morphological changes, along the tuff sea cliff this submersion has been accompanied by sea cliff pure retreat, reaching a maximum value of 15 m (corresponding to a rate of 7.5 mm/y).

Along the pocket beaches alternating with the high rocky coast on the other hand, the abovementioned submersion has probably not always led to a retreating coastline. In fact in the case of Seiano, the fluvial inputs with high sediment load following the 79 CE eruption, advanced the coastline >200 m but only for several decades. Due to the wave erosion the coastline quickly retreated to the original position.

Finally in this study, for the first time, the northern sector of the Sorrento Peninsula was studied in order to evaluate the relative sea level rise in the last two millennia, and the obtained data confirm a substantial stability in terms of regional tectonics. This behaviour started many thousands of years ago, not later than the Last Interglacial (Brancaccio et al., 1978; Cinque and Romano, 1990; Riccio et al., 2001; Ferranti et al., 2006; Iannace et al., 2015), in contrast to the adjacent depression of the Gulf of Naples which is subsiding at rates of 1 or more mm per year (Milia and Torrente, 2015). However, immediately north of the stable Sorrento Peninsula there are the subsiding sectors including the Sarno R. plain, Vesuvian and Neapolitan coasts. The subsidence has been proved on land by the lowered Roman beaches of ancient *Neapolis* (Romano et al., 2013), *Pompeii* (Cinque and Romano, 1990; Pescatore et al., 2001) and *Herculaneum* (at about 4 m b.s.l. from Cinque and Irollo, 2008) and, in the Gulf, by the anomalous position of the shelf break (between 140 and 180 m b.s.l., from Milia et al., 2003).

Acknowledgements

The authors would like to thank Professor Francesco Giordano for his invaluable help during the marine surveys and interpretations of the geophysical data, Dr. Mario Russo for the archaeological interpretations, and Prof. Fulvio Russo for the biological interpretations. Sincere thanks are also due to Luigi De Luca, Alberto Giordano and Francesco Peluso for their valuable support during the marine surveys.

The authors gratefully acknowledge the two anonymous reviewers for their critical reviews which greatly improved the manuscript.

References

Aiello, G., Budillon, V., Cristofalo, G., D'Argenio, B., De Alteriis, G., De Lauro, M., Ferraro, L., Marsella, E., Pelosi, N., Sacchi, M., Tonielli, R., 2001. Marine geology and morphobathymetry in the bay of Naples (South-eastern Tyrrhenian Sea, Italy). In: Faranda, F.M., Letterio, G., G., S. (Eds.), Mediterranean Ecosystems 2001. Springer Milan, pp. 1–8.

Antonioli, F., Anzidei, M., Lambeck, K., Auriemma, R., Gaddi, D., Furlani, S., Orrù, P., Solinas, E., Gaspari, A., Karinja, S., Kovačić, V., Surace, L., 2007. Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data. Quat. Sci. Rev. 26 (19), 2463–2486.

Antonioli, F., Ferranti, L., Fontana, A., Amorosi, A., Bondesan, A., Braitenberg, C., Dutton, A., Fontolan, G., Furlani, S., Lambeck, K., Mastronuzzi, G., Monaco, C., Spada, G., Stocchi, P., 2009. Holocene relative sea-level changes and vertical movements along the Italian and Istrian coastlines. Quat. Int. 206 (1), 102–133.

Anzidei, M., Antonioli, F., Benini, A., Lambeck, K., Sivan, D., Serpelloni, E., Stocchi, P., 2011. Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. Quat. Int. 232 (1), 13–20.

Aucelli, P., Cinque, A., Giordano, F., Mattei, G., 2016. A geoarchaeological survey of the marine extension of the roman archaeological site villa del Pezzolo, Vico Equense, on the Sorrento Peninsula, Italy. Geoarchaeology 31 (3), 244–252.

Auriemma, R., Solinas, E., 2009. Archaeological remains as sea level change markers: a review. Quat. Int. 206 (1), 134–146.

Brancaccio, L., Capaldi, G., Cinque, A., Pece, R., Sgrosso, I., 1978. Th-U dating of corals from a Tyrrhenian Beach in Sorrentine Peninsula (Southern Italy). Quaternaria. Storia Naturale e Culturale del Quaternario 20, 175–183.

Brancaccio, L., Cinque, A., Romano, P., Rosskopf, C., Russo, F., Santo, A., Santangelo, N., 1991. Geomorphology and neotectonic evolution of a sector of the Tyrrhenian flank of the Southern Apennines, (Region of Naples, Italy). Zeit. Geo morph., N.F., Suppl. Bd. 82, 47–58.

Brancaccio, L., Cinque, A., Romano, P., Rosskopf, C., Russo, F., Santangelo, N., 1995. L'evoluzione delle pianure costiere della Campania: geomorfologia e neotettonica. Assetto fisico e problemi ambientali delle pianure italiane, Memorie della Società Geografica Italiana, LIII, In, pp. 313–336.

