Rendiconti Lincei. Scienze Fisiche e Naturali
https://doi.org/10.1007/s12210-018-0715-6

SATELLITE POSITIONING FOR GEOSCIENCES

Tyrrhenian sea level at 2000 BP: evidence from Roman age fish tanks and their geological calibration

Kurt Lambeck[1,2] · Marco Anzidei[3] · Fabrizio Antonioli[4] · Alessandra Benini[5] · Vladimiro Verrubbi[4]

Received: 16 October 2017 / Accepted: 10 May 2018

Abstract

Following the pioneering work of Schmiedt et al. (1972) on establishing the level of the Tyrrhenian Sea in Antiquity, a number of studies have examined this evidence from Roman Period fish tanks but with significantly different outcomes due primarily to different interpretations of the functional level of these pools at the time of their construction. As part of a longer term project to understand the causes of sea-level change around the Italian coast, we have reexamined and resurveyed 12 well-documented fish tanks, all based on the same construction principles, from the Tyrrhenian coast (between Formia and Orbetello) for which it can be established that they were in open contact with the sea at the time of operation. The structural features that tidally control the exchange of water used to define the ancient local sea level are identified as the channel thresholds, the sluice gate and sliding post positions, and the lowest level crepido. These are consistent for all the tanks examined, permitting the local sea-level change over the past 2000 years to be established at each location with a precision of ± 20 cm and against which other coastal archaeological features can be calibrated. We conclude that published local sea levels that are based on the present-day elevations of the foundations of protective walls constructed around the tanks and lie ~ 50 cm above our inferred levels are inconsistent with the successful functioning of the water exchange and have to be rejected. In one case, for Santa Liberata, we have been able to calibrate our interpretation against sedimentary evidence from the nearby Orbetello Lagoon that confirm our interpretation of the functional control level of the tanks and we conclude that the accuracy of our local sea levels is also ± 20 cm. The causes of sea-level change along this section of the coast are several, including land motion driven by tectonic and glacio-isostatic processes and any change in ocean volume. The individual estimates for the observed local sea levels range from − 0.9 to − 1.5 m with a mean value of − 1.22 ± 0.20 m. These values show that the spatial variability of the local levels is small and consistent with model-inferences of the glacio-isostatic process that indicate near-constant contributions for this section of coast and with tectonic inference from the elevations of the Last Interglacial shoreline.

Keywords Mediterranean · Roman Period · Sea-level change

1 Introduction

One of many important questions about climate change is whether the present-day observed trends, recorded instrumentally in indicators such as global atmospheric temperature and sea level, can be extrapolated securely both back into the past and forward into the future. After all, if

This contribution is the written, peer-reviewed version of a paper presented at the Conference "Satellite Geodetic Positioning for Geosciences", held at the Accademia Nazionale dei Lincei in Rome on March 8, 2017.

✉ Marco Anzidei
marco.anzidei@ingv.it

1 Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia

2 Departement des Geosciences, Ecole Normale Superieure, Paris, France

3 Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy

4 ENEA, via Anguillarese 301, S. Maria di Galeria, 0060 Rome, Italy

5 Rome, Italy

anthropogenic factors are important today, their origin will lie in the onset of the industrial revolution which also corresponds to the start of most global-scale instrumental observations and anthropogenic and background 'natural' factors cannot be observationally separated. Hence, an important focus of climate research has been on identifying proxies of these changes for preinstrumental times, for example—in the case of sea level—changes in oxygen isotope ratios of sea water, or the positions of fossil corals with respect to present-day sea-level. But often, other factors will also influence the proxies used and it becomes important to find means of calibration of these preinstrumental records whenever possible. We discuss here one such calibration, using an observation pioneered by Michele Caputo (Schmiedt et al. 1972; Caputo and Pieri 1976): the use of inferences of past sea levels from archaeological remains whose original constructions were closely linked to the sea level at their time. We focus particularly on the fish tanks (piscinae) constructed during the Roman Period between about 2100 and 1900 BP for which the relationship between individual elements of the pools and sea levels at the time of construction, that also define the functional elevation, are well documented in the historical literature of the epoch (see Sect. 3 for references). These constructions are of near-uniform design in contrast to other pools whose original purpose and relation to sea level are less well understood. Many of these features have been surveyed, thanks to the work initiated by Caputo in collaboration with maritime archaeologists (Schmiedt et al. 1972), supplemented with recent reexamination of these and additional structures (see Fig. 1 for the location of the investigated sites). For most, these piscinae occur today at levels where they are no longer functional and the discrepancy provides a measure of the local relative sea-level change that has occurred during the past 2000 years, a change that will be the sum of land movements (with respect to the earth's center of mass) and of changes in ocean volume in this time interval. Features that make these pools important for geophysics include: (1) for successful functioning of the pool, the water exchange between sea and pool is regulated by the tides, and because of the small tidal amplitudes for much of the Mediterranean coast, the pools form gauges of local sea level with an accuracy better than the tidal amplitude; (2) their age is well determined from historical records for the sites; (3) they occur at many locations around the Mediterranean and, therefore, provide a Mediterranean-wide benchmark for sea level at ~ 2000 years ago; (4) in most instances, they have been carved into or built on rock, such that they have not been subject to sediment compaction or slumping and can, in most instances, be assumed to be in their original position within the landscape; (5) in some cases, independent geological sea-level observations also exist for the same locality, such that an inter-calibration of the proxy indicators become possible. However, their interest is not restricted to geophysics alone, and for archaeology, they provide a potentially important calibration for the functioning of other harbour and coastal structures. For example, elevations of ancient piers, harbour quays, and bollards are often a function of the dimensions of the predominant type of ships that used the ports, and if a precise sea level can be established from nearby fish tanks, such as at Ventotene, it also becomes possible to establish the functional height of these features. Or, if the relation between fish-tank levels and the minimum levels of quarry excavations (as also is possible at Ventotene) can be established, this information can be transferred to comparable epoch quarry sites where there are no benchmark fish tanks.

As noted above, the measure of sea-level change contains the sum of two pieces of information; land movement, and change in ocean volume to which must be added any redistribution of water in the ocean due, for example, to long-period changes in winds and ocean currents. The geophysical challenge is how to separate these various components. To do this successfully requires geophysical models of the processes at work, models that are quantified by a minimum possible number of parameter that are estimated from the observations themselves and from additional geophysical and geological data. This paper is part of a longer term project (see Acknowledgements) to address these questions that will lead to an understanding of the causes of sea-level change around the Italian coast, including a predictive capability, (Antonioli et al. 2017; Anzidei et al. 2014, 2017; Lambeck et al. 2004a, 2011). In Sect. 2, we briefly discuss the causes for sea-level change in the Mediterranean over recent millennia and attempt to quantify some of the more important ones. In Sect. 3, we examine the key structures that make the fish tanks an effective tide gauge; in Sect. 4, we summarize new results from sites for which the structures controlling the exchange of water between the open sea and the tank interiors can be identified; in Sect. 5, we provide

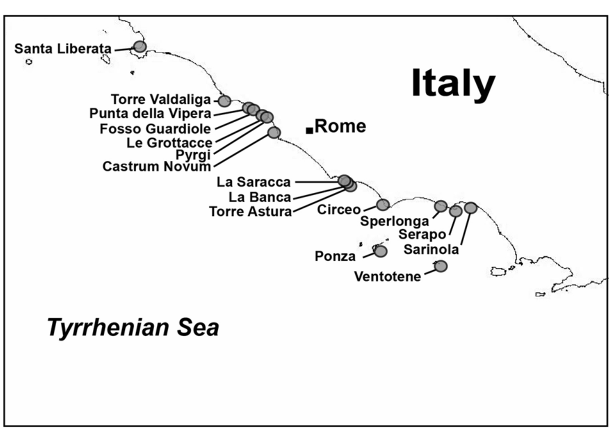

Fig. 1 Site location (see Table 2 for data)

one example of a geological–archaeological intercomparison that demonstrates the validity of our interpretation of the fish-tank data; in Sect. 6, we summarize the results and address the whys and wherefores for future work.

