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SEA LEVEL CHANGE ALONG THE TYRRHENIAN COAST FROM EARLY HOLOCENE TO THE PRESENT

INTRODUCTION

In any discussion of the evolution of a river basin, the history of sea-level change is important since river gradients and delta developments are strongly influenced by local sea level. Also, sea level provides a reference for inferring past vertical tectonic stability from the geological record. Hence it is appropriate that the discussion on the Tiber basin starts with sea level change along the Tyrrhenian coast during the Holocene.

The past evidence for sea level comes from inferences of the position of the sea surface with respect to the present. Hence it is a relative measure; a function of both the changing position of the ocean surface and of the land surface or an integrated measure of changes in ocean volume, land movement and redistribution of water within the ocean basins. The observation therefore contains information on all the processes that change these surfaces: on geophysical, glaciological and oceanographic processes.

A consequence is that sea levels have a memory of the past. One process is the changing ice volume on the continents during glacial cycles. Because of the mantle viscosity the planet continues to deform long after deglaciation has ended and the 'glacial isostatic' signal is still very much in evidence today – not only in the formerly glaciated regions but also in areas far from the past ice sheets. The present-day tectonic movements of the land surface have their origins in the past evolution of the planet's interior and

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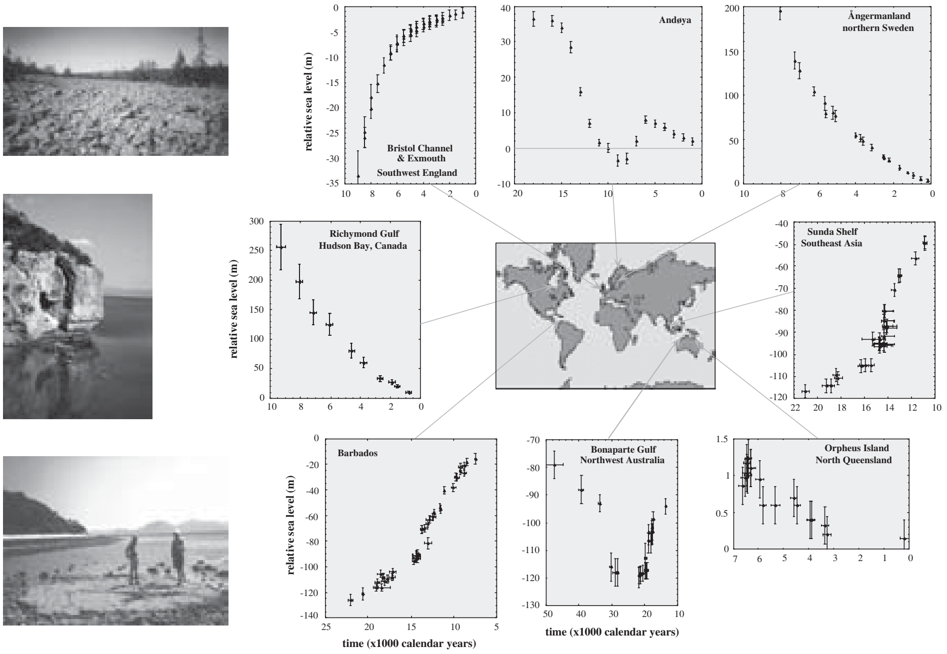

Fig. 1 – Observations of sea level change in different parts of the world from what are believed to be tectonically stable areas. The time scale is in 1000 years and is not the same for all sites. The vertical scale is the relative sea-level change in meters. This scale is not the same for all sites. The three illustrations on the left indicate some of the geological evidence on which the sea level curves have been constructed. Top: A boulder beach in northern Sweden which is now at ~200 m above sea level but which formed about 10000 years ago. Middle: Uplifted erosion notches in the Gulf of Corinth. The highest notch is about 3 m above sea level and dates from ~ 5000 years ago. This example indicates rapid uplift as a consequence of seismic activity. Bottom: A fossil coral colony that is now above its growth limits by about 1.5 m and which dates at ~ 6000 years before present. This example is from Orpheus Island on the Great Barrier Reef of Australia. Other 'micro-atolls' from the same area indicate that here sea level has been falling slowly for the past 60000 years.

what we see today was pre-ordained millions of years back in time, in the Italian case, largely by the convergence of the African and European continents. On a shorter time scale, the sea surface response to thermal pulses is not instantaneous, reflecting the convective time constants of the oceans.