Carannante, G., Ruberti, D., Sirna, M., 2000. Upper Cretaceous ramp limestones from the Sorrento Peninsula (southern Apennines, Italy): micro-and macrofossil associations and their significance in the depositional sequences. Sediment. Geol. 132 (1), 89–123.

Casciello, E., Cesarano, M., Pappone, G., 2006. Extensional detachment faulting on the tyrrhenian margin of the southern Apennines contractional belt (Italy). J. Geol. Soc. Lond. 163, 617–629.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., ... Payne, A.J., 2013. Sea Level Change. PM Cambridge University Press.

Cinque, A., 1986. Guida alle escursioni geomorfologiche (Penisola Sorrenrina, Capri, Piana del Sele e Monti Picentini). Riunione annuale Gr. Naz. Geogr. Fis. Geomorf., Amalfi, Pubbl. n. 33. del Dip. Scienze della Terra, Univ. di Napoli (119 pp.)

Cinque, A., 1991. La trasgressione versiliana nella Piana del Sarno (Campania). Geogr. Fis. Din. Quat. 14, 63–71.

Cinque, A., Irollo, G., 2008. La paleogeografia dell'antica Herculaneum e le fluttuazioni, di origine bradisismica, della sua linea di costa, Atti del Convegno Internazionale Nuove Ricerche Archeologiche nell'area Vesuviana (Scavi 2003-2006), Roma. pp. 425–438.

Cinque, A., Robustelli, G., 2009. Alluvial and Coastal Hazards Caused by Long-range Effects of Plinian Eruptions: The Case of the Lattari Mts. After the A.D. 79 eruption of Vesuvius. Geological Society, London, Special Publications, pp. 155–171.

Cinque, A., Romano, P., 1990. Segnalazione di nuove evidenze di antiche linee di riva in Penisola Sorrentina (Campania). Geogr. Fis. Din. Quat. 13, 23–36.

Cinque, A., Patacca, E., Scandone, P., Tozzi, M., 1993. Quaternary kinematic evolution of the Southern Apennines. Relationships between surface geological features and deep lithospheric structures. Ann. Geofis. 36, 249–259.

Cinque, A., Aucelli, P.P.C., Brancaccio, L., Mele, R., Milia, A., Robustelli, G., Romano, P., Russo, F., Russo, M., Santangelo, N., Sgambati, D., 1997. Volcanism, tectonics and recent geomorphological change in the Bay of Napoli. 4th Int. Conf. on Geomorph. — Italy 1997, Guide for the Excursion, Suppl. Geogr. Fis. Din. Quat. suppl III, t. 2, pp. 123–141.

Cinque, A., Robustelli, G., Russo, M., 2000. The consequences of pyroclastic fallout on the dynamics of mountain catchments: geomorphic events in the Rivo d'Arco basin (Sorrento peninsula, Italy) after the plinian eruption of Vesuvius in the 79 AD. Geogr. Fis. Din. Quat. 23, 117–129.

Cinque, A., Irollo, G., Romano, P., Ruello, M.R., Amato, L., Giampaola, D., 2011. Ground movements and sea level changes in urban areas: 5000 years of geological and archaeological record from Naples (Southern Italy). Quat. Int. 232 (1), 45–55.

D'Argenio, B., Barattolo, F., Budillon, F., Cesarano, M., Donadio, C., Pappone, G., Pugliese, A., Putignano, M.L., Aucelli, P.P.C., Russo Ermolli, E., Sgrosso, A., Terlizzi, F., Ferrari, G., Lamagna, R., 2012. Carta Geologica della Regione Campania, Note Illustrative della Carta Geologica alla scala 1: 10.000, Foglio 484 Isola di Capri, Regione Campania-Assessorato Difesa del Suolo.

Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orru, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of the last interglacial sea-level high stand along the coast of Italy: tectonic implications. Quat. Int. 145, 30–54.

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. J. Virtual Explor. 36 (Paper 30).

Flemming, N.C., 1969. Archaeological evidence for eustatic change of sea level and earth movements in the Western Mediterranean in the last 2000 years. Geol. Soc. Am. Spec. Pap. 109, 125.

Flemming, N.C., Webb, C.O., 1986. Tectonic and eustatic coastal changes during the last 10,000 years derived from archeological data. Zeitschrift für Geomorphologie NF 62, 1–29.

Giaccone, G., Alongi, G., Cossu, A.V.L., Di Geronimo, R., Serio, D., 1993. La Vegetazione marina bentonica nel Mediterraneo sopralitorale e mesolitorale: proposte di aggiornamento. Bollettino dell'Accademia Gioenia di scienze naturali 26 (341), 245–291.