2 Causes of sea-level change

Changing sea level is measured with respect to the land, a surface that itself is a variant with respect to the planet's center of mass and only the satellite altimetry measurements define the sea surface with respect to this absolute reference point. The measurement is a relative one and contains information on changes in ocean volume, changes in the configuration of ocean basins and redistribution of water within these basins, and on coastal land movements. Usually, all such changes occur in the geological and instrumental records, and all need to be considered in successful scenarios for future change. Combined, they result in a complex time and spatial spectrum of change from global scale to local scale reflecting oceanographic (currents, thermal expansion), atmospheric (winds, surface pressure), climatic (glacial cycles), tectonic (coastal uplift and subsidence), and global dynamic (changes in planetary gravity and rotation including tides and including mantle convection and mantle–lithospheric interactions) processes. The abundant evidence throughout the geological record provides solid evidence for all of these processes having occurred, since the first oceans formed. The challenge is to derive a predictive (both in foresight and in hindsight) capability of the land–sea relationship through time that is consistent with observational evidence and understood physical processes.

The time interval of interest here is from that of the glacial cycles to years, being also the major part of the human time scale, when the major contributions are from the exchange of water between oceans and ice sheets, complicated around the Mediterranean basin by vertical tectonics associated within the African–European collision. Within these limits of space and time, the contributions from the former are largely predictable in their broad spatial and temporal pattern that can be scaled by observational evidence if sites can be identified that have been (relatively) free from tectonic contributions. This interpolation is possible using the theory of glacial isostatic adjustment that has been well developed and well tested over many decades (O'Connell 1971; Peltier 1974; Cathles 1975; Nakada and Lambeck 1987; Mitrovica and Milne 2003; Lambeck et al. 2003). The theory (generally referred to as glacial isostasy) includes the changes in ocean volume as ice sheets grow or decay, the deformation of the 'solid' planet under the changing ice load in the areas of former glaciation (and areas of present change), the redistribution of water in the ocean basins that are deforming in response to the changing ice–water surface load, and the changes in the planetary gravity field (including changes in the centrifugal force) that ensure that the ocean surface remains an equipotential surface. It rests on physical assumptions about the rheology of the planet and of past ice sheets, both parameterised in terms of known and unknown parameters with the latter estimated from inversions of observational evidence of the planet's response (Lambeck 2014). For the Mediterranean, the key glacial-isostatic elements contributing to the sea-level change are:

1. The change in ocean-water volume, expressed as the ice-volume equivalent sea level (ESL), the globally averaged sea-level change due to a change in grounded ice volume, with respect to today (defined in Lambeck et al. 2003). This is a function of time t.
2. The combined deformational and gravitational change in the crustal and ocean surfaces is due to the changing ice loads $\delta\zeta_{\text{ice}}$. This is a function of t and position ϕ.
3. The combined deformational and gravitational change in the crustal and ocean surfaces is due to the changing ice loads $\delta\zeta_{\text{water}}$, a function of both t and ϕ.
4. The consequences of the above changes on the planet's rotation and change in centrifugal force.

Figures 2, 3 show representative model-predicted total sea-level change, assuming no tectonic (or other) contributions:

$$\Delta\zeta_{\text{rsl}} = \Delta\zeta_{\text{esl}}(t) + \delta\zeta_{\text{ice}}(\phi, t) + \delta\zeta_{\text{water}}(\phi, t), \quad (1)$$

for the Mediterranean basin near the end of the last maximum glaciation at $t = 20{,}000$ years ago. The pattern (Fig. 2) is one of a smoothed outlines of the shoreline geometry, the result of $\delta\zeta_{\text{water}}$, superimposed upon which is an approximately NNW–SSE gradient resulting from the $\delta\zeta_{\text{ice}}$ contribution from the northern hemisphere ice sheets (including an Alpine deglaciation). Departures from uniform $\Delta\zeta_{\text{esl}}$ are

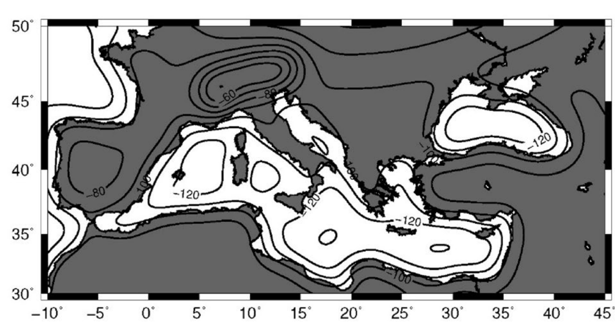

Fig. 2 Predicted relative sea-level change since the late glacial maximum at ~ 20,000 years ago for the Mediterranean region predicted for nominal earth- and ice-model parameters [see Lambeck and Purcell (2005)] for similar results for other epochs and for the breakdown into the $\delta\zeta_{\text{ice}}$ and $\delta\zeta_{\text{water}}$ contributions from the major ice sheets. For this period, the nominal $\Delta\zeta_{\text{esl}}$ is − 127 m. Contour interval = 10 m

