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New insights on the relative sea level change during Holocene along the coasts of Tunisia and western Libya from archaeological and geomorphological markers

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A R T I C L E I N F O

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A B S T R A C T

New data of sea level changes for the Mediterranean region along the coasts of northern Africa are presented. Data are inferred from archaeological sites of Punic-Roman age located along the coast of Tunisia, between Tunis and Jerba island and along the western coast of Libya, between Sabratha and Leptis Magna. Data are based on precise measures of presently submerged archaeological markers that are good indicators of past sea-level elevation. Nineteen selected archaeological sites were studied in Tunisia and four in Libya, all aged between ~2.0 and ~1.5 ka BP. The functional elevations of significant archaeological markers were measured with respect to the sea level at the time of measurements, applying corrections for tide and atmospheric pressure values. The functional elevations of specific architectural parts of the sites were interpreted, related to sea level at the time of their construction providing data on the relative changes between land and sea. Observations were compared against sea level change predictions derived from the glacio-hydro-isostatic model associated with the Last Glacial cycle. The results indicate that local relative sea level change along the coast of Tunisia and Libya, has increased 0.2 ÷ 0.5 m since the last ~2 ka. Besides minor vertical tectonic movements of the land, the observed changes are produced by eustatic and glacio-hydro-isostatic variations acting in the Mediterranean basin since the end of the last glacial maximum.

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1. Introduction

This paper provides new data and interpretations on the relative sea-level change since the last ~2 ka along the coastlines of North Africa, in Tunisia and western Libya, where the recent relative sea-level changes have not yet been adequately constrained. For this purpose, coastal geoarchaeological installations and markers provide a powerful source of information from which the relative motions between the land and the sea can be estimated. Results are interpreted taking into account that sea-level change is the sum of eustatic, glacio-hydroisostatic and tectonic factors. While the first is global and time dependent, the other two also vary according to location and can be influenced by tectonics.

Recent studies have proved that archaeological evidence from small tidal range areas such as the Mediterranean Sea provide significant information for the estimation of relative sea-level changes since historical times, using ancient coastal structures (Schmiedt, 1965, 1974; Lambeck et al., 2004b; Antonioli et al., 2007). The latter are interpreted for their functionality, being precisely defined by their relationship to sea level at the time of construction. The Mediterranean shores are unique in the world in displaying a large number of archaeological remains, often well dated and sometimes very well preserved, that can be successfully used to provide constraints on relative sea level. Ancient fish tanks, piers and harbours constructions generally built around 2 ± 0.3 ka BP are the best indicators and provide a valuable insight of the regional variation in sea level in the last two millennia (Flemming, 1969; Schmiedt, 1974; Caputo and Pieri, 1976; Pirazzoli, 1976; Felici, 1998, 2000; Lambeck et al., 2004a, 2004b, in press; Antonioli et al., 2007, and references therein). Slipways and quarries carved along the coastlines and located near fish tanks and harbours or villas of the same age can provide additional data, both on the past water level and on their own functional elevation above sea level, although they are not very precise indicators (Flemming and Webb, 1986; Lambeck et al., 2004b).

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Archaeological evidence was examined from the North African coasts of western Libya and Tunisia, where maritime constructions since the Phoenician and Punic times can still be found. During the Roman age, extensive development of coastal installations occurred, as North Africa was an important Roman province. Here, many well-preserved remains are still present today. The best preserved sites provide information on their constructional levels that can be accurately related to the local mean sea level between ~2000 and ~1500 BP. Unpublished archaeological markers are used as benchmarks recording the relative vertical motion between land and sea since their construction or formation. The heights of the significant markers were measured and compared with the present sea level, applying corrections for tide amplitude and pressure values at the time of the surveys. These data, together with their relative error estimation (elevation and age), are compared with sea-level predictions using the prediction model of Lambeck and Purcell (2005) for the Mediterranean coast, recently applied in Lambeck et al. (2004b) and Antonioli et al. (2007) for the Mediterranean region. This model uses a new equivalent sea-level (esl) function (the ice-volume esl change; Lambeck and Chappell, 2001) that assumes a small continuous melting of the Antarctic ice sheet until recent times. The accuracy of these predicted values is a function of the model parameter's uncertainties is defining the earth response function and the ice load history (esl). The results provide new insights on the rates of relative sea level rise and on the vertical tectonic stability in this region during the last ~2 ka.