Another important general point is that the sea level change is not spatially uniform. On the short term there are dynamic ocean effects from winds and currents. On the longer term the ocean is an equipotential surface and changes as the gravity field is modified by any redistribution of mass within the planet and on its surface. Also, land movements are spatially variable. Together, this results in a complex spatial pattern of sea-level change, as well as the time-dependent pattern, and this is well documented in the geological record even in the absence of vertical tectonic movements (Fig. 1) (Lambeck and Chappell, 2001). If this is true for the past, then it will also be true for present and future change and a description of the change by a single number is of limited value.

To reiterate, sea level has changed relative to the land for as long as there have been oceans due to geological processes that change the ocean-basin configurations and cause land movements; to the glaciological cycles of more recent geological time, that cause changes in ocean volume, in the gravity field and in the shape of the 'solid' surface; and to oceanographic and climate forcing. These changes at any time are not uniform over the surface and they are on-going. Thus the old truism, that we must learn from the past to understand the future is valid for sea level studies because part of what we measure today has its origins in the past and provide the 'natural' background signals upon which any 'climate change' signals will be superimposed.

The consequences of this change have been felt on the human time scale from the time man started the journey out of Africa. At periods of low sea level landbridges formed or waterways were much restricted in width such that most of the major land masses could be reached without losing sight of land. At times of rapidly rising sea levels coastal communities in middle and low latitudes were systematically threatened by the encroaching sea and ultimately inundated, giving rise to the various flood legends (Lambeck, 1996) and to the separation of groups of people from their ancestors by water bodies too wide to be crossed as, for example the separation of Tasmania from mainland Australia (Lambeck and Chappell, 2001). In some regions the rising sea supplied the sediments for accretion of the coastal zone, particularly with human assistance such as in the Netherlands. In other regions, the sea reached above its present level, such as in the Pacific at ~ 6000-4000 years ago, creating the atoll islands that today are under renewed threat from sea-level rise.

Sea level change during glacial cycles

In the absence of tectonics the principal driver of sea level change during quaternary time has been climate with the growth and decay of the land-based ice sheets following the planetary rhythms. This description is provided by the glacio-hydro isostatic theory for the deformation of the earth and of its gravity field under time-dependent and spatially realistic surface loads of ice and water.

This theory includes the following components (Cathles, 1975; Peltier, 1998; Lambeck and Johnston, 1998):

- As an ice sheet grows it takes water out of the ocean by an amount, if distributed uniformly over the ocean, referred to as the ice-volume equivalent sea level change. In the absence of any other processes affecting ocean volume it equates to eustatic sea level change. When the ice sheet melts, the melt water is added into the oceans. The ice sheets growth and decay is constrained by geological evidence for ice margin location through time and by ice thickness estimates based on geological evidence (rarely) or on glaciological models (more often).
- As the ice sheet grows or decays the gravitational attraction between ice and water is modified and the sea surface follows the new equipotential surface. This modifies the water distribution within the ocean basin. This changed water load in turn modifies the mass distribution and the gravitational potential. The meltwater is distributed into realistic descriptions of the ocean basins.
- Under the changing ice load the load stresses are transmitted via the lithosphere to the mantle which induces mantle flow away from the stressed areas and subsidence of the crust beneath and in the immediate vicinity of the ice. Hence the gravity field is further modified and there is an additional feedback to sea-level change.
- The water added or removed from the oceans modifies the ocean-load stress and hence the mantle stress field. This induces further mantle flow, surface deformation, gravity change and sea level modification.
- During the rise and fall of sea level the ocean basins deform and the basin margins migrate adding further complexity to the feedback process.
- Finally, with the mass redistribution the planet’s inertia tensor is modified, changing thereby its rotation and centrifugal force and hence the equipotential surface.

To quantify the theory, the Earth’s response functions must be known - its elasticity and viscosity structure - as must the history of the ice movements. Neither is particularly well known and will be partly constrained by observations of the sea level itself. Thus sea level change data from within the former ice margins are sensitive primarily to the ice thickness and mantle rheology, whereas sea-level observations far from the former ice margins are particularly sensitive to the total amount of ice added or removed from the oceans at any time. By a selective analysis of sea level data from different locations around the globe it becomes possible to develop an internally consistent description of the rheology and ice parameters that are consistent with the patterns of sea level, as recorded in Fig. 1, for example.