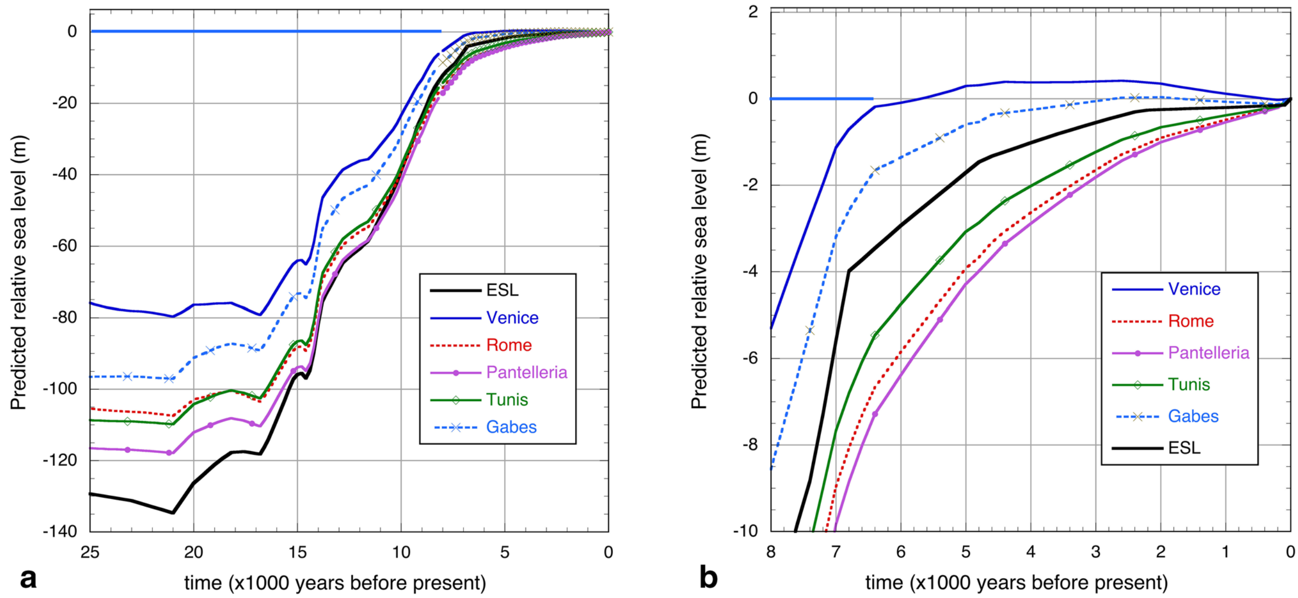

Fig. 3 Representative time series for predicted relative sea-level change at sites along an approximately north–south section across the Mediterranean basin from Venice (Italy) to the Gulf of Gabes (Tunisia). **a** From 25,000 years ago to the present. **b** For the past 8000 years. The predictions in this and Fig. 2 are ice- and earth-model dependent whose parameters are estimated from sea-level analyses from areas where vertical tectonic rates are low. Ice-model parameters are from Lambeck et al. (Lambeck et al. 2014, 2017) and earth parameters are from a preliminary 'best fit' analysis of Mediterranean sea-level data

from − 10 m near the centers of the basins to + 30 m at some present-day coastline locations. This spatial pattern of change is preserved throughout the subsequent 20,000 years up to the present. The time dependence is illustrated in Fig. 3 for five sites along an approximately north–south section. This demonstrates the important variation in the local sea-level function from one location to another, one that cannot be adequately represented by a simple time-only dependent function.

The parameters quantifying the earth response function and any glaciological unknowns embedded in the predictions through the three terms of (1) are evaluated primarily from inversions of the sea-level evidence from areas that are understood to be free of tectonic deformation which, for the Mediterranean, we have defined as regions of low instrumental and historical seismicity and where the last interglacial shorelines (from ~ 130,000 to 120,000 years before present) are within a few meters of the present-day sea level. Large sections of the Tyrrhenian coast and areas such as Sardinia approximate these conditions (Antonioli et al. 2009; Ferranti et al. 2006). These calibrated models are then to interpolate and extrapolate sea-level change across the region to provide a reference for vertical tectonic movements (Lambeck et al. 2004a). Here, we limit ourselves to the specific question of calibration of the fish tank observations along this central part of the Tyrrhenian coast, using geological information on sea-level change from the wider area to quantify the model predictions, and taking advantage of the model prediction that along this section of coast the glacial-isostatic contributions are nearly constant. (Lambeck et al. 2004a, b).

3 The anatomy of the fish tanks

Roman fish tanks or piscinae were built mainly along Tyrrhenian coast of the Italian peninsula where they occurred near large Roman villas, and less frequently in other areas of the Mediterranean Roman Empire (Schmiedt et al. 1972; Anzidei et al. 2014 and references therein). Plinius (Naturali Historia, IX, 168) records that Sergio Orata was the first to create vivarium (i.e., fish tanks) for oysters in Baia in the first century B.C., and most subsequent constructions based on similar functional principles were built in a restricted interval between 100 B.C. and 100 A.D. As a consequence of their high construction and maintenance costs, the building of new tanks ceased after the second century A.D. Of those found beyond the Tyrrhenian coast many lack the sophisticated design features of their Tyrrhenian counterparts and may have served different purposes.

The fish tanks may consist of a single tank or a number of tanks inter-connected with channels to control the flow between them and with the open sea. Their construction can be classified into two types based on archaeological observations and the descriptions lefts by the Latin authors Columella and Varro: (1) excavated into bedrock (e.g., at Ponza) or (2) built on the rocky shore using bricks and hydraulic mortar (e.g., at Torre Astura, Fig. 4). In some instances, a combination of the two methods also occurs (e.g., at Ventotene). External walls surrounding the inner pools were often built by a "box-like" technique creating a framework of wooden poles and boards filled in with hydraulic mortar and stones (Felici, 1993, 1998, 2004). As described by Plinius, Columella, and Varro, the elevations of the channels, sluicegates, and walking and working surfaces (the crepido) were determined by the local mean sea level and tidal range that controlled the inflow and outflow of sea water. According to the Latin author Varro (De Re Rustica III), a further classification of the fish tanks is possible according to their purpose: for fish culture—with a distinction for different fish species; flat fish or others, for example, that required less saline water during breeding—or as 'water gardens' to embellish villas of wealthy Romans.

Fig. 4 Two of the investigated fish tanks along the Tyrrhenian coast of Italy. Top) Aerial view of Punta della Vipera with the submerged pools and the three external vaulted channels. Bottom) Aerial view of Torre Astura fish tank, with the submerged pools and the aqueduct built to feed the pools with fresh water to make the aquatio. The outer walls with intersecting channels and the inner walls between tanks are among the typical features of these structures. The lowest level crepido is often buried by debris below the present water level (photo M.Anzidei)

The constructional features of the fish tanks that are of interest are the channels, sluicegates, and crepido which, where well-preserved, bear directly on mean sea level at the time of construction and provide a precise measure of the local sea–land relationship. Contemporaneous accounts by classical authors (including Plinius the Elder, Columella, and Varro) define these features. Of most significance for our investigation are the discussions of the relationships of the various constructional features to sea level at the time of use. According to Columella (De re Rustica, XVII, 1, 3), the exchange of water inside the fish tank is tidally controlled, to allow continuous exchange with the sea and without stagnation or overheating inside the basin. In addition to the principal pool being in contact with the sea, the construction often included a fresh-water tank and aqueduct at the back of the complex to produce less saline environments (a technique called aquatio) to attract certain fish species such as seabass and mullet. In consequence, some fish tanks were constructed near coastal springs or lakes such as on the Circeo promontory south of Rome or even fed with fresh water from aqueducts, like at Torre Astura (Fig. 4). To control the freshwater input, these latter complexes contained additional features such as internal sluice gates at levels above the local Roman mean sea level. Other than the design elements, another relevant feature for dating the maritime structures is the building material used. To resist mechanical erosion and chemical dissolution typical of marine environments, the Romans used a hydraulic mortar to build fish tanks, as well as for harbors and other maritime structures, that consisted of a mixture of binder (limestone and volcanic rocks) and aggregate (pozzolana, a volcanic ash from the Roman city of Puteoli near Naples) with enhanced mechanical and chemical properties relative to the conventional concrete used for the construction of terrestrial buildings at that time (McCann 1987; Mertens et al. 2009; Marra et al. 2016). This was used only after the first century B.C. (Felici 1993) and its occurrence provides a control on a lower limit of the age of construction (Jackson et al. 2017). Despite the relatively large number of such fish tanks found in the Mediterranean only a small number, mainly located along the Italian coast, preserve one or more precise sea-level markers.