Giordano, F., 1995. Marine geophysical methods for archaeological investigation of volcanic and bradyseismic areas. Ann. Geofis. XXXVIII, 5–6.

Giordano F. 2010. Metodi Geofisici per l'Archeologia Subacquea, Gaia. (ISBN 978-88-89821-72-5).

Giordano, F., Mattei, G., Parente, C., Peluso, F., Santamaria, R., 2015. MicroVeGA (micro vessel for geodetics application: a marine drone for the acquisition of bathymetric data for GIS applications. 1. ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, pp. 123–130.

Giordano, F., Mattei, G., Parente, C., Peluso, F., Santamaria, R., 2016. Integrating sensors into a marine drone for bathymetric 3D surveys in shallow waters. Sensors 16 (1), 249–269.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Glob. Planet. Chang. 63 (2), 90–104.

Hearty, P.J., 1986. An inventory of last interglacial (sensu lato) age deposits from the Mediterranean Basin: a study of isoleucine epimerization and U-series dating. Z. Geomorph. N. F., Suppl. 62, 51–69.

Iannace, A., Merola, D., Perrone, V., Amato, A., Cinque, A., Santacroce, R., Sbrana, A., Sulpizio, R., Budillon, F., Conforti, A., D'Argenio, B., 2015. Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000 fogli 466–485 Sorrento-Termini.

Janni, P., 1996. Il mare degli Antichi (Bari).

Lambeck, K., Chappell, J., 2001. Sea-level change during the last glacial cycle. Science 292, 679–686.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., Esposito, A., 2004a. Sea level in Roman time in the Central Mediterranean and implication for recent change. Earth Planet. Sci. Lett. 224, 563–575.

Lambeck, K., Antonioli, F., Purcell, A., Silenzi, S., 2004b. Sea-level change along the Italian coast for the past 10,000 yr. Quat. Sci. Rev. 23 (14), 1567–1598.

Lambeck, K., Antonioli, F., Anzidei, M., Ferranti, L., Leoni, G., Scicchitano, G., Silenzi, S., 2011. Sea level change along the Italian coast during the Holocene and projections for the future. Quat. Int. 232 (1), 250–257.

Leoni, G., Dai Pra, G., 1997. Variazioni del livello del mare nel tardo olocene (ultimi 2500 anni) lungo la costa del Lazio in base ad indicatori geo-archeologici. Interazioni fra neotettonica, eustatismo e clima. ENEA, Dipartimento Ambiente, Centro Ricerche Casaccia, Roma (RT/AMB/97/8).

Lundberg, J., Ford, D.C., 1990. Late Pleistocene sea level change in the Bahamas from mass spectrometric U-series dating of submerged speleothem. Quat. Sci. Rev. 13, 1–14.

Mattei, G., 2016. Ricostruzione del paesaggio costiero in epoca Romana nel Golfo di Napoli: valutazione e interpretazione sulla base di indagini geoarcheologiche integrate (PhD Thesis).

Mattei, G., Giordano, F., 2015. Integrated geophysical research of Bourbonic shipwrecks sunk in the Gulf of Naples in 1799. J. Archaeol. Sci. Rep. 1, 64–72.

Milia, A., Torrente, M.M., 2015. Tectono-stratigraphic signature of a rapid multistage subsiding rift basin in the Tyrrhenian-Apennine hinge zone (Italy): a possible interaction of upper plate with subducting slab. J. Geodyn. 86, 42–60.

Milia, A., Torrente, M.M., Russo, M., Zuppetta, A., 2003. Tectonics and crustal structure of the Campania continental margin: relationships with volcanism. Mineral. Petrol. 79 (1–2), 33–47.

Milia, A., Torrente, M.M., Massa, B., Iannace, P., 2013. Progressive changes in rifting directions in the Campania margin (Italy): new constrains for the Tyrrhenian Sea opening. Glob. Planet. Chang. 109, 3–17.

Mingazzini, P., 1946. Forma Italiae: Latium et Campania. De Luca Ed, Surrentum.

Morhange, C., Marriner, N., 2015. Archaeological and biological relative sea-level indicators. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), Handbook of Sea-Level Research. Wiley, pp. 146–156.

Morhange, C., Marriner, N., Laborel, J., Todesco, M., Oberlin, C., 2006. Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean fields caldera, Italy. Geology 34 (2), 93–96.

Mush, D.R., Kennedy, G.L., Rockwell, T.K., 1994. Uranium-series ages of marine terrace corals from the Pacific coast of North America and implications for the last-interglacial sea level history. Quat. Res. 42, 72–87.

Pappone, G., Casciello, E., Cesarano, M., D'Argenio, B., Conforti, A., Russo, F., Esposito, E., Porfido, S., Perriello, Z.S., Violante, C., Conforti, A., Sacchi, M., 2010. Note Illustrative della Carta Geologica d'Italia alla scala 1: 50000, Foglio 467 Salerno, Regione Campania-Assessorato Difesa del Suolo.

