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Sea level in Roman time in the Central Mediterranean and implications for recent change

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Abstract

Instrumental records indicate that ocean volumes during the 20th century have increased so as to raise eustatic sea level by ~ 1–2 mm/year and the few available records suggest that this is higher than for the previous century. Geological data indicate that ocean volumes have increased since the main phase of deglaciation about 7000 years ago but whether this continued into the recent past remains unclear. Yet, this is important for establishing whether the recent rise is associated with global warming or is part of a longer duration non-anthropogenic signal. Here, we present results for sea-level change in the central Mediterranean basin for the Roman Period using new archaeological evidence. These data provide a precise measure of local sea level of -1.35 ± 0.07 m at 2000 years ago. Part of this change is the result of ongoing glacio-hydro isostatic adjustment of the crust subsequent to the last deglaciation. When corrected for this, using geologically constrained model predictions, the change in eustatic sea level since the Roman Period is -0.13 ± 0.09 m. A comparison with tide-gauge records from nearby locations and with geologically constrained model predictions of the glacio-isostatic contributions establishes that the onset of modern sea-level rise occurred in recent time at ~ 100 ± 53 years before present.

Keywords: sea-level change; Mediterranean; Roman Period; recent eustatic change

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1. Introduction

Sea-level change is a measure of the relative vertical movement between land and sea surfaces and any observed change reflects both land movement and change in ocean volume. In the absence of tectonic processes, the principal contribution is from the growth and decay of ice sheets which introduces changes in ocean volume, in the shape of the ocean surface, and in the vertical position of the Earth's surface. Superimposed on this will be any vertical land movements, driven by tectonic forces or by sediment loading, and changes in volume caused,

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for example, by changes in the thermal structure of the oceans. Inferences of the changes in ocean volume from sea-level data, therefore, require an independent estimate of land movements that are the result of the tectonic processes and of the earth's isostatic response to ice and water loads during glacial cycles [1,2]. Estimation of this change during the present interglacial interval is important in the debate on the impact of humans on climate; for establishing whether processes such as thermal expansion of the oceans or the exchange of mass between the oceans and ground and surface water contribute to present or recent sea-level rise [3].

For the past five or six millennia, following the end of major deglaciation, changes in sea level have generally been small [1] and often less than the local tidal range. Thus, the preserved geological records of change loose resolution, and it is usually only possible to place upper limits of ~ 0.5 m on the accuracy of fluctuations in global ocean levels for this interval. The much more precise instrumental records for the past 100 or so years indicate that changes of the order 1–2 mm/year have occurred, but the duration of this change or the time of its onset remains uncertain [3,4].

Archaeological evidence from areas of small tidal range can provide significant information for this time interval using coastal structures whose successful functioning requires a precisely defined relationship to sea level at time of construction. Along Mediterranean shores, in particular, the increasing sophistication of human development has led to there being a number of archaeological remains that can be used to establish constraints on relative sea level although they often provided limiting values only [5–7]. We restrict ourselves here to one class of construction that is particularly important for defining precisely past sea levels, namely complexes of the coastal fish tanks (*piscinae*), constructed during the Roman Period from about 100 BC to 100 AD. These possess constructional elements that relate precisely to sea level [8,9].

In this paper, we examine the evidence from the central Tyrrhenian coast of Italy (Fig. 1). This is the region where the development of piscinae reached its greatest concentration in Roman time and where many well-preserved remains occur today. The best preserved of these sites have been re-examined providing new information on constructional levels of the piscinae that can be accurately related to mean sea level 2000 years ago. Isostatic and tectonic contributions to this change are then estimated from observational and model considerations to establish the eustatic change over this period. Comparison with estimates of present-day sea-level change recorded at nearby tide gauges, similarly corrected for isostatic and tectonic signatures, then permits the timing of the onset of the recent rate of eustatic change to be inferred.

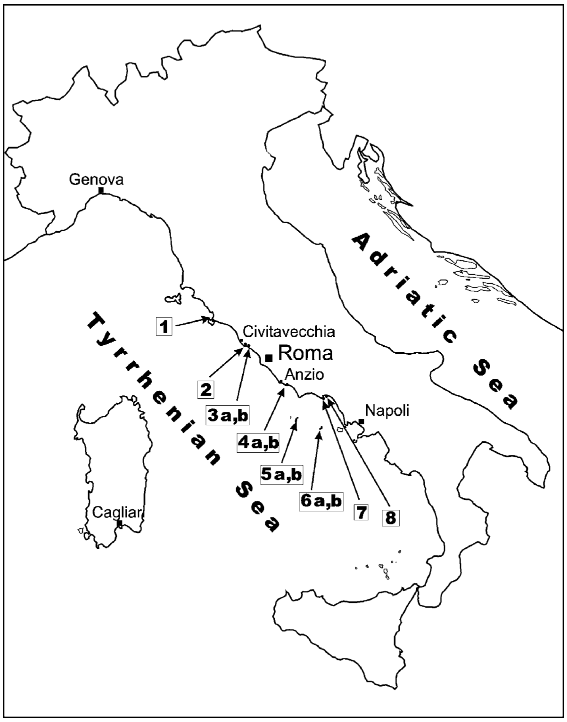


Fig. 1. Location map of the Roman epoch piscinae and tide-gauge sites along the central Tyrrhenian coast of Italy: (1) Santa Liberata, (2) Punta della Vipera, (3a) Santa Marinella Odescalchi, (3b) Santa Marinella Le Grottacce, (4a) La Banca, (4b) Torre Astura, (5a.b) Ponza (outdoor and indoor fish tank), (6a,b) Ventotene harbour and fish tanks, (7) Serapo and (8) Sarinola. The four tide gauge sites are located at Genoa, Civitavecchia, Naples and Cagliari.