2. Materials and methods

Nineteen archaeological markers was surveyed along the coasts of Libya (4 sites) and Tunisia (15 sites) (Table 1). Analysis was performed through four subsequent steps: 1) measurements of the elevation of the significant archaeological markers of maritime structures with respect to the present sea level; 2) correction of the elevation measurements for tide and atmospheric pressure effecting the level of the sea surface at the time of surveys, using the data and algorithms adopted by the Permanent Service Mean Sea Level (PSMSL, www.pol.ac.uk, as well as Woodworth, 1991; Woodworth and Player, 2003) for the Mediterranean Sea (atmospheric corrections are based on the inverted barometer assumption using the closest available meteorological data obtained at www.metoffice.com); 3) error estimation for ages and elevation measurements of the archaeological markers, after their functional heights were evaluated on the basis of accurate archaeological interpretations (age errors are estimated from the architectural features; elevation errors derive from the measurements, corrections and estimates of the functional heights. For example, the lower limiting values for the quarries); 4) examination of the predicted and observed sea levels, by comparing the current elevations of the markers (i.e. the relative sea-level change at each location) with the sea-level elevation predicted by the last geophysical model for each location. Tectonic stability is hypothesized at the sites where the elevations of the markers are in agreement with the predicted sea-level curve. Conversely, an area has experienced tectonic subsidence or uplift when the elevations of the markers are below or above that of the predicted sea-level curve.

Field surveys were performed during September 2005 in Libya, and May 2007 and January 2008 in Tunisia. All elevation measurements were done by optical or mechanical methods during calm sea and they were related to the sea-level position for that particular moment. Since the investigated archaeological structures were originally used year round, the defining levels correspond to the