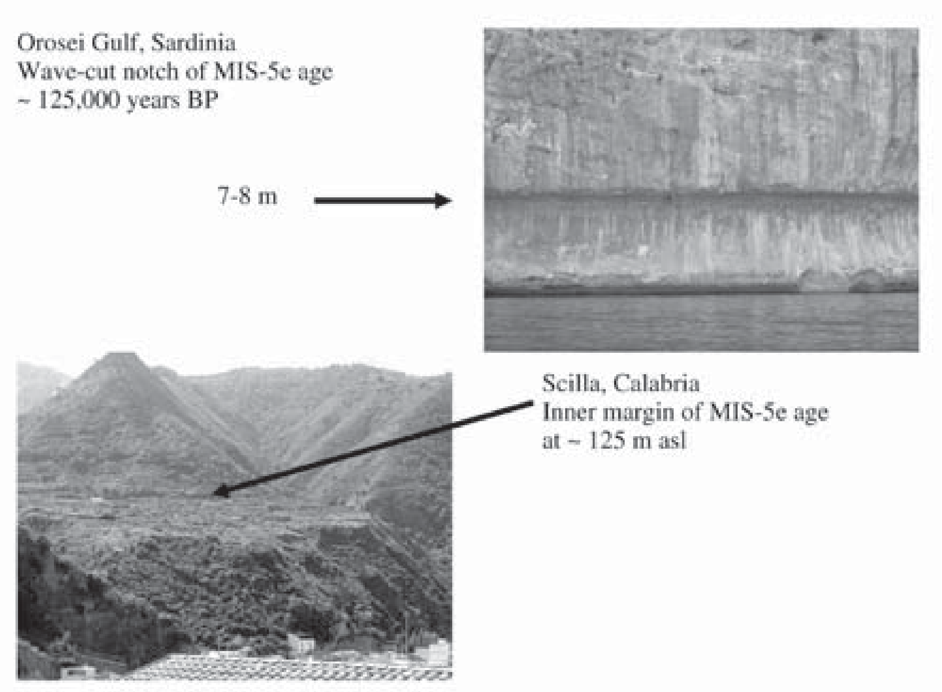

Fig. 2 – Two examples of the Last Interglacial (~125,000 years ago) shoreline location.

Sea level change along the Italian coast

For Italy, the past sea levels are the result of two main processes: the tectonic evolution of the Mediterranean region as a whole, and the response of the sea and the land to the glacial cycles. The tectonic influence is significant in some localities, as illustrated in Fig. 2. The erosion notch seen in the Gulf of Orosei in Sardinia formed during the Last Interglacial, at ~ 125,000 years ago, when sea levels globally were only a few meters above their present value and this area is believed to be tectonically stable to a high degree (Antonioli *et al.*, 2007). The elevated inner margin of the Last Interglacial sea in Calabria, in contrast, is at ~ 170 m above sea level and this is clearly a region of turmoil (Ferranti *et al.*, 2006). Sea level data from Sardinia will provide information on the glacial signal and data from Calabria will provide information on this and the tectonic signal. With the proviso that we can extrapolate the glacial signal from Sardinia to Calabria then the tectonic movements at this latter site can be established. This requires the quantitative theory for how the ocean and land surfaces respond to the glacial cycle and the parameters that define the ice history and the earth rheology.

For Italy, the main components of the glacial-cycle signature since the time of the last glaciation, are (Lambeck *et al.*, 2004a):