2. Roman piscinae as sea-level indicators

Roman piscinae have constructional elements that bear directly on sea level at the time of construction [8] and well-preserved remains of these features provide a precise measure of sea-level change [5–

7,9]. According to Plinius [10] and Varro [11], the use of piscinae as holding tanks and fish culture was introduced between the end of the second century and early first century BC. But because of high construction and maintenance costs, they were used for a relatively short period only and the building of new tanks ceased during the second century AD [8,11]. Most of the known fish tanks in Italy (∼ 54 sites) occur along the Tyrrhenian coastline [9,12] near large Roman villas and only one is known along the Adriatic coast [13]. Only for a small number of these known sites have precise sea-level markers been preserved or identified (Figs. 1 and 2). Remains of piscinae are also found along the Mediterranean coasts beyond the Italian borders [5,14] but these are often lacking in the very features that give the

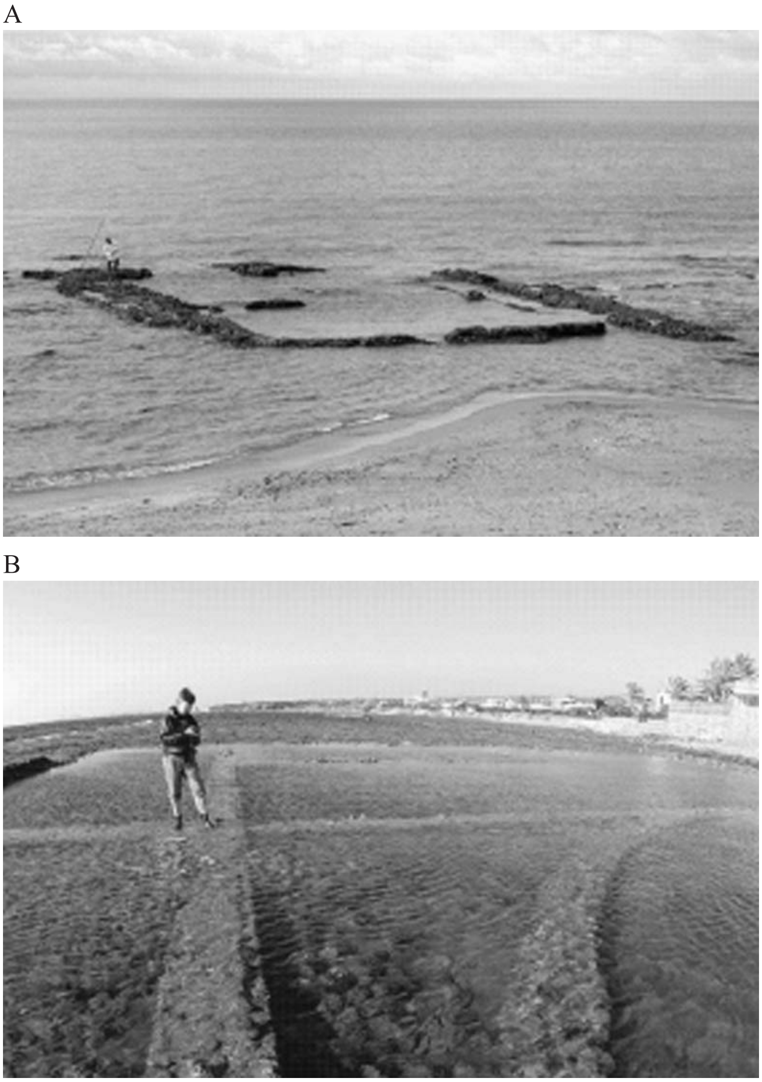
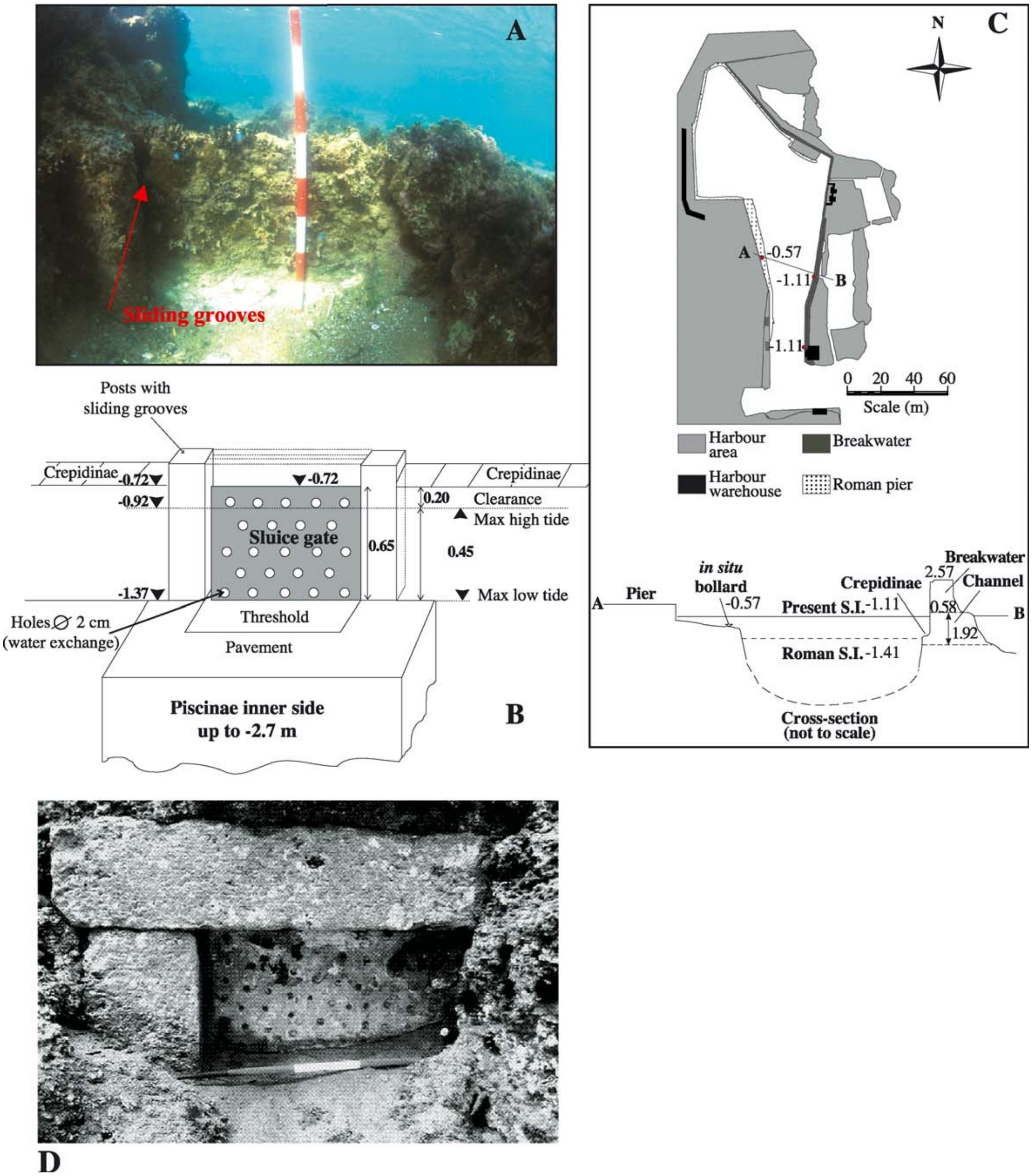