The principal constructional markers that we use here are (1) the channels and associated system for controlling the water exchange within the basin and (2) the crepido or narrow foot walks surrounding the inner basins. Of these, the first are the most precise and include sluice gates, sliding posts, and channel thresholds. These markers all have a "functional elevation", i.e., the elevation with respect to the local mean sea level at the time of its construction, which depends on the type of structure, its use, and on the local tide amplitudes. These elements and their relation to sea level, in particular their minimum elevation above the local highest tides, are described in the historical sources of the Latin authors Columella and Varro.

The foot walks (crepido) The foot walks bordering the internal pools may occur at up to two or three levels, possibly depending on the function of the pool. Often, the lowest levels of crepido are today buried by debris and have not always been recognized or interpreted in earlier investigations. Lambeck et al. (2004b) consider the lowest level crepido as significant sea-level markers, based on the following descriptions from the Latin authors Plinius the Elder, Varro, and Juvenale: *marginum eam partem, quae aquas spectat* (part of that margin that looks at the water, from Naturalis Historia, Plinius the Elder, 23–79 A.D.); *de lacu, aut stagno, ubi servantur anates* (the side of the lake or pond where ducks sit, from De re rustica, Marcus Terentio Varro, 116 B.C.–27 A.D.); *locus editior, vel in ripa fluminis, vel in portu maris, vel rectius ad latera viarum, and ubi stare solent mendici stipem petituri* (level placed on the bank of the river, or the sea port, or on the roadside, where the beggars are begging, from Juvenale 1992). It is, therefore, reasonable to conclude that their lowest level was built to remain at a small elevation above sea level, even during high tides, to facilitate walking around the inner basins.

Channel systems The surrounding walls of the fish tanks, the inner basins, and the crepido are all intersected by channels, equipped with sluice gates, that permit tidally controlled water exchange between the tanks and the open sea. Often, these channels are covered by sand and have not always been recognized or interpreted in the previous investigations. A typical fish tank will include: (1) channels for water exchange within the basins; (2) channels for water exchange with open sea; and (3) sluice gates (single or multiple) within these channels, with sliding posts (see below), and a threshold stone placed at the bottom of the sluice gate itself. As previously noted, channels may occur at different elevations to separate different levels of pools within the fish tank complex, according to function and fish species kept. Examples are provided by the Torre Astura, Tiberio, and Lucullo fish tanks (Schmiedt et al. 1972). The first of these shows two levels of channels; a lower level that provides the tidal control, and a higher level that would have been above the tidal limit and which was connected by pipe to the nearby freshwater aqueduct. The Tiberio fish tank, near the Sperlonga promontory, is an exemplary case of a still working tank for fresh-water species and was built at about 3 m above sea level of 2 ka BP and is still fed by a local spring upwelling from the limestone hills facing the coast (Gazzetti et al. 2000). The third example, the Lucullo fish tank at the Circeo promontory, is located along the Torre Paola channel that connects the sea to the brackish Paola lake (Chiappella 1965). The water level within this fish tank was controlled by a combination of sea and fresh waters (http://www.parcocirceo.it/ita_219_Piscina-di-Lucullo.html), the latter provided by groundwater from the nearby limestone of Mt.Circeo (Gazzetti et al. 2000). Other than these fish tanks, the remaining ones discussed in this paper are mostly equipped with large water tanks at their back and were most likely used for the aquatio (Columella). In all cases, a complete description of the pool complex is required to identify those features that relate directly to the local sea level at time of construction.

Sluicegates and channel thresholds The sluice gates that control the flow through the channels are placed mainly where the channel enters the pool but also along their course and between pools. These features, wholly consistent with the descriptions left by Columella, are (Fig. 5):

- a lower horizontal stone surface that defines the threshold and is cut by a groove to receive the gate;
- the threshold slab coincides with the level of the base of the channels;
- two vertical posts with grooves to guide the vertical movement of the gate (our sliding posts). In some cases, the gates have been built into the walls surrounding or within the pools;

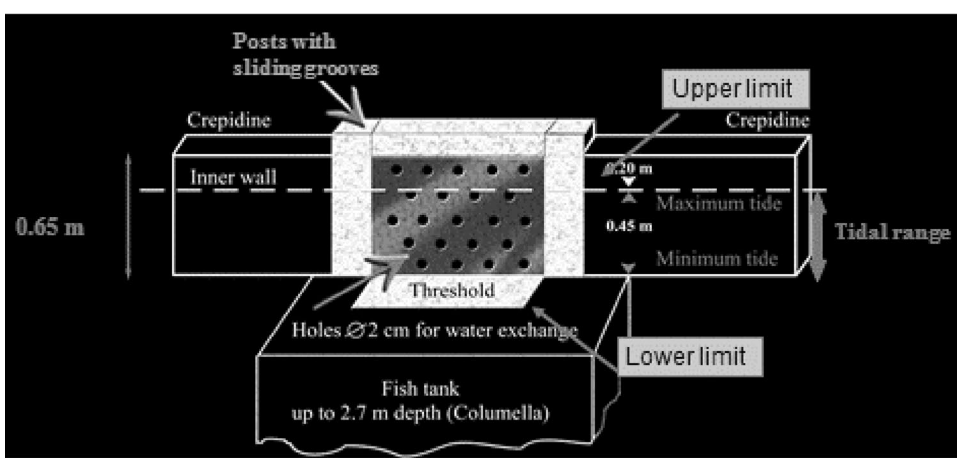

Fig. 5 Sketch of the channel sluice gate with sliding posts, threshold, and lowest level crepido as viewed from within the fish tank. The threshold defines the lower limit estimate and a level 20 cm below the lowest foot walk defines the upper limit estimate. The top of the sluice gates coincides with the elevation of the lowest level foot walks and corresponds to a position above the highest tide (from Lambeck et al. 2004b)

- in some instances, an upper stone slab with a slot covers the channel for extracting or inserting the gate in a vertical position during fish tank maintenance;
- the top of the sluice gate coincides with the elevation of the lowest level foot walk. To keep a safety margin above sea level to protect the inner basins from sea waves and storms, the tops correspond to a position above the highest tide level;
- the gate itself, built of stone or lead, has small holes (generally ~ 3 cm of diameter but up to ~ 9 cm, as in the fish tank of Torre Valdaliga) to permit water exchange but to prevent the escape of fish;
- in general, a height of between 60 and 90 cm (equal to two or three roman feet), to be functional for the local tidal ranges in the Mediterranean;
- a width of mostly 0.9 m (3 roman foot) although sometimes narrower, as in Israel (Anzidei et al. 2011);

From sites with complete preservation of sluice gates, channels, and foot walks, we obtain relationships between the heights of the various features. In particular, the lowest level crepido occurred between the high tide level and about 20 cm higher, while the bottoms of the channels coincide closely with the minimum lower tide level, but without producing the drying of the basins (note that the bottoms of the pools were always below this level and up to 2.7 m deep, as reported by Columella). In the Tyrrhenian Sea, the mean tidal range is mainly 45–50 cm and up to 75 cm for only a few hours a year (Antonioli et al. 2015), from the analysis of www.mareografico.it tidal data.