Table 1
(A) Site numbers (in brackets are listed according to our data base); (B) names as indicated in Figs. 4 and 5; (C) country; (D) type of archaeological remain; (E) and (F) are the WGS84 coordinates of the sites; (G) age estimates based on historical documentation; (H) functional elevation of the significant markers; (I) elevation error estimates; (K) limiting value of survey data: UL = upper limit, LL = lower limit; (L–O) are the predicted sea levels at 2 ka according to different parameters used in the model; (P) tectonic environment. Architectural features used to define sea level: P = pools; H = harbour; Q = quarry, N = notch, FT = fish tank, SW = slipway, S = sewerage, BW = breakwater, PV = pavement, RD = road, G = geology. The lowest cuttings of quarries are assumed to be at 0.30 m above high tide and the sidewalk (crepidinae) in the fish tanks at 0.20 m above high tide. For the pools of Sidi Mansour and Maamoura, perhaps dedicated to small flat fishes or production of *garum* (roman fish sauce), the minimum functional elevation corresponds to at least 0.3 m above the maximum local high tide. The current elevation of the road at Sidi Salem above the mean sea level is 0.43 m. For this marker, assuming a maximum tidal range of 0.90 m (from the Tide Gauge of Humtsuk) to keep the road always dry, indicates a sea level change of at least 0.45 m or, conversely, a relative sea level change < 0.45 m (if the road could be submerged during max high tides). Elevation data are the average values of multiple measurements collected at the best preserved parts of the investigated structures. All elevation data are corrected for tides and atmospheric pressure. The maximum tidal range in northern Africa is ~0.40 m with the exception of a limited part of the Gulf of Gabes that is subjected to tides up to 1.8 m. Tidal corrections have been performed used the algorithms of the PMSLS (http://www.pol.ac.uk). 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 http://www.metoffice.com. Columns K to N give predicted isostatic contributions for four earth models discussed in text. The tectonic rates assume uniform uplift since the time of construction of the archaeological markers. The uncertainty estimates include observational and model uncertainties.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Site No	Site name	Country	Marker	Latitude	Longitude	Age (ka)	Obs. rslc	σ obs.	Limit	ma3C	ma3A	ma2C	ma2A	Tectonic Rate
1 (9)	Gammarth	Tunisia	S	36.921	10.296	1.8 ± 0.05	−0.58	0.3	UL	−0.83	−0.61	−0.68	−0.49	0.12 ± 0.20
2 (8)	Carthage	Tunisia	SW	36.845	10.327	2.0 ± 0.1	−0.55	0.5	UL	−0.93	−0.69	−0.78	−0.56	0.17 ± 0.28
3 (10)	Mraissa	Tunisia	Q	36.976	10.868	2.0 ± 0.15	−0.48	0.2	UL	−1.09	−0.84	−0.89	−0.67	0.27 ± 0.16
4 (7)	Sidi Daoud	Tunisia	FT	37.002	10.894	1.8 ± 0.25	−0.28	0.1	LL	−0.97	−0.74	−0.78	−0.58	0.35 ± 0.14
5 (6)	Maamoura	Tunisia	P	36.455	10.804	1.5 ± 0.05	−0.46	0.2	UL	−0.62	−0.44	−0.52	−0.36	0.12 ± 0.18
6 (13)	Sidi Mansour	Tunisia	P	35.771	10.843	1.9 ± 0.1	−0,46	0.3	UL	−0.7	−0.47	−0.64	−0.44	0.13 ± 0.19
7 (11)	Salakta 1	Tunisia	P	35.388	11.042	1.7 ± 0.15	−0,55	0.3	LL	−0.6	−0.4	−0.55	−0.36	0.04 ± 0.21
8 (12)	Salakta 2	Tunisia	BW,P	35.388	11.041	1.7 ± 0.15	−0,58	0.3	UL	−0.6	−0.4	−0.55	−0.36	0.03 ± 0.21
9 (20)	El Grine	Tunisia	G	33.655	10.568	–	0.31	0.05	LL					–
10 (18)	Sidi Salem 1	Tunisia	RD	33.895	10.829	1.9 ± 0.1	−0,20	0.3	LL	−0.33	−0.12	−0.38	−0.19	0.11 ± 0.19
11 (14)	Lalla Hadria	Tunisia	PV	33.789	11.059	1.9 ± 0.1	−0,28	0.3	UL	−0.38	−0.17	−0.41	−0.22	0.09 ± 0.19
12 (16)	El Kantara (Meninx)	Tunisia	BW	33.683	10.920	2.0 ± 0.15	−0,31	0.3	UL	−0.33	−0.11	−0.39	−0.19	0.05 ± 0.19
13 (19)	Ersifet	Tunisia	Q	33.559	10.944	1.8 ± 0.1	−0,30	0.2	UL	−0.26	−0.06	−0.31	−0.13	0.02 ± 0.16
14 (17)	Rass Segala	Tunisia	H	33.532	10.925	1.8 ± 0.1	−0,34	0.3	UL	−0.25	−0.05	−0.30	−0.13	−0.00 ± 0.20
15 (15)	Gigtis	Tunisia	H	33.533	10.680	1.9 ± 0.15	−0,37	0.3	UL	−0.2	0.01	−0.28	−0.10	−0.04 ± 0.19
16 (1)	Sabratha	Lybia	P	32.808	12.486	2.0 ± 0.05	−0.48	0.2	LL	−0.43	−0.21	−0.44	−0.23	−0.00 ± 0.15
17 (5)	Fondough en Naggaza	Lybia	FT	32.717	14.100	2.0 ± 0.05	−0.24	0.2	UL	−0.75	−0.52	−0.66	−0.44	0.25 ± 0.15
18 (4)	Wadi Jabrum	Lybia	FT,Q	32.717	14.105	2.0 ± 0.05	−0.37	0.2	UL	−0.75	−0.52	−0.66	−0.44	0.19 ± 0.15
19 (3)	Villa Silin	Lybia	Q,N	32.709	14.178	2.0 ± 0.05	−0.38	0.2	UL	−0.76	−0.54	−0.67	−0.45	0.19 ± 0.15
20 (2)	Leptis Magna	Lybia	H	32.638	14.300	2.0 ± 0.05	−0.48	0.2	UL	−0.75	−0.52	−0.66	−0.44	0.13 ± 0.15