Fig. 2. Remains of Roman Epoch fish tanks at (A) La Banca and (B) at Punta della Vipera. At La Banca, the foundations of the outer walls that were built to protect the tanks from wave action are clearly visible but they cannot be directly related to sea level at the time of their construction. The inner walls of the tanks rising above present sea level represent the highest-level foot-walks that surround the now-submerged tanks (see Fig. 3 for details). At Punta della Vipera, these upper-level walks are more clearly seen and occur just below modern sea level. In both examples, the lowest level of foot-walks are now covered by sand and marine growth.

high accuracy for the Tyrrhenian examples and most of them have not yet been examined in detail.

The selected Roman fish tanks were, with one exception, carved into rock to a depth of 2.7 m or less *. . .in pedes novem defondiatur piscina. . .* depending on fish species, the exception being Sarinola where the tanks were built on limestone bedrock. Thus, local basin subsidence is negligible. The basins themselves were protected from wave and storm action by exterior walls, "*Mox praeiaciuntur in gyrum moles, ita ut conplectantur sinu suo et tamen excedant stagni modum*" [8], whose foundations have mostly been



preserved but whose relation to sea level is not defined. From Latin publications and new field surveys, the significant sea-level markers that have been identified including foot-walks (crepidines), channels, sluice gates with posts, sliding grooves and, in some cases, the actual sliding gates, and thresholds (Fig. 3) [9–12]. The foot-walks border the internal pools and occur at two or three levels but in most piscinae examined the lowest levels of crepidines are covered by sand and were not recognized or interpreted in earlier investigations [5–7,9,15]. The lowest surface is cut by channels that permit water exchange between the tanks and the open sea, with the flow being controlled by sluice gates. These gates consist of (i) a horizontal stone surface that defines the threshold and is cut by a groove to receive the gate; (ii) two vertical posts with grooves to guide the vertical movement of the gate; (iii) an upper stone slab with horizontal slot to extract the gate; and (iv) the gate itself with small holes to permit water exchange and prevent the escape of fish. The base of the channels coincides with the position of the threshold slab. The top of the sluice gate coincides with the elevation of the lowest level foot-walk and, to keep a safety margin, corresponds, as reported by Columella [8], "*Spissi deinde clatri marginibus infiguntur, qui super aquam semper emineant, etiam cum maris aestus intumuerit*," to a position above the highest tide level. From sites with complete preservation of sluice gates, channels and foot-walks, we estimate that the level of the lowest crepidine occurred at ~ 20 cm above the highest tide level. In the Tyrrhenian Sea the maximum tidal excursion is ≤40–45 cm [16], equal to the observed depths of the channels, and this indicates that the flow of water into the holding tanks was tidally controlled.

3. Piscinae results

Table 1 summarizes the local relative sea-level estimates for 15 sea-level indicators from 10 different localities. Only well-preserved sites, constructed on or in bedrock, have been used, particularly one where this sediment cover provided protection of important features of the basins. Upper-limit estimates are from the lowest foot-walks that coincide with the top of the sluice gate and lower-limit estimates are from the channel thresholds. At some sites (Santa Liberata, La Banca, Ponza, Ventotene), both levels have been independently observed and the differences between the two limits correspond to the tidal range of 40–45 cm. At other sites, only one of the two limits has been directly observed and, based on the evidence from the sites with complete records, the missing limit has been estimated at 40 cm lower or higher, depending on whether the observation is an upper or lower limiting value. The two pairs of closely spaced sites, La Banca and Torre Astura and Santa Marinella Odescalchi and Santa Marinella Le Grottacce, provide a means of verifying the interpretations. At Ponza and Ventotene, independent measurements have been obtained from different foot-walks, channels and sluice gates, as well as from channels and foot-walks within the nearby harbour of Ventotene and their intercomparison provides further verification of the interpretation and the estimation of the precision of the observations as well as confirming that there has been no differential vertical displacements within the construction. In compiling Table 1, we have avoided using thresholds of channels that control water exchange within the pool complex itself because in some piscinae brackish-water environments were created for fish breeding by mixing fresh