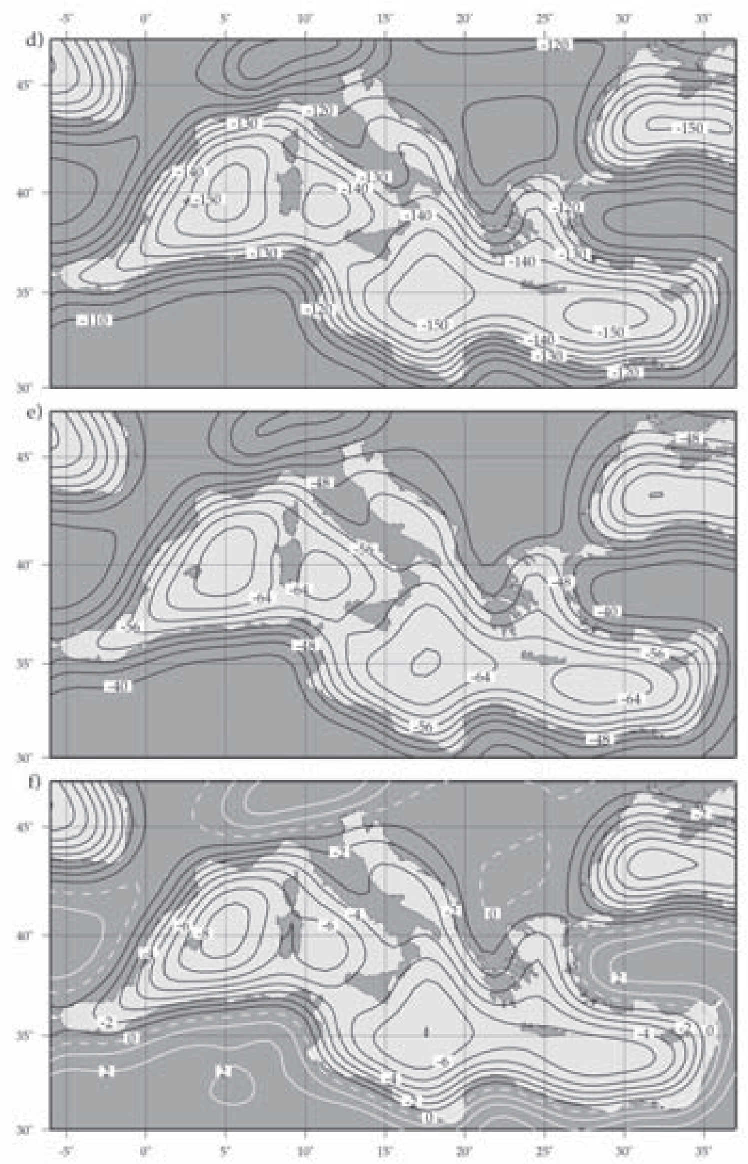

Fig. 3 – Predicted sea levels for the Mediterranean at three epochs. Top: 20,000 years before present (BP); Middle, 12,000 years BP; Bottom (6000 years BP).

- The ice-volume equivalent sea level signal, the globally average and spatially independent measure of ice-volume change.
- The mantle response to the deglaciation of the northern ice sheets (Eurasia, North America, Greenland) which in these cases is manifested by a slow subsidence of the crust of a broad uplifted zone that developed around the ice sheets during the ice sheet growth.

- The sea-floor response to the influx of meltwater into the Mediterranean basin.
- A contribution in the north from Alpine deglaciation.

Secondary effects include the contributions from Antarctic melting and from the glaciation-induced changes in planetary rotation. Nominal predictions of the total change are illustrated in Fig. 3 (Lambeck and Purcell, 2005). They show the spatial variability largely due to the water loading effect (120 m of meltwater added into the oceans if regionally isostatically compensated by the lithosphere would result in a sea floor subsidence of about 35m in the middle of a large basin and about half that amount at the basin margin). Visually this pattern largely masks the regional northerly to southerly trend from the mantle response to the ice sheet deglaciation but it can be seen in the asymmetry in the zero contour at 6000 years BP at the north and south margins of the Mediterranean, for example. Patterns such as these are substantiated by comparison with observational data across the region as well as for other parts of the world and the theory provides a good framework for discussing sea level along the Italian coast line.

The process for testing the model is then as follows:

- Schematically we define the relative sea level as

  $$\Delta\zeta_{\mathrm{rsl}} = \Delta\zeta_{\mathrm{esl}} + \Delta\zeta_{\text{É}} + \Delta\zeta_{\mathrm{T}}$$

  where $\Delta\zeta_{\mathrm{rsl}}$ is the (observed) sea level change, $\Delta\zeta_{\mathrm{esl}}$ is the ice-volume equivalent sea level change, $\Delta\zeta_{\mathrm{esl}}$ is the total isostatic signal (ice and water load, deformation and gravitation, and rotational changes), and $\Delta\zeta_{\mathrm{T}}$ is the tectonic component.
- We adopt the null hypothesis that there are areas of vertical tectonic stability, even within Italy, based on the evidence of the elevation of the Last-Interglacial shoreline and on the historical record of seismicity, or absence of seismicity.
- We use sea level data from these areas to test the models and infer model Earth-model parameters (*E*) that describe best the agreement between observations and predictions.
- We calculate the isostatic corrections $\Delta\zeta_{\mathrm{I}}$ and the $\Delta\zeta_{\mathrm{esl}} = \Delta\zeta_{\mathrm{rsl}} - \Delta\zeta_{\mathrm{I}}$ for the observation sites and epochs where we believe tectonic stability is plausible.
- If the $\Delta\zeta_{\mathrm{rsl}}$ agree with expected values from analyses outside of the Mediterranean where we have greater confidence in the stability assumption, or where we can correct for it, then we accept the null hypothesis. Otherwise we calculate the tectonic component $\Delta\zeta_{\mathrm{T}} = \Delta\zeta_{\mathrm{rsl}}$ (obs) – $(\Delta\zeta_{\mathrm{I}} + \Delta\zeta_{\mathrm{esl}})$.