4 Results

During the last decades, several studies have reconstructed past sea levels from coastal fish tanks in Italy (Schmiedt et al. 1972; Caputo and Pieri 1976; Auriemma and Solinas 2009; Evelpidou et al. 2012; Antonioli et al. 2007; Aucelli et al. 2017; Lambeck et al. 2004b; Anzidei et al. 2013; Profumo, 2007) with differences (Table 1) that can be attributed to: (1) difficulty in the identification of the most precise sea-level indicators available from these archaeological remains; (2) different corrections for atmospheric pressure effects, and (3) differences in the treatment of land movements of tectonic and glacio-isostatic origin.

To examine the reasons for these differences and to establish the validity of the observational data and our interpretation of them, we have reviewed the evidence from fish tanks built along the central Tyrrhenian coast of Italy (Fig. 1). Table 2 and Fig. 6 summarize the results from our investigations of 15 Tyrrhenian fish-tank complexes, including resurveys of those previously discussed in Lambeck et al. (2004b), and 3 from the latter that have not yet been resurveyed. For all, one or more of the sea-level defining structural elements could be securely identified and all have been reduced to a consistent interpretation of the local mean sea level (Fig. 5). The relative sea-level estimates (last column) have been reduced to present mean sea level, corrected for tidal amplitudes and atmospheric pressure at the time of survey (www.mareografico.it). Uncertainties include survey errors and the uncertainties of the functional elevations of the different constructional features. The mean value for all sites is − 1.22 m with a standard deviation of 0.23 m, comparable to the a priori error estimates, suggesting that any regional variation across this region is small. This is consistent with a previous conclusion that the glacio-isostatic variability across the region is predicted to be of order ± 0.06 m and that any variability in vertical tectonic displacement has been equally small.

5 A geological calibration

As all the archaeological data refer to the same functional level, this consistency between sites does not demonstrate that the choice of the reference level is the correct one. For this, we need to make direct comparisons between archaeological and geological indicators of past sea level, but so far, this has been possible at only one locality, Santa Liberata near Orbetello lagoon. This fish tank has been investigated

Table 1 RSLC results from different studies for Punta della Vipera fish tank

RSLC (m) at Punta della Vipera fish tank						
Evelpidou et al. (2012)	Lambeck et al. (2004b)	Leoni and Dai Pra (1997)	Caputo and Pieri (1976)	Pirazzoli (1976)	Schmiedt et al. (1972)	This paper
− 0.58 ± 0.05 m	− 1.28±0.20 m	− 0.32 m	− 0.62 and 0.75 m	− 0.45 m	− 0.65 m	− 1.29±20 m
Top of walls	Channels, threshold and crepido	Top of walls	Top of walls	Top of walls	Top of walls	Channels, sluice gate, crepido

The lower row identifies the archaeological sea-level indicators used to estimate the relative sea-level change at this site. The last column corresponds to the new estimates discussed below (Table 2)

Table 2 Local relative sea-level change (RSLC) estimated at 12 resurveyed fish tanks of the Tyrrhenian coast of Central Italy and 3 (13–15) additional results from Lambeck et al. (2004b)

A n.	*B* Site	*C* Age	*D* Survey date	*E* Archaeological indicator	*F* RSLC (cm)
1	Santa Liberata	1950 ± 50	Lambeck et al. (2004b)	Channels with threshold; top and bottom of channels; crepido; missing sluice gate	104 ± 25
2	Torre Valdaliga	2000 ± 50	Aug 4, 2013	External channel with sluice gate and posts; internal channel with sluice gate and posts between pools	87 ± 20
3	Punta della Vipera	2000 ± 50	June 15, 2013 June 8, 2013 June 9, 2013	Crepido; channels within the pool; channel with fixed sluice gate; bottom of pool; external vaulted channels	128.6 ± 20
4	Fosso Guardiole A	2000 ± 50	Aug 6, 2013 Sept. 5, 2013	Crepido; bottom of channel; breakwater/pier around the pools	Mean of the two fish tanks 117.0 ± 20
	Fosso Guardiole B	2000 ± 50	July 5, 2013 Aug 6, 2013	Channels; upper and lower levels of crepido; bottom of channel; channel with sluice gate	
5	Le Grottacce fish tank	2000 ± 50	Sept 4, 2013 June 6, 2014	Lower crepido; channels with posts, sluice gates and thresholds	138.5 ± 20
6	Pirgy (Odescalchi)	2000 ± 50	June 22, 2013	Lower crepido	137.5 ± 20
7	Castrum Novum (S.Marinella)	2000 ± 50	Sept 26, 2013	Pavement; double thresholds of sluice gates; crepido; top and bottom of channels; channel with missing fixed sluice gate	106.5 ± 20
8	Astura La Saracca	2000 ± 50	Aug 24, 2013	Top and bottom of external channel; channels, posts; crepido	93.5 ± 20
9	Astura La Banca	2000 ± 50	Aug 7, 2013	Upper and lower crepido; channel with sluice gate and posts	109 ± 20
10	Astura	2000 ± 50	Aug 30, 2013	Top and bottom of channels, thresholds; Lower crepido; bottom of pools	97.4 ± 20
11	Ponza indoor	2000 ± 50	Sept 27, 2013	Channels with posts and threshold; channel with fixed sluice gate and posts; lower, middle and upper levels of crepido	158 ± 20
12	Ponza outdoor	2000 ± 50	Sept 27, 2013	Channels with posts	137.2 ± 20
13	Ventotene	2000 ± 50	Dec 11, 2013	Channels with threshold; top and bottom of channels; crepido; missing sluice gate; fixed sluice gate	154.5 ± 20
14	Serapo	1950 ± 100	Lambeck et al. (2004b)	Crepido	148 ± 20
15	Sarinola	1950 ± 100	Lambeck et al. (2004b)	Channels with threshold; top and bottom of channels; crepido; missing sluice gate	108 ± 20

Marine observations have been corrected for tides at the time of surveys using tidal data retrieved from www.mareografico.it. Uncertainties include survey errors and the functional elevation estimated from the constructional features. Mean RSLC is 122 ± 06 cm

A site number as in Fig. 6, *B* site name, *C* archaeological age, *D* survey date, *E* archaeological sea-level indicator, *F* relative sea-level change

by numerous investigators resulting in some significantly different outcomes (Table 3), largely the consequence of different interpretations of the archaeological measurements. Of note is that the wall elevations yield results that are 45–65 cm above the channel system and lowest crepido estimate.