Fig. 3. (A) Underwater photo of the in situ sluice gate at La Banca. The complete gate consist of: (i) a horizontal stone surface that defines the threshold with a groove to receive the gate; (ii) two vertical posts with grooves to guide the movement of the gate; (iii) an upper stone slab with horizontal slot to extract the gate; (iv) the gate itself, ~ 65 cm high, with small holes for water exchange. In this illustration, the gate is partially covered by sand and the bright zone is that part of the gate that has been cleaned of sand and biological growth. The threshold, covered by sand, lies ~ 10 cm below the measuring rod that is calibrated at 10-cm intervals. (B) Sketch of the channel sluice gate with sliding posts, threshold and lowest level crepidinae as viewed from within the fish tank. 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. In this example, the lowest foot-walk is now 0.72 m below the sea surface at the time of measurement and the threshold is 1.37 m below present sea level. (C) Plan and cross-section of the Ventotene Roman harbour indicating structures that identify limiting values to sea level, including the lowest level foot-walks and bollards carved into the rock. Roman time sea level is ~ 1.40 m below present mean sea level (m.s.l.), the now-submerged bollard would have been at ~ 0.85 m above m.s.l. and the lowest level quay-side foot-walks are estimated to have been ~ 0.30 m above m.s.l. The channel through the breakwater at B for flushing the harbour remained operational at all tidal levels. (D) Detail of the submerged sluice gate within the interior of the pool complex at Ventotene. The gate with the holes to permit water exchange is clearly visible as is the lower-threshold stone at the base of the gate.

Table 1
Local relative sea level inferred from the Roman fish tanks

Point, type	Age	Significant features	Δh Below sea level (m) [UL, LL]	Previous measurements (m)			MIS 5.5 (m), Tectonic rate (mm/year)	Isostatic change in the last 2 ka, and reduced observed levels in brackets (m)
				A	B	C		
(a)	(b)	(c)	(d)	(e)			(f)	(g)
Santa Liberata								
1	0–100	SP, TH	0.79 UL m	−0.61	−0.45	−0.30/	6	−1.16
PEL	AD	CH	1.29 LL m			−0.40	−0.01 ± 0.05	(−1.11)
			1.04 ± 0.25					
Punta della Vipera								
2	0–100	TH, CH	1.08 UL m	−0.65	−0.45	−0.32/	30	−1.15
PES	AD		1.48 LL e			−0.44	0.18 ± 0.05	(−1.75)
			1.28 ± 0.20					
Santa Marinella Odescalchi								
3a	50 BC/	TH, CH	1.29 UL e	–	–	–	30	−1.14
PES	50 AD		1.69 LL e				0.18 ± 0.05	(−1.93)
			1.49 ± 0.20					
Santa Marinella Le Grottacce								
3b	50 BC/	CR, SG	1.17 UL m	−0.60	−0.40	−0.65	30	−1.14
PES	50 AD	SP	1.57 LL e				0.18 ± 0.05	(−1.81)
			1.37 ± 0.20					
La Banca								
4a	50 BC/	CR, SG	0.92 UL m	–	–	–	10	−1.22
PET	50 AD	SP	1.37 LL m				0.02 ± 0.05	(−1.19)
			1.145 ± 0.225					
Torre Asture								
4b	50 BC/	CR	0.82 UL m	−0.65	−0.50	−0.30/	10	−1.22
PET	50 AD		1.22 LL m			−0.50	0.02 ± 0.05	(−1.06)
			1.02 ± 0.20					
Ponza								
5a	20 BC/	CR, SP	0.92 UL m	–	–	–	n.d. (7.5)	−1.35
OPER	30 AD	TH	1.32 LL m				0.0 ± 0.5	(−1.00)
			1.12 ± 0.20					
			0.73 UL e					
OPER		SP	1.88 LL m					
		TH	1.30 ± 0.57					(−1.18)
5b	20 BC/	SP, TH	0.91 UL m	−1.05	–	–	n.d. (7.5)	−1.35
IPER	30 AD	CR, SG	1.34 LL m				0.0 ± 0.5	(−1.00)
			1.13 ± 0.22					
		CR	0.86 UL e					
IPER		TH	1.66 LL m					
			1.26 ± 0.40					(−1.14)
Ventotene								
6a	20 BC/	CH, CR	1.30 UL m	>−0.48	–	–	7.5	−1.30
HET	30 AD	BA (pier)	1.70 LL m				0.0 ± 0.05	(−1.42)
			1.50 ± 0.20					
6b	20 BC/	CR (tunnel),	1.35 UL m	−0.80/	–	–	7.5	−1.30
PET	30 AD	TH, SG,	1.70 LL m	−1.33			0 ± 0.05	(−1.45)

Table 1 (*continued*)

Point, type (a)	Age (b)	Significant features (c)	Δh Below sea level (m) [UL, LL] (d)	Previous measurements (m) (e)			MIS 5.5 (m), Tectonic rate (mm/year) (f)	Isostatic change in the last 2 ka, and reduced observed levels in brackets (m) (g)
				A	B	C		
		SP, CH	1.53 ± 0.18 1.30 UL e 1.70 LL m 1.50 ± 0.20					(– 1.42)
Serapo								
7 PES	0–100 AD	CR	1.28 UL m 1.68 LL 1.48 ± 0.20	–	–	–	4.0 – 0.03 ± 0.05	– 1.32 (– 1.37)
Sarinola								
8 PBL	50 BC/ 100 AD	CR, TH SP, CH	0.88 UL m 1.28 LL m	– 0.55	– 0.40	– 0.32/ – 0.36	6.0 – 0.01 ± 0.05	– 1.32 (– 0.98)

(a) Site names and numbers as indicated in Fig. 1 and the type of archaeological remain: PEL = piscinae excavated in limestone; PES = piscinae excavated in sandstone; PET = piscinae excavated in tuff; OPER = outdoor piscinae excavated in ryolithe; IPER = indoor piscinae excavated in ryolithe; HET = harbour excavated in tuff (east side); PBL = piscinae built on limstone.