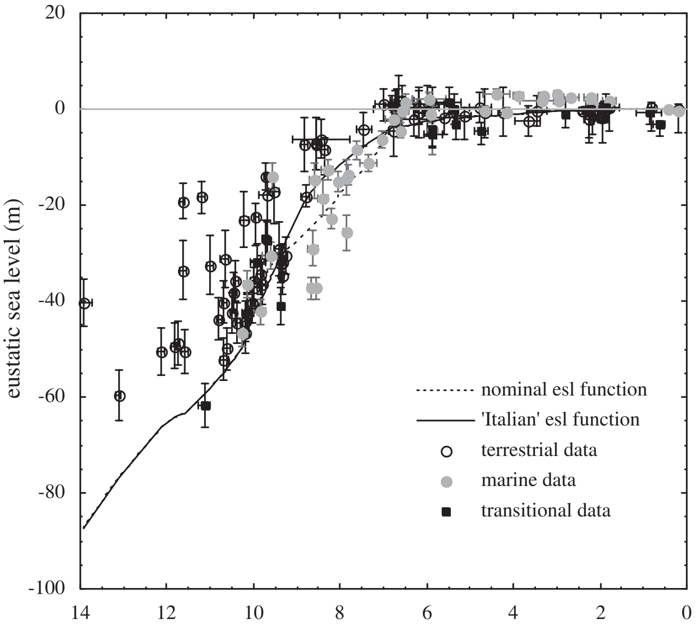

Fig. 4 – Comparison of the 'reduced' observational data, the $\Delta\zeta_{esl}$ estimates with the global $\Delta\zeta_{esl}$ function (the dashed line). The open circle markers correspond to terrestrial data points and should lie above the $\Delta\zeta_{esl}$ function. The grey markers refer to material formed below sea level and should lie below this function. The solid black square points are believed to have been formed in the intertidal zone and should, therefore, lie on the red-dashed line. The error bars include both the observational uncertainties and the uncertainties of the model predictions.

The observational evidence for sea level change is from both archaeological and geological sources. The latter are mainly from sediments that were deposited in shallow marine waters or in a terrestrial or supra-tidal environment. As such they form limiting values: terrestrial sediments found at -10 m indicate that sea levels were below this level at the time of deposition. The ages of deposition are determined from radiocarbon dating with the ages calibrated to a uniform time scale.

By way of illustration, Fig. 4 is a preliminary result based on a 2004 compilation of Italian sea level data (Lambeck *et al.*, 2004a). The areas of assumed tectonic stability are the Tyrrhenian coast with the exception of the Naples area, Puglia, western and southeastern Sicily, Sardinia and the Gulf of Genoa (Ferranti *et al.*, 2006). Agreement between observations and predictions for data within these localities is generally satisfactory when the uncertainties of both the observations and the predictions are taken into consideration. Around 8000 years ago there is however, some systematic discrepancy between the observed and predicted with marine data points

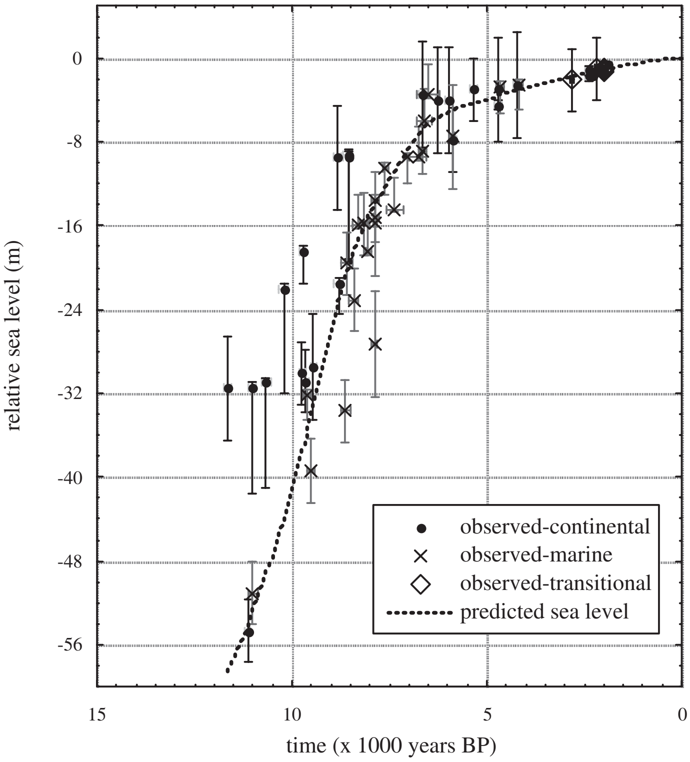

Fig. 5 – Predicted (dotted line) and observed sea level reduced to Roma-Tiber, from continental, marine and transitional data.