The analysis of a recently collected shallow core sample from the Orbetello lagoon (~ 3 km from the fish tank) revealed the presence of marine and lagoonal species, such as *Hydrobia sp*., *Loripes lacteus, Abra sp., Cerastoderma glaucum e Cerithium* vulgatum that occur at the transition between zones III and IV of Guelorget and Perthuisot (1983), including « mixed » species such as *Loripes lacteus* and those typical of paralic environment such as *Hydrobia sp*., *Abra sp*., and *Cerastoderma glaucum* (these predate modifications resulting from an artificial channel opening of the lagoon). Radiocarbon dates for a *Loripes lacteus* specimen at − 1.37 m below mean sea level, within a sandy lagoonal mud layer between ~ − 1.05 and − 1.40 m, yielded the results as summarized in Table 4.

Within measurement uncertainties, this independent estimate of local sea level at Orbetello is consistent with that of Lambeck et al. (2004b) based on the nearby (~ 3 km) Santa Liberata fish-tank evidence inferred from the channel and uncertainty estimates of both measurements consistent with the fish tank result of − 1.04 ± 0.25 at ~ 2000 BP. This rules out the inferences drawn from the elevation of the walls surrounding the pool by Schmiedt et al. (1972) as well as those based on the other, not clearly specified structural features. Neither observation is yet

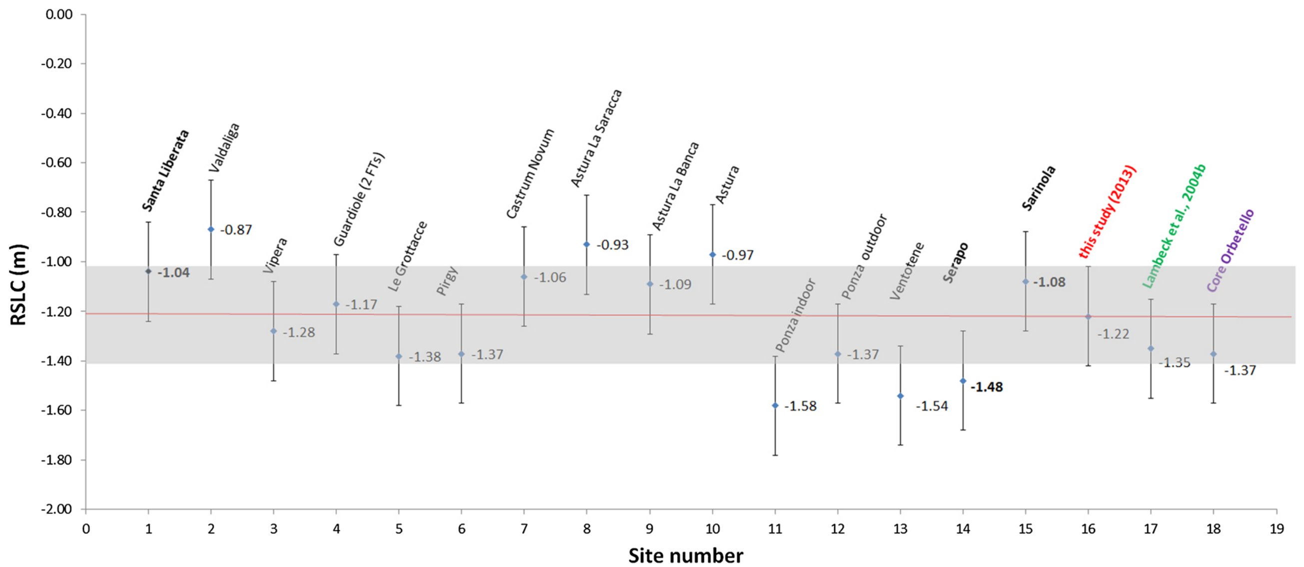

Fig. 6 Relative sea-level change inferred from the set of revised fish tanks of the central Tyrrhenian Sea and biological data from a shallow core. At right of the plot are reported (1) the RSLC inferred from biological data collected by the shallow core at Orbetello lagoon, consistent with the RSLC inferred by the fish tanks (1.37 m, in violet); (2) the mean RSLC from Lambeck et al. 2004b (1.35 m, in green); (3) the mean RSLC from the revised fish tank data (1.22 m, in red). The horizontal red line represents the mean RSLC from the revised fish tanks data with the related standard error of the mean of ± 6 cm, as shown by the transparent grey box. In bold are the fish tanks of S. Liberata, Serapo, and Sarinola, with RSLC values from Lambeck et al. 2004b

Table 3 Local sea-level change results from different studies for Santa Liberata fish tank

Lambeck et al. (2004b)	Leoni and Dai Pra (1997)	Caputo and Pieri (1976)	Pirazzoli (1976)	Schmiedt et al. (1972)
− 1.04 ± 0.25 m	− 0.39 m	− 0.50 m wrt 1884 msl	− 0.45 m	− 0.61 m
Sliding posts, threshold, channels	Top of channel	Stone bases of fishpond walls	Not specified[a]	Top of wall

[a]It is not stated in this paper what is measured for this particular fish tank, but, from the analogy with the other measurements in that paper, we interpret this as the elevation of the surrounding wall

Table 4 Age and depth for lagoonal fossil sampled in the Orbetello lagoon which is located at about 3 km from the Santa Liberata fishpond

Site name	Age	Age Cal BP Calib 7.4 1 sigma	Altitude (m wrt msl)	Altitude error (± m)		Biological Marker	Coordinates
				Upper limit	Lower limit		
Orbetello	1913 ± 45	1653 ± 55 1771 ± 55	− 1.27 ± 0.20	0.2	0.2	*Loripes lacteus*	42°25′53.3″N 11°11′12.9″E

The lagoonal fossils were placed at − 1.27 m of elevation from the ground surface. The two calibrated ages correspond to 50 and 20% marine mixing. See also Fig. 1 for location

of sufficient accuracy to provide a thorough test of our hypothesis concerning the level of functionality within about ± 0.20 m, other than that the comparison is inconsistent with the inferences drawn from wall-elevation observations which appear to result in higher (~ 50 cm) levels. Such a discrepancy is more clearly seen for Punta della Vipera fish-tank results where the 'wall' estimates are consistently higher by 70–90 cm. The tops of the outer walls were of sufficient height so as to protect the inner basins from wave action, and the inner walls were built up to an elevation to keep the inner pools separate during the highest tides, we conclude that (1) estimates based on the wall elevations only provide upper limit estimates to past local sea levels and (2) that there is no well-defined relationship between the elevation of the walls above past sea level and the structural elements of the channel system that control the water exchange.

6 Discussion and conclusions

We have limited the discussion in this paper to the sea-level evidence from the Roman period fish tanks from that part of the Tyrrhenian coast (of ~ 180 km length from Civitavecchia in the north to Formia in the south) for which (1) the documentation of the construction methods and the purpose of the tank are mostly complete, (2) the pools were cut into, or built on, solid rock, (3) the spatial variation in the glacio-hydro isostatic contribution to relative sea level is significantly less than the observational precisions, and (4) differential vertical tectonic contributions in recent millennia are also small. We have reexamined the evidence for the functional elevations of those fish tanks that were clearly in open contact with the sea as distinct from those that were designed to maintain brackish or fresh water conditions. The structural features used here to define the functional elevation are tidally controlled and all relate to the channel systems within and outside of the tanks that they were protected by exterior walls. The elements making up the adopted system include the channel thresholds, sliding posts, and sluice gates and the lowest level foot walks or crepido. Table 5 summarizes their relative elevation relationships.