(b) Age estimates are based on historical documentation [9,12] or on the assumption that they were built in a 100-year interval from 50 BC to 50 AD. Due to high construction and maintenance costs the piscinae were used during a short period only and the building of new tanks ceased in the second century AD [10,11].

(c) Architectural features used to define sea level: SP = sliding posts; TH = threshold; CH = channel; CR = crepidinae; SG = sluice gate; BA = bollard. The lowest crepidinae are assumed to be at 20 cm above high tide [8].

(d) Survey data: UL = upper limit, LL = lower limit, m = measured position, e = estimated position. UL, LL, m and e as well as the final values have been corrected for tides and atmospheric pressure. The maximum tidal range for the Tyrrhenian Sea is 0.40 m and tidal corrections are based on data from the Instituto Geografico della Marina, *Tidal Data Base 2002*. The atmospheric pressure correction is for the difference in pressure at the time of observation and the mean annual pressure for the site and is based on the inverted barometer assumption using nearby station data from www.metoffice.com.

(e) Previous measurements (A = Schmiedt [9], B = Pirazzoli [7], C = Leoni and Dai Pra [15]).

(f) Height of the MIS 5.5 shoreline (m) and vertical tectonic rate (mm/year) based on assumption of uniform uplift rate, an elevation of 7.5 ± 2.5 m for this shoreline in the absence of tectonics, and a formation age of 124 ± 5 ka. n.d. = not determined and assumed to be tectonically stable.

(g) Glacio-hydro-isostatic sea level change based on geologically calibrated models for Italy of the adjustment of the Earth to the redistribution of ice and water loads during the last glacial cycle [28]. The numbers in parenthesis are the estimates of sea level reduced to the Torre Astura site for the differential isostatic corrections, vertical tectonics and to the common epoch of 2000 years ago.

and marine waters and in these cases the internal thresholds may not relate precisely to sea level.

All measurements of the depths of the archaeological features were made at times of little wave action and with respect to the instantaneous sea-level position. Because the piscinae were used year round, the defining levels are assumed to correspond to annual mean conditions at the time of construction. The measurements are therefore reduced to mean sea level using tidal corrections from the Instituto Geografico della Marina, *Tidal Data Base 2002* [16]. The atmospheric pressure effect on sea level is calculated to allow for the difference in pressure between the time of observation and the mean annual pressure for the site. These corrections are based on the inverted barometer assumption using nearby station meteorological data [17].

Differences between results for the coastal localities may occur if all observations do not correspond to the same epoch. For some of the piscinae, the exact period of construction can be established from the historical documentation [9] and where they differ from 2000 before present (BP) they have been reduced to this common epoch using the rates of sea-level rise for this epoch that has been estimated from the geologically constrained isostatic model (see discussion later). When direct age estimates are not available, the adopted ages are based on the assump-