annual mean conditions at the time of construction. The measurements are therefore reduced to mean sea level applying tidal corrections at the surveyed sites, using the data of the nearby available tide gauges or the tidal predictions of the PSMSL. Corrections are generally within a few cm (the mean amplitude of Mediterranean tides is $<$45 cm) but, estimating and correcting for tide amplitudes are crucial for the central part of the Gulf of Gabes (Tunisia), as this area is affected by large tides (Sammari et al., 2006).

The *functional heights* of the archaeological benchmarks were defined in order to estimate the sea-level change in each location. This parameter has been extensively described in Lambeck et al., 2004b and applied in other studies (Auriemma and Solinas, 2009). It is defined as the elevation of specific architectural parts of an archaeological structure with respect to an estimated mean sea level at the time of their construction. It depends on the type of structure, on its use and on the local tide amplitudes. Functional heights also define the minimum elevation of the structure above the local highest tides. This information can also be deduced from previous publications (Schmiedt, 1965, 1974; Flemming, 1969; Flemming and Webb, 1986), from historical documents (Hesnard, 2004; Vitruvius), from the remnants of the Roman Age shipwrecks (which provided data on the size of the ships or boats and their draughts, as reported, for example, in Charlin et al., 1978; Steffy, 1990; Pomey, 2003; Medas, 2003) and through rigorous estimation of the functional heights of the piers, by using and interpreting different type of markers on the same location (Lambeck et al., 2004b). The use of these structures, their age and conservation, the accuracy of the survey and the estimation of the functional heights were all used in considering the observational uncertainties at each site. Concerning the functional height of quarries, found along the coast in Tunisia and Libya in proximity of coastal archaological sites, a value of at least 0.3 m was used. This value was estimated by the relationships between the lowest elevation of the mining place and sea level as inferred by the quarry in Ventotene island (Italy), compared with the functional elevations of the fish tank and the pier located in close proximity (Lambeck et al., 2004b). The latter provide precise estimates of the elevation of the Roman markers related with sea level and were used to calibrate the elevation of the quarry. This value was successfully applied to the other quarries in the Mediterranean (Antonioli et al., 2007). Besides archaeological markers, in one case biological indicators such as *Strombus bubonius* and *Lithophaga* were used. The latter was found still in situ at El Grine, southeastern Tunisia. It was extracted from the limestone units and was chosen among those fossils placed at the highest elevations above sea level. Its elevation has been measured at $+0.3$ m with respect to the local mean sea level, after tidal and pressure correction were applied.