For this section of the coast for which the tidal range is small and nearly constant (Antonioli et al. 2015), these distinct features occur at the same differential elevations for all pools considered, such that where only one or two of these elements have been preserved, the elevations of the others can be reconstructed. The channel threshold defines the lower limit estimate (Fig. 5). The top of the sluice gates coincides with the elevation of the lowest level foot walks and corresponds to a position above the highest tide and a level 20 cm below this defines the upper limit estimate. Features such as the foundations of the walls, used by many previous authors, only provide upper limits to the past sea levels and the comparisons at the Punta della Vipera and Santa Liberata sites indicate that they lie ~ 50 cm or more above local mean sea level (Tables 1, 3).

The comparisons of the 12 newly resurveyed pool results and the three additional ones based on the same methodology (Table 2) yield consistent results for the local sea level of − 1.22 ± 0.06 m (standard error of the mean) and a standard deviation for a single pool of ~ ±20 cm. This confirms that differential vertical land movements, of whatever origin, for 'hard rock' sites have been insignificant on a 2000 year time scale along this section of coast.

To test the hypothesis that the elevations of the various structural features associated with the water exchange between the pool interior and the open ocean are controlled by the mean sea level at the time of construction, we have attempted a calibration of the fish-tank evidence by examining sedimentological evidence for sea-level change at a nearby site, Orbetello Lagoon. This yielded a result consistent with the fish-tank data within uncertainties of the two measurements (Table 4) and which excludes the archaeological estimate based on the wall elevations (Compare Tables 3 and 4). Hence, we have established a reference surface for sea level during the Roman Period between about 2100–1900 BP that was about 1.20 ± 0.20 m below present, and with respect to which other coastal archaeological features within this age range can be quantified; for example, the lowest level of quarry floors at coastal sites or the heights of bollards constructed for different purposes. Exemplary are (1) the quarries at Ventotene island where the lowest cuttings are submerged at same elevation of the lowest level foot walks and (2) the bollards of the Roman age harbor carved into the rock, indicating that these structures identify limiting values of historical sea level that are consistent with the observations of the channel systems in the nearby fish tank (Lambeck et al. 2004b).

The explanation for this departure from the present-day sea-level lies in a combination of factors, but mainly the glacio-isostatic consequence of the last deglaciation, long-wavelength tectonic land uplift, and changing ocean volumes, Separation of the three is only possible through expanding the research area to a greater region; using geological evidence for sea-level change in the Mediterranean to establish both the isostatic parameters required and a regional pattern of tectonic displacement and using tide gauge records to establish the rates of recent local sea-level change. A preliminary attempt at this concluded that the observed level was consistent with the isostatic contributions plus tectonic inferences based on the elevations of the Last Interglacial, and the assumption that the modern sea-level rise was initiated at or after ~ 150 years ago (Lambeck et al. 2004a, b). With the glacio-isostatic theory, underpinned by the earth and ice parameters from regional inversions of geological evidence for sea-level change, it

Table 5 Summary of relationship between structural features and sea level $\zeta(t_P)$ is the elevation with respect to present sea level (in m) reduced to mean sea level and corrected for atmospheric loading; $\delta\zeta_T$ is the local tidal range (in m) (assumed to have remained constant unless there has been a major shoreline change)

Relationships between structural features and sea level	
Feature	Palaeo sea level (m)
Threshold only	$\zeta(t_P) + \delta\zeta_T/2$
Lowest foot walk only	$\zeta(t_P) - 0.20 - \delta\zeta_T/2$
Top of sluice gate only	$\zeta(t_P) - 0.20 - \delta\zeta_T/2$
Sliding post	As for the lower foot walk level or ~ 20 cm higher if there was an upper slab with groove

becomes possible to remove at least this component and to extrapolate the sea levels for 2000 years ago to beyond the Tyrrhenian coast and to use this as a reference surface for assessing the regional patterns of vertical tectonic movements and for testing the hypothesis that the recent sea-level rise recorded by tide gauges across the region is a signal of a recent (100–150 years) change rather than part of a much longer change.

Preliminary results suggest that the science is at a stage where scenarios can be developed, based on climate scenarios, for changing sea levels and concomitant shoreline migrations into a centennial-scale future (Lambeck et al. 2011; Antonioli et al. 2017; Anzidei et al. 2017), but to have greater confidence in these outcomes will require amongst other things and in addition to improved climate scenarios, further calibration of the models used here, including (1) an extension of the Roman Period archaeological evidence beyond the Tyrrhenian boundaries, (2) a more complete spatial and temporal coverage of accurate geological evidence for sea-level change, and (3) improved understanding of the broad-scale vertical tectonic movements on millennia time scales. Finally, our observations contribute to the improvement of sea-level database of relative sea-level data points for the Mediterranean region, like shown in Vacchi et al. (2016), providing high-accuracy constraints of relative sea levels at 2100–1900 years BP.

Acknowledgements This research was initially funded by INGV (1998) and the Italian National Research Council (CNR-Agenzia 2000). Further studies have benefitted from funds by the Italian Ministry of Education, University and Research within the National Research program (PRIN 2006; 2011–2013, Vector and RITMARE projects), ENEA, and the Australian National University. We thank Prof. M. Caputo, who first recognized the importance of the Tyrrhenian fish tanks as historical sea-level indicators.

References

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

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 coastline. Quat Int 206:102–133

Antonioli F, Lo Presti V, Rovere A, Ferranti L, Anzidei M, Furlani S, Mastronuzzi G, Orru PE, Scicchitano G, Sannino G, Spampinato CR, Pagliarulo R, Deiana G, De Sabata E, Sansò P, Vacchi M, Vecchio A (2015) Tidal notches in Mediterranean sea: a comprehensive analysis. Quat Sci Rev 119:66–84

Antonioli F, Anzidei M, Amorosi A, Lo Presti V, Mastronuzzi G, Deiana G, De Falco G, Fontana A, Fontolan G, Lisco S, Marsico A, Moretti M, Orrù PE, Sannino GM, Serpelloni E, Vecchio A (2017) Sea-level rise and potential drowning of the Italian coastal plains: flooding risk scenarios for 2100. Quat Sci Rev 158:29–43

Anzidei M, Antonioli F, Benini A, Gervasi A, Guerra I (2013) Evidence of vertical tectonic uplift at Briatico (Calabria, Italy) inferred from Roman age maritime archaeological indicators. Quat Int 288:158–167

Anzidei M, Lambeck K, Antonioli F, Furlani S, Mastronuzzi G, Serpelloni E, Vannucci G (2014) Coastal structure, sea-level changes and vertical motion of the land in the Mediterranean. In: Martini IP (eds) Sedimentary coastal zones from high to low latitudes: similarities and differences. Special publications 388. The Geological Society, London. https://doi.org/10.1144/SP388.20