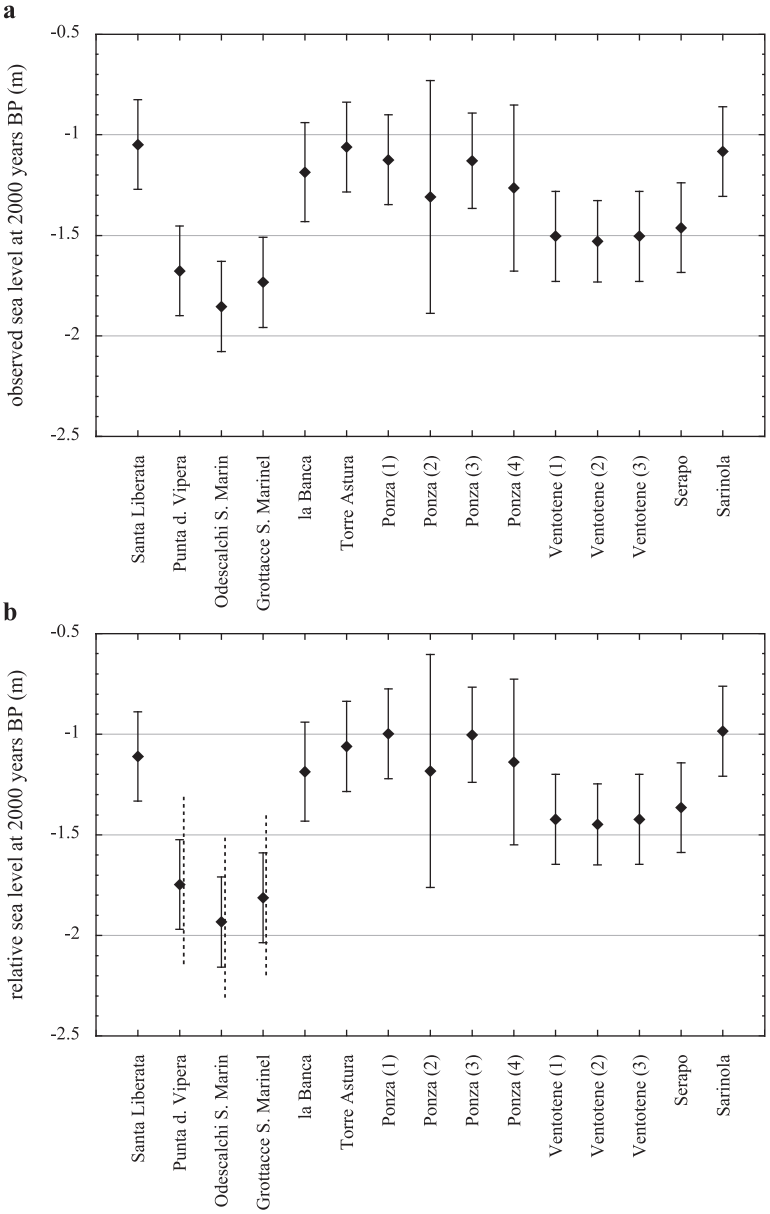


Fig. 4. (a) Observed positions of Roman Epoch sea level, relative to present (meters). All results have been corrected for tidal and atmospheric pressure differences between the time of observation and the modern annual mean values and have been reduced to the common epoch of 2000 years BP. The error bars for the individual estimates include all known sources of uncertainty. (b) The same as (a) but the results for each site have been corrected for vertical tectonic movement inferred from the elevation of the MIS 5.5 shoreline and for differential isostatic displacement of the site with respect to Torre Astura. The mean value represents the estimate of sea level at Torre Asture at 2000 years BP in the absence of tectonics but includes the glacio-hydro-isostatic signal for this location. The dashed error bars for Punta della Vipera, Santa Marinella Odescalchi and Santa Marinella Le Grottace assume that the uncertainty of the tectonic correction is equal to the magnitude of the applied correction.

tion that the piscinae were built in a 100-year interval from 50 BC to 50 AD. The uncertainty that this introduces is not significant here with all differential corrections less than a few centimeters. But because of the short duration of the construction period, the piscinae data do not span a sufficiently long time interval to establish the rate of sea-level change in Roman time. Also, an examination of harbour and quarry remains from earlier Etruscan and Hellenic [7,14] periods have not yet yielded sufficiently precise sea-level markers to be useful for estimating the rate of change.

Fig. 4a illustrates the tidally and atmospherically reduced results and reduced to the common epoch of 2000 years BP. Independent estimates from within the same pool complex (e.g., Ponza, Ventotene) are internally consistent, as are estimates from pool features from nearby complexes (the two Santa Marinella fish tanks and T. Astura and La Banca) and the pool and harbour results from Ventotene. The results indicate that at the time of construction, sea levels were between 1.1 and 1.8 m lower than today and up to 0.6 m lower than previously determined [6,7,9,15]. This latter difference is primarily because the previously unrecognized lowest-level foot-walks, with their close positional relationship to the sluice gates and channel thresholds, have been used here rather than the higher levels used in the earlier investigations. Also, we have not used thresholds that control water exchange inside the pool complex, nor have we used elevations of the remains of the outer protective walls because these do not bear a precise relationship to mean sea level.

4. Tectonic and isostatic contributions to vertical land movements

The central Tyrrehenian coast is a comparatively stable tectonic province and has been devoid of major seismic activity for the past 2000 years [18–20]. Stability is also indicated by the MIS 5.5 shoreline (formed 129,000 to 119,000 years BP), which is well defined along the Tyrrhenian coast by geomorphological features and by the occurrence of the Senegalese fauna that is characteristic of this interglacial interval [21]. It occurs mostly at elevations of between 5 and 10 m, which is consistent with its position at tectonically stable regions of Sardinia and elsewhere [22–24]. But between Punta della Vipera and Anzio, this shoreline occurs at higher elevations, reaching ~ 30 m at Punta Della Vipera [25,26] possibly as a result of lithospheric flexure and/or thermal effects associated with nearby Late Quaternary volcanic loading. In calculating the rate of vertical tectonics and the accuracy of this rate, we assume that the ‘expected position’ of this shoreline in this region is, in the absence of tectonics, at 7.5 ± 2.5 m above present sea level. We also assume an age of 124 ± 5 ka for this shoreline and assume that uplift has been uniform. (However, the absence of historically recorded earthquakes from this region suggests that these average rates may not be representative of the last few thousand years.) Table 1 includes the estimated elevation of the MIS 5.5 shoreline and the resulting average rate of vertical movement.

Sea levels along the Tyrrhenian coast, like elsewhere in the Mediterranean [27–29], are subject to the isostatic response of the planet to glacial unloading of high-latitude ice sheets during the last deglaciation as well as to the loading of the ocean floor by the melt water (glacio-dhydro-isostasy) at rates that are functions of the glacial history of the ice and of the rheology of the mantle. The glacio-isostatic response is one of an ongoing collapse of a broad bulge that formed around the ice sheet at the time of glacial loading and which extends into the eastern Mediterranean region [29–31]. The hydro-isostatic response is one of the loading of the sea floor by the glacial melt water and superimposes a shorter wavelength spatial variability on the more regional glacio-isostatic response. Both include the effect of the change in gravity field due to the redistribution of surface mass and the deformation of the solid planet [1,2]. The predominant consequence of the isostatic rebound is that sea levels have continued to rise up until recent time along the entire length of the Italian coast at a rate that is a function of distance from the centres of former glaciation but which is also a function of the coastal geometry. Because of the high precision of the observational data the solution of the isostatic sea-level equation [32] has been carried out to the ninth iteration to ensure convergence at the millimetre level.