lying above their expected limits, and that leads us to conclude that the ice volume equivalent sea-level function $\Delta\zeta_{esl}$ may need some refinement. The nominal function used in this analysis is not in fact well constrained for this time, the emphasis of the original solution being on the earlier period, and from more recent evaluations, as yet unpublished, we conclude that the 'Italian' $\Delta\zeta_{esl}$ gives a better representation for this interval. We conclude that within the observational and model uncertainties that the assumption of tectonic stability for the selected sites is valid.

For the coastline at the mouth of the Tiber we are interested in obtaining a 'best' sea level curve that is representative of this area. This zone is affected by continuous sedimentation that has caused the coastline to advance up to modern times (Bencivenga *et al.*, 1995; Bellotti *et al.*, 1994). There are some observations from core sites near Roma airport but generally there is insufficient data to observationally construct a sea-level function. Instead we use observational data from a number of regional sites (at locations ϕ and epochs t) to calculate the differential isostatic corrections

Fig. 6 – Roman epoch indicators of sea level. *Top-left*: Remains of fish tank at La Banca. The outer wall foundations that protected the tanks form wave action are clearly visible. The inner walls arising above sea level represent the highest level of the footwalks that now surround the submerged tanks. *Top-right*: The Roman epoch harbour at Ventotene where the footwalks are now submerged. *Lower-left*: The insitu sluice gate at La Banca. *Lower-right*: Detail of the submerged sluicegate within the pool complex at Ventotene. By establishing sea level for the roman epoch from this sluicegate the original elevation of the footwalks at Ventotene can be established.

$$\varepsilon\zeta_{I} = \Delta\zeta_{I}\,(\phi,t) - \Delta\zeta_{I}\,(ref,\,t)$$

between these sites and a reference location (*ref*, *t*) within the Tiber plain, and then calculate the 'reduced' observational value for the reference site – the value that would have been observed if site f coincided with the reference site. That is

$$\Delta\zeta_{\mathrm{obs}}\,(ref,\,t) = \Delta\zeta_{\mathrm{obs}}\,(\phi,t) - \varepsilon\zeta_{I}\,(\phi,t)$$

The advantage of this approach is that the isostatic corrections change only gradually along the Tyrrhenian coast such that the differential corrections are more accurate than their absolute values. The result is shown in Fig. 5 and this represents our best estimate of the sea level rise along the coast of Latium for the past 12,000 years, this limit in time being the result of an absence of older observations in the region.

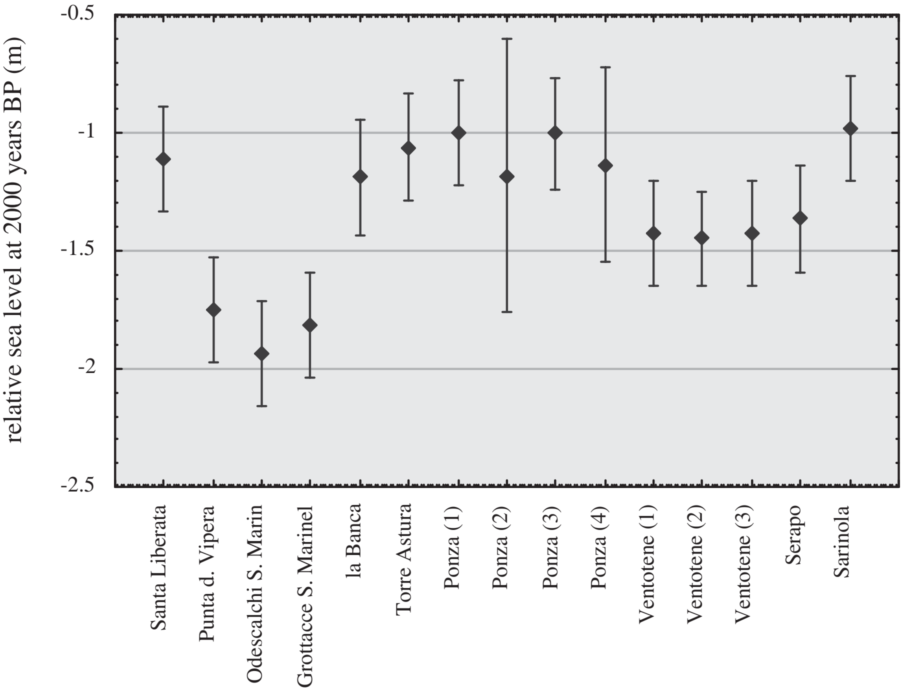

Fig. 7 – The Roman epoch sea level estimates from 15 fishtanks, corrected for tectonics and differential isostasy to reduce all estimates to Torre Astura. Their mean value is an estimate of sea level at this reference site in the absence of vertical tectonics.