Anzidei M, Bosman A, Carluccio R, Casalbore D, D'Ajello Caracciolo F, Esposito A, Nicolosi I, Pietrantonio G, Vecchio A, Carmisciano C, Chiappini M, Chiocci FL, Muccini F, Sepe V (2017) Flooding scenarios in coastal volcanic areas due to land subsidence and sea level rise: a case study for Lipari Island (Italy). Terra Nova 29:44–51. https://doi.org/10.1111/ter.12246

Aucelli P, Cinque A, Mattei G, Pappone G (2017) Historical sea level changes and effects on the coasts of Sorrento Peninsula (Gulf of Naples): new constrains from recent geoarchaeological investigations. Palaeogeogr Palaeoclimatol Palaeoecol 463(2016):112–125

Auriemma R, Solinas E (2009) Archaeological remains as sea level change markers: a review. Quat Int 206:1–13

Caputo M, Pieri L (1976) Eustatic variation in the last 2000 years in the Mediterranean. J Geophys Res 81(1976):5787–5790

Cathles LM (1975) The viscosity of the Earth's mantle. Princeton University Press, Princeton

Chiappella VG (1965) Esplorazione della cosiddetta "Piscina di Lucullo" sul lago di Paola. Atti Accademia Nazionale dei Lincei. Notizie degli scavi di Antichità, Serie 8 (19):46–160

Columella, De Re Rustica, XVII

Evelpidou N, Pirazzoli P, Vassilopoulos A, Spada G, Ruggieri G, Tomasin A (2012) Late Holocene Sea level reconstructions based on observations of Roman fish tanks, Tyrrhenian coast of Italy. Geoarchaeology 27:259–277

Felici E (1993) Osservazioni sul porto neroniano di Anzio e sulla tecnologia romana delle costruzioni portuali in calcestruzzo, in Archeologia subacquea. Studi ricerche e documenti I:71–104

Felici E (1998) La ricerca sui porti romani in cementizio: metodi e obiettivi. In: Volpe G. (a cura di), Come opera l'archeologo sott'acque : storie delle acque, VIII ciclo di lezioni sulla ricerca applicata in archeologia. Edizioni all'insegna del Giglio, Firenze 275-340

Felici E (2004) Ricerche sulle tecniche costruttive dei porti romani. Rivista di topografia antica XVI II:59–84

Ferranti L, Antonioli F, Amorosi A, Dai Pra G, Mastronuzzi G, Mauz B, Monaco C, Orrù P, Pappalardo M, Radtke U, Renda P, Romano P, Sansò P, Verrubbi V (2006) Elevation of the last interglacial highstand in Italy: a benchmark of coastal tectonics. Quat Int 145–146:30–54

Gazzetti C, Loy A, Rossi S, Sarandrea P (2000) Atlante delle sorgenti della provincia di, Latina edn. Gangemi, Roma

Jackson MD, Mulcahy SR, Chen H, Li Y, Li Q, Cappelletti P, Wenk HR (2017) Phillipsite and Al-tobermorite mineral cements produced through low-temperature water-rock reactions in Roman marine concrete. Am Mineral 102:1435–1450

Juvenale (1992) The satires, trans. Oxford University Press, Niall Rudd, Oxford

Lambeck K (2014) Of moon and land, ice and strand: sea level during glacial cycles. The annual Balzan lecture, vol 5. Leo S. Olschki, Florence, pp 13–54

Lambeck K, Purcell A (2005) Sea-level change in the Mediterranean since the LGM: model predictions for tectonically stable areas. Quat Sci Rev 24:1969–1988

Lambeck K, Purcell A, Johnston P, Nakada M, Yokoyama Y (2003) Water-load definition in the glacio-hydro-isostatic sea-level equation. Quat Sci Rev 22:309–318

Lambeck K, Antonioli F, Purcell A, Silenzi S (2004a) Sea-level change along the Italian coast for the past 10,000 years. Quat Sci Rev 23:1567–1598. https://doi.org/10.1016/j.quascirev.2004.02.009

Lambeck K, Anzidei M, Antonioli F, Benini A, Esposito E (2004b) Sea level in Roman time in the Central Mediterranean and implications for modern sea level rise. Earth Planet Sci Lett 224:563–575

Lambeck K, Antonioli F, Anzidei M, Ferranti L, Leoni G, Scicchitano G, Silenzi S (2011) Sea level change along Italian coast during Holocene and a projection for the future. Quat Int 232(1–2):250–257. https://doi.org/10.1016/j.quaint.2010.04.026

Lambeck K, Rouby H, Purcell A, Sun Y, Sambridge M (2014) Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proc Natl Acad Sci 111(43):15296–15303. https://doi.org/10.1073/pnas.1411762111

Lambeck K, Purcell A, Zhao S (2017) The North American Late Wisconsin ice sheet and mantle viscosity from glacial rebound analyses. Quat Sci Rev 158:172–210. https://doi.org/10.1016/j.quascirev.2016.11.033

Leoni G, Dai Pra G (1997) Variazioni di livello del mare nel tardo Olocene lungo la costa del Lazio in base ad indicatori geoarcheologici. ENEA Tech. Rep. RT/AMB/97/8, Rome

Marra F, Anzidei M, Benini A, D'Ambrosio E, Gaeta M, Ventura G, Cavallo A (2016) Petro-chemical features and source areas of volcanic aggregates used in ancient Roman maritime concretes. J Volcanol Geotherm Res 328:59–69

McCann AM (1987) The Roman port end fishery of Cosa. A center of ancient trade. Princeton University Press, Princeton

Mertens G, Snellings R, Van Balen K, Bicer-Simsir B, Verlooy P, Elsen J (2009) Pozzolanic reactions of common natural zeolites with lime and parameters affecting their reactivity. Cem Concr Res 39(3):233–240

Mitrovica J, Milne GA (2003) On post-glacial sea level: 1, general theory. Geophys J Int 154:253–267

Nakada M, Lambeck K (1987) Glacial rebound and relative sea-level variations: a new appraisal. Geophys J R Astron Soc 90:171–224

O'Connell RJ (1971) Pleistocene glaciation and the viscosity of the lower mantle. Geophys J 23:299–327

Peltier WR (1974) The impulse response of a Maxwell Earth. Rev Geophys 12:649–669

Pirazzoli PA (1976) Sea level variations in the northwestern Mediterranean during roman times. Science 194:519–521

Plinius, Naturalis Historia, IX

Profumo MC (2007) Archeologia della costa: la situazione marchigiana. Atti congresso Trieste L'archeologia dei paesaggi costieri e le variazioni climatiche 8–10.11.2007. II Progetto Interreg Italia-Slovenia ''AltoAdriatico'', pp 49–50

Schmiedt G, Caputo M, Conta G, Guidi F, Pellegrini M, Pieri L (1972) Il livello antico del mar Tirreno, Testimonianze da resti archeologici. Ed. L.S. Olschki, Firenze

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. https://doi.org/10.1016/j.earscirev.2016.02.002

Varro, De Re Rustica III