Pappone, G., Alberico, I., Amato, V., Aucelli, P.P.C., Di Paola, G., 2011. Recent evolution and the present-day conditions of the Campanian Coastal plains (South Italy): the case history of the Sele River Coastal plain. WIT Trans. Ecol. Environ. 149, 15–27.

Passaro, S., Barra, M., Saggiomo, R., Di Giacomo, S., Leotta, A., Uhlen, H., Mazzola, S., 2013. Multi-resolution morpho-bathymetric survey results at the Pozzuoli–Baia underwater archaeological site (Naples, Italy). J. Archaeol. Sci. 40 (2), 1268–1278.

Pescatore, T., Senatore, M.R., Capretto, G., Lerro, G., 2001. Holocene coastal environments near Pompeii before the A.D. 79 eruption of Mount Vesuvius, Italy. Quat. Res. 55, 77–85.

Pirazzoli, P.A., 1997. Sea-level changes: the last 20,000 years. Oceanogr. Lit. Rev. 8 (44), 785.

Potter, E.K., Lambeck, K., 2004. Reconciliation of sea-level observations in the Western North Atlantic during the last glacial cycle. Earth Planet. Sci. Lett. 217 (1), 171–181.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. Science 315 (5810), 368–370.

Riccio, A., Riggio, F., Romano, P., 2001. Sea level fluctuations during oxygen isotope stage 5: new data from fossil shorelines in the Sorrento Peninsula (Southern Italy). Z. Geomorphol. 121–137.

Romano, P., 1992. La distribuzione dei depositi marini pleistocenici lungo le coste della Campania: stato delle conoscenze e prospettive di ricerca. Studi Geol. Camerti 1, 265–269.

Romano, P., Di Vito, M.A., Giampaola, D., Cinque, A., Bartoli, C., Boenzi, G., ... Liuzza, V., 2013. Intersection of exogenous, endogenous and anthropogenic factors in the Holocene landscape: a study of the Naples coastline during the last 6000 years. Quat. Int. 303, 107–119.

Russo, M., 2006. La villa romana di Capo di Sorrento. In: Memoria, S.I.e., Fiorentino, G. (Eds.), Percorsi di cultura e arti visive.

Sangree, J.B., Widmier, J.M., 1978. Seismic stratigraphy and global changes of sea level, part 9: seismic interpretation of clastic depositional facies. AAPG Bull. 62 (5), 752–771.

Santacroce, R., Cioni, R., Marianelli, P., Sbrana, A., Sulpizio, R., Zanchetta, G., ... Joron, J.L., 2008. Age and whole rock–glass compositions of proximal pyroclastics from the major explosive eruptions of Somma-Vesuvius: a review as a tool for distal tephrostratigraphy. J. Volcanol. Geotherm. Res. 177 (1), 1–18.

Schmiedt, G., Caputo, M., 1972. Il livello antico del Mar Tirreno: testimonianze dei resti archeologici. Olschki, Firenze.

Shackleton, N.J., Opdyke, N.D., 1973. Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen irotope temperatures and ice volumes on a 10^5 Years and 10^6 Years scale. Quat. Res. 3, 39–55.

Shackleton, N.J., Sánchez-Goñi, M.F., Pailler, D., Lancelot, Y., 2003. Marine isotope substage 5e and the Eemian interglacial. Glob. Planet. Chang. 36 (3), 151–155.

Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I., Smeed, D.A., 2003. Sea-level fluctuations during the last glacial cycle. Nature 423 (6942), 853–858.

Sigurdsson, H., Cashdollar, S., Sparks, S.R.J., 1982. The eruption of Vesuvius in AD 79: reconstruction from historical and volcanological evidence. Am. J. Archaeol. 1982, 39–51.

Ulzega, A., Hearty, P.J., 1986. Geomorphology, stratigraphy and geochronology of late Quaternary marine deposits in Sardinia. Z. Geomorph. N. F. Suppl. 62, 119–129.

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A., Rovere, A., 2016. Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: sea-level variability and improvements in the definition of the isostatic signal. Earth Sci. Rev. 155, 172–197.

Vacher, H.L., Hearty, P.J., 1989. History of stage 5 sea level in Bermuda: review with new evidence of a brief rise to present sea level during substage 5a. Quat. Sci. Rev. 8, 159–168.

Vogel, S., Maerker, M., 2010. Reconstructing the Roman topography and environmental features of the Sarno River Plain (Italy) before the AD 79 eruption of Somma–Vesuvius. Geomorphology 115, 67–77.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., Lambeck, K., McManus, J.F., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quat. Sci. Rev. 21, 295–305.