SEA-LEVEL CHANGE FOR THE PAST 2000 YEARS

The geological evidence for sea level change for the past 2000-3000 years is generally of relatively low accuracy for this part of the coast but instead we have some high-quality archaeological data within this interval, notably the fish tank information from the Roman epoch of ~2000 years BP. These structures and their functioning have been fully described in the classic literature such that there is not the usual uncertainty associated with archaeological data of having to guess the functionality of the structures. For them to be functional the inlet and outlet channels and sluice gates must lie within the tidal oscillations and because the tidal range is small along much of the Italian coast where these structures are found, the present locations of these features relative to present sea level provide a precise estimate of change (Fig. 7).

The significance of the Roman epoch fish tanks for sea level studies was first recognised by M. Caputo who commissioned the authoritative surveys of Roman epoch fish tanks by Schmiedt (1972) and who made the first attempt to quantify the change in sea level since Roman times (Caputo and

Pieri, 1976). It was noted that for most locations the tanks were no longer functional, sea level having risen to a level where the channels and sluice gates are below sea level. This is an important observation because it should be possible to compare this change with the modern instrumental records to establish whether the latter are representative of a period longer than their actual record. The issue is that these records started mostly in the early twentieth century, so that it is not possible to assess whether the observed signal is part of the natural background signal or related to a human-induced climate change signal whose first impacts can be expected within that century.

Recently we revisited the question of whether we could obtain improved estimates of sea-level change from this archaeological data set, using our improved understanding of the isostatic and tectonic movements to correct the data for isostatic and tectonic contributions. Fig. 7 illustrates the results from 15 fish tanks in which it was possible to identify the channels, the positions of the sluice gates and their posts and sliding grooves, and the levels of the crepidenes (footwalks). They are distributed from near Argentario to Gaeta. Vertical tectonics along this section of the coast, as measured by the elevations of the last interglacial shorelines (formed ~ 125,000 years ago) and as indicated by a relatively low level of seismic activity, are believed to be small (Boschi et al. 1995). Also, the isostatic change over the past 2000 years is nearly constant for these localities so that it becomes possible to predict the differences in isostatic displacements for the sites to considerable accuracy and to reduce the measurements for all sites to a common location, in the same way as done for the geological data.

For the results in Fig. 7, all measurements have been reduced to Torre Astura, have been corrected for tidal differences and the ocean response to atmospheric pressure between the time of observation and the annual mean tide, for tectonics and for differential isostasy. The three anomalous results from Punta della Vipera and Santa Marinella may be the result of tectonics because here the last interglacial shoreline is higher (at ~ 30 m) than for the other sites where it is found at between 4 and 10 m. We have assumed that the uplift has been uniform over the past 125,000 years, whereas these results indicate that this may not have been appropriate. We have kept these numbers, however, with an appropriately large uncertainty to calculate the mean sea level change at Torre Astura over the past 2000 years as a rise of 1.35 ± 0.07 m.

We also analysed the tide gauge records for this section of the coast. There does not appear to be a single continuous record from the late 19th century to the present but we have been able to construct a composite record from overlaps between individual records and by correcting for differential isostasy to reference it to Torre Astura (Fig. 8). From this we conclude that sea level here has been rising at an average rate of 1.56 ± 0.20 mm/year.