Abundant geological evidence exists for the sea-level change for the past ~ 14 ka and, together with evidence for the elevation of the Last Interglacial shoreline, this provides the means of estimating the rebound-model parameters and of separating this rebound from other tectonic influences [28]. Analysis of data from Italy for the past 14 ka yields response parameters that are consistent with analyses from other regions of the world [1,28] and Table 2 summarises the range of earth-model parameters that yield solutions that are consistent with the geological data. The glacio-hydro-isostatic rebound model is based on an ice history that extends back through two full glacial cycles with the assumption that, while most melting has ceased by 7000 years BP, a small increase in ocean volume continued until about 3000 years before present, consistent with sea-level evidence from localities inside and outside the Mediterranean [2,27,33,34] as well as with observations of decreasing Late Holocene ice volumes in Antarctica [35].

The adopted error model for the isostatic calculations is based on the predicted values for a range of earth- and ice-model parameters that are consistent with the geological evidence along the Tyrrhenian coast. This range is specified by the parameters in Table 2 for the earth models while for the ice-sheet contribution different models for Scandinavia and North America have been used [28], that are consistent with rebound analyses for these two regions. The resulting uncertainty estimates of the isostatic corrections are less than 10% of the corrections themselves. Some spatial variability in the isostatic response occurs, with some sites (e.g., Santa Liberata) closer to the former ice sheets than others (e.g., Sarinola) and two sites located offshore (Ponza and Ventotene). But for this section of the Tyrrhenian coast, the spatial variability of the isostatic response is small, ~ 20 cm at 2000 years BP, and to facilitate intercomparison, sea-level observations from the piscinae sites have been reduced to a common location by applying differential isostatic corrections. The Torre Astura site has been adopted here as the reference point although any other site could have been equally adopted.

Table 2
Earth-model parameter range for the three-layer mantle model

Lithospheric thickness:	$H_1 = (50-100)$ km
Upper mantle viscosity:	$\mu_{\mathrm{um}} = (2-5) \times 10^{20}$ Pa s
Lower mantle viscosity:	$\mu_{\mathrm{lm}} = (5-20) \times 10^{21}$ Pa s

The upper–lower mantle boundary occurs at 670 km depth. Elastic moduli and density profiles follow standard seismic models for mantle structure.

Fig. 4b illustrates the tectonically corrected estimates of relative sea-level change at 2000 years BP that have also been reduced for the differential isostatic corrections. These corrections are earth-model dependent, but their magnitudes are small and we adopt the centroid value for the range defined in Table 2. The precision of this estimate has been evaluated by subdividing the parameter space defined in Table 2 uniformly in log-space for viscosity and at 10-km intervals for lithospheric thickness and the isostatic values have been predicted for each combination of parameters within this space. These individual estimates are then weighted according to the ‘distance’ of the individual parameters from the mean values and the results in Fig. 4b are for weights of 1 for models near the centroid value (corresponding to ~ 15% of the total model space defined by Table 2), 0.25 for the outermost zone (corresponding to ~ 50% of the total model space) and 0.5 for the intermediate region. However, different weights, including equal weights, result in insignificant differences for the precision estimates and the final choice is unimportant.

The consistency between the individual site estimates is high and mostly within the estimated observational uncertainties for the individual results. The possible exceptions are for Punta Della Vipera, Santa Marinella Odescalchi and Santa Marinella Le Grottacce which yield lower estimates than the other sites. This suggests that the assumed uplift, based on the elevation of the nearby MIS 5.5 shoreline, may not be appropriate for the shorter time interval and that these sites may actually have been subject to some subsidence over the past 2000 years. But without further information on the tectonic history of the region, we use the tectonically corrected values for these sites and we conclude that the Roman piscinae evidence provides a precise and reliable estimate of sea level. Furthermore, we adopt the weighted mean of the individual site estimates as a measure of sea level for a tectonically stable site at Torre Astura, where the weights are defined as the inverse of the sum of the observational and tectonic-correction variances, and conclude that sea level at 2000 years ago was 1.35 ± 0.07 m (standard deviation of the mean) lower than today. (This uncertainty estimate is based on the range of individual estimates in the earth-model and site-location space and is consistent with the value obtained from analysis of the individual error contributions.) This estimate of sea level at 2000 years BP is also in agreement with estimates of sea level based on less precise sedimentological evidence from the central Tyrrhenian coast [28] and, in the absence of further information on the uniformity or otherwise of the tectonic component, we adopt the latter value. (If the tectonic uncertainties of the Punta Della Vipera, Santa Marinella Odescalchi and Santa Marinella Le Grottacce sites are increased to the amplitude of the tectonic correction itself, then the estimated sea level at 2000 years BP is -1.26 ± 0.06 m.)

The total isostatic contribution to the change in sea level over the past 2000 years at Torre Astura is estimated at -1.22 ± 0.06 m at 2000 years BP for the weighted mean earth model. When compared with the observed value, this indicates that eustatic sea level in Roman time was at -0.13 ± 0.09 m.

5. Tide gauge results

Modern tide-gauge results are available for the Tyrrhenian coast from Naples, Civitavecchia, Genoa and Cagliari (see Fig. 1 for locations). The records extend back into the late nineteenth century, but no single record is continuous. The longest record is from Genoa, but it suffers from a major gap in the data. However, the other records, while of shorter duration, bridge this interval. Also, because they exhibit considerable coherence (Fig. 5) and there is some overlap, a pseudo-observational record can be established. This has been achieved here using the annual mean 'RLR' data set from the Permanent Service for Mean Sea Level [36] and a least squares parameter estimation for relative datum shifts and regional secular sea-level trend, after corrections for differential isostatic rebound, have been applied. (The RLR files contain some annual means that are marked as being less reliable than the others and in all parameter estimations these points have been given a weight of 0.5 compared with 1 for the others. Solutions in which this difference is increased do not lead to significantly different results.) Two separate records from Naples give overlapping and internally consistent results, and these have been combined into a single record by calculating the offset between the two records from the common time data points. Of the four sites, only Civitavec-

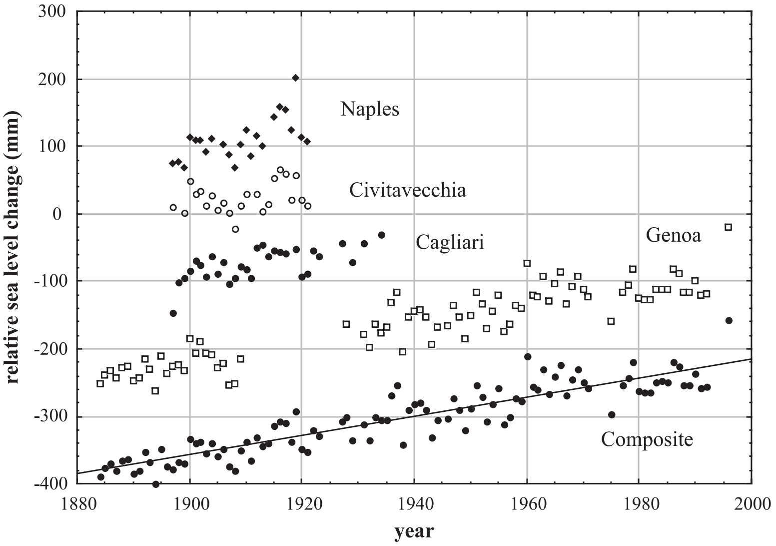


Fig. 5. The individual sea-level records from the annual means at four modern tide gauge records for the Tyrrhenian coast and Cagliari (see Fig. 1) and the composite record. Tectonic corrections have been applied where appropriate and differential isostatic corrections have been applied to reduce the results to a fictitious site at Torre Astura. The secular trend for the composite record is shown by the black line. This is the present-day rate of change that would be observed at a tectonically stable site at Torre Astura and includes the isostatic signal for this site.

chia, near Punta della Vipera, is from a region that may have been subjected to tectonic vertical movement if the elevation of the MIS 5.5 shoreline is used as a tectonic indicator. Thus, the above-discussed long-term geological estimate has been applied to the record although, because this record is relatively short, analyses for the regional secular change with or without this correction are not significantly different.

The differential isostatic corrections reduce the tide-gauge records to the ‘observed’ value at a fictitious site at Torre Astura, using the previously discussed isostatic model and parameter range. The dependence of the secular rate on the choice of earth model is small with values ranging from -1.51 to -1.60 mm/year across the earth-model space. Calculations with different weighting schemes discussed above for calculating the mean earth-model result give essentially the same result and we adopt -1.56 ± 0.20 mm/year for the ‘observed’ present-day relative sea-level rise reduced to Torre Astura. (If the above tectonic uplift rate of 0.18 ± 0.02 mm/year for nearby Punta della Vipera is applied to the Civitavecchia record with an increased uncertainy equal to the rate of uplift itself, then the composite estimate for the eustatic sea-level rise is 1.53 ± 0.21 mm/year.) The standard deviation is based on the covariance matrix of the least squares solution for the trend and datum shifts and has been scaled by the variance of unit weight estimated from the differences between observed and predicted sea levels. The isostatic sea-level correction for Torre Astura, based on the weighted mean earth model, is -0.54 ± 0.03 mm/year resulting in a eustatic sea-level estimate of -1.02 ± 0.21 mm/year. This estimate for the regional sea-level rise along the central Tyrrhenian coast compares with global analyses of sea level that indicate an averaged rise, corrected for the isostatic signal, of 1.8 ± 0.2 mm/year [37] but with significant regional departures from the mean value, with some regional trends as low as 1.0 mm/year [3,37]. In particular, it has been previously noted [38,39] that not only has sea-level rise in the Mediterranean been less than global estimates but that the rate of rise decreased significantly, or even changed sign, in the 1960–1990 interval.

Despite the isostatic corrections being relatively large and uncertain, the comparison of the isostatically reduced observation of the integrated eustatic change over 2000 years with the present rate of change is valid because consistent isostatic model corrections are applied to both data sets and the difference in isostatic rates for the two epochs is less dependent on the choice of model parameters then on the magnitude estimates. Then, if the present-day eustatic rate is extrapolated linearly back in time, the time at which the Roman Epoch value of the total eustatic change is reached can be estimated and this defines the time of onset of the modern sea-level rise. To allow for the correlation between the integrated and present-day rate of the eustatic change introduced by the isostatic corrections to the two components, this interval has been calculated for the range of earth models in the defined parameter space of Table 2 from which the weighted mean and variance is calculated as before. This yields 100 ± 53 years ago as the best estimate for the onset of the present-day sea-level rise. This result remains unchanged (96 years) if the tectonic uncertainties of the three sites are increased as discussed above for both data types. Solutions with different weighting schemes for averaging across the earth-model space give the same results within the above error bars.

The comparison of the Roman piscinae and tide-gauge results for eustatic sea level indicate that the present-day rate of change can only be representative of a short interval of time unless sea levels in the intervening period were actually lower than the Roman values. In the absence of evidence for this, the comparison indicates that this duration was of the order 100 ± 50 years and, while the uncertainties in this estimate remain large, the results are consistent with an onset of the present sea-level rise in the late nineteenth century or early twentieth century.

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