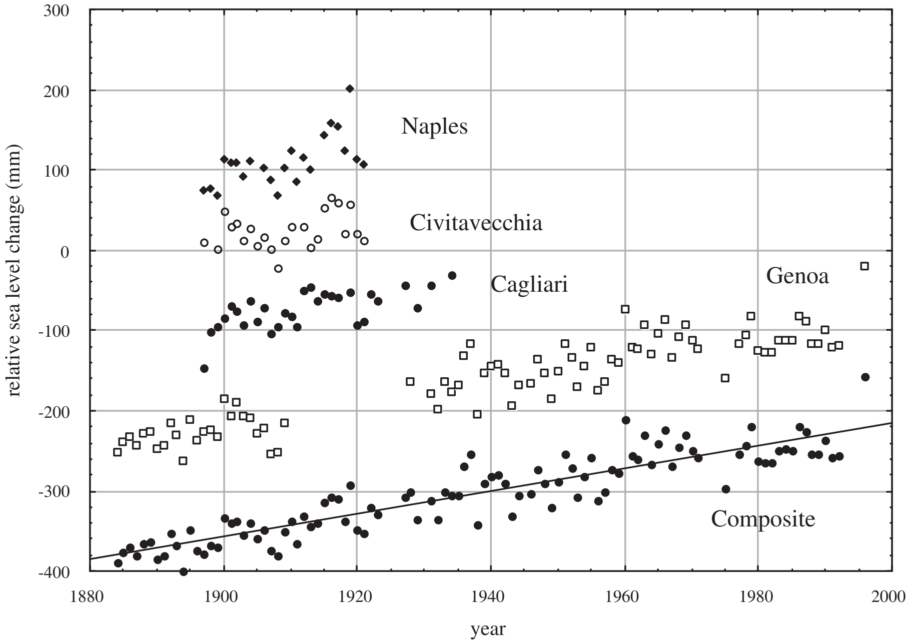

Fig. 8 – Tide gauge (annual mean values) records from four sites. Tectonic corrections have been applied where appropriate. Differential isostatic corrections have been applied to reduce the individual records to the Torre Astura site. The composite record is also shown. This includes the isostatic contribution for this site as well as any eustatic change.

Both the sea-level at 2000 BP and the present rate of change are affected by the isostatic signal from the past deglaciation and over the past 2000 years this signal has not been linear. When corrected for this, the 'eustatic' sea level at Torre Astura is 0.13 ± 0.09 m below present and the corrected present day eustatic rate is 1.02 ± 0.21 mm/year(1). Extrapolating this back in time means that the Roman epoch sea level is reached about 100 years ago (Lambeck *et al.*, 2004*b*). Uncertainties remain large, but the results indicate that the non-isostatic part of the modern observed sea level rise started about 100 years ago.

We are currently revising this work, using improved geological data sets, improvements in the resolution of the numerical modelling, and searching for additional archaeological records but we anticipate that the essential conclusions remain unchanged, that sea levels along the Tyrrhenian coast are - in the absence of tectonics - rising from both the 'natural' background signal and from a 'modern' signal that may be attributable to climate change.

(1) Strictly this contribution measures the local effect of recent increases in ocean volume due mainly to recent melting of glaciers and ocean warming. This contribution may vary regionally (see below).

FUTURE CHANGE

What the past record has shown is that there are natural background signals in sea level against which any 'human-induced' signals must be measured. A principal part of this background signal is the glacio-hydro-isostatic contribution that for Italy is not insignificant and that results in a rising future sea level even if there is no further climate-signal contribution. This rise is predictable with a high degree of confidence that can be improved by examining the past geological and archaeological records and by understanding the deglaciation history of the now-gone ice sheets and ice caps. For northern Italy, the influence from the Alpine deglaciation is not unimportant (Lambeck and Purcell, 2005). The other component of the natural signal is the tectonic one (we include subsidence by sediment compaction and sediment loading). This is less predictable and some analyses of sea-level change on different geological time scales indicate that the rates of vertical movement have not been constant. Forward prediction of these tectonic effects are no better than the prediction of earthquake activity. But the geological record does reveal which areas are particularly prone to vertical movement. The spatial scale of the tectonic movements is generally much shorter than that of the isostatic change and a greater density of field data is desirable in order to develop an improved understanding of these contributions to the land stability and to the relative sea-level change. (In some areas the tectonic contribution may be dominated by the consequences of sediment discharge from river systems and predictive models for this can be developed with some confidence.)

Two contributions to the 'human-induced' sea level signals must be recognised. One is land movements caused by extraction of fluids from the near-surface crust and this is essentially a local problem for local resolution. The other is the signal introduced by global warming, through thermal expansion of the oceans, melting of mountain glaciers and polar ice caps, and changes in the surface and ground water storage (Church *et al.*, 2001; Church *et al.*, in press). Estimates for these contributions are all still of low accuracy and are not yet at a point where they can unequivocally explain what is occurring today. We do not therefore address this contribution here but we do make one observation. Just as in the past, sea level has varied spatially so will it do so in the future. This is because of the earth's response to changes in the surface loads as water is added to or removed from the oceans and because of the ocean's response to the changing heat content within it. Both are capable of realistic evaluation under different climate scenarios provided that quality observations systems exist for calibrating and fine-tuning these evaluations through the time ahead.

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