3. Data along the coast of Tunisia

The $\sim$1300 km coastlines of Tunisia is abundant with archaeological installations whose ages date to the Punic age (Slim et al., 2004), although the best preserved sites are of Roman age of $\sim$2 ka BP (Fig. 1a and 2). As the aim of this paper is to provide new analysis and interpretation on the sea level changes since the last 2 ka, the archaeological features of the investigated sites are discussed briefly; readers are referred to specific archaeological publications. The survey data show a general evidence of coastal submersion since Roman time, from the elevation of urban structures, fish tanks, harbours, quarries and roadways (Fig. 3). Some sites, such as the fish tank at Sidi Daoud equipped with channels tidal controlled for water exchange (see Lambeck et al., 2004b for description of channel systems of fish tanks), provide an excellent estimation of the intervening relative sea level rise since its construction 0.28 $\pm$ 0.10 m (Fig. 4b). Other significant sites are the harbours of Gigtis and Rass Segala (Fig. 4c) that provide relative sea level rise values of 0.37 $\pm$ 0.30 m and 0.34 $\pm$ 0.30 m, respectively, from the functional elevations of the pier surfaces (see Lambeck et al., 2004b, and Antonioli et al., 2007, for description of the functional elevations of piers). Valuable data came from the two submerged pools of Maamoura (Fig. 4a) and the seven pools of Sidi Mansour (Fig. 4d). These sites, perhaps used as fish tanks for small flat fishes or garum sauce (Slim et al., 2004), both provide relative sea level rise of 0.46 $\pm$ 0.20 m and 0.46 $\pm$ 0.30 m, respectively. Data are inferred from the functional elevations estimated from the relationships between the differential elevation among the pool floors, the narrow channels for water exchange and the presently submerged walking surfaces. The latter were dry and above the high tides at the time of their construction. Other data are from the submerged buildings walls of Salakta (Fig. 4i), El Kantara and the roadway of Sidi Salem (Fig. 4e). The latter is presently in the tidal range. The quarries of Ersifet and Mraissa (Fig. 4f) indicated relative sea level rises of 0.30 $\pm$ 0.20 m and 0.48 $\pm$ 0.10 m, respectively (see Lambeck et al., 2004b, and Antonioli et al., 2007, for description of the functional elevations of quarries). The pavement of Lalla Hadria, the slipways of Carthage and the sewerage of Gammarth, are additional archaeological markers that show a relative sea level rise ranging between 0.58 $\pm$ 0.50 m and 0.28 $\pm$ 0.3 m. These sites have been included in the analysis, although they are less precise due to less constrained functional elevations. All these sites along the coast of Tunisia, are in agreement to show a relative sea level rise since the last $\sim$2 ka, in the range of 0.18 $\pm$ 0.2 m and 0.43 $\pm$ 0.3 m, with the exception of the less constrained markers as the slipway of Carthage (0.24 $\pm$ 0.5 m). The most precise data are from the fish tank of Sidi Daoud (0.05 $\pm$ 0.1 m) (Table 1).

Besides the archaeological remains, fossils of *Lithophaga* and *S. bubonius* were found. The first, placed at a corrected elevation of $+0.31 \pm 0.05$ m, was collected at El Grine, in SE Tunisia. The sample was dated through ^{14}C analysis and provided an age of 5846–5700 calibrated (CALIB 5.1, lab. N° DSH83). Its dating and position are in agreement with other biological data previously published (Jedoui et al., 2003; Morhange and Pirazzoli, 2005 and references therein). As regards the geological evidence of the Last Interglagial, a deposit containg *S. bubonius* at Monastir (Fig. 4g) occurs at 14 m above sea level. Elsewhere the elevation of similar Last Interglacial Aeolian and beach ridge deposits vary between 0 and 45 m above current sea level (Richards, 1996; Bouaziz et al., 2003; Elmejdoub and Jedoui, 2009).

4. Data along the coast of Libya

The Mediterranean coasts of western Libya show several coastal archaeological installations, such as urban structures, pools, harbours and quarries. Unfortunately, some are not well preserved, preventing their use for this study. Approximately 200 km of the western Libyan coast from the ancient cities of Sabratha to Leptis Magna was investigated (Fig. 2), where coastal installations such as the great harbour of Leptis Magna, the pools of Sabratha, and Villa Silin, can still be found. Other less precise sea level indicators, such as coastal quarries, provide additional information (Table 1).

The harbour of Leptis Magna is the most important archaeological site of this area and displays several sea level indicators consisting mainly in very well preserved piers with bollards (Fig. 5a). This harbour, which was abandoned after it was filled by sand caused by the failure of the dam placed at the mouth of the river which exits into the harbour basin, was surveyed for the first time in 1958 by Bartoccini (1960) who published exhaustive plans, including elevations of significant sea level indicators. In 2005, from the elevation of the piers (presently at 1.2 m above sea level) and the bollards, a relative sea level rise of 0.48 $\pm$ 0.2 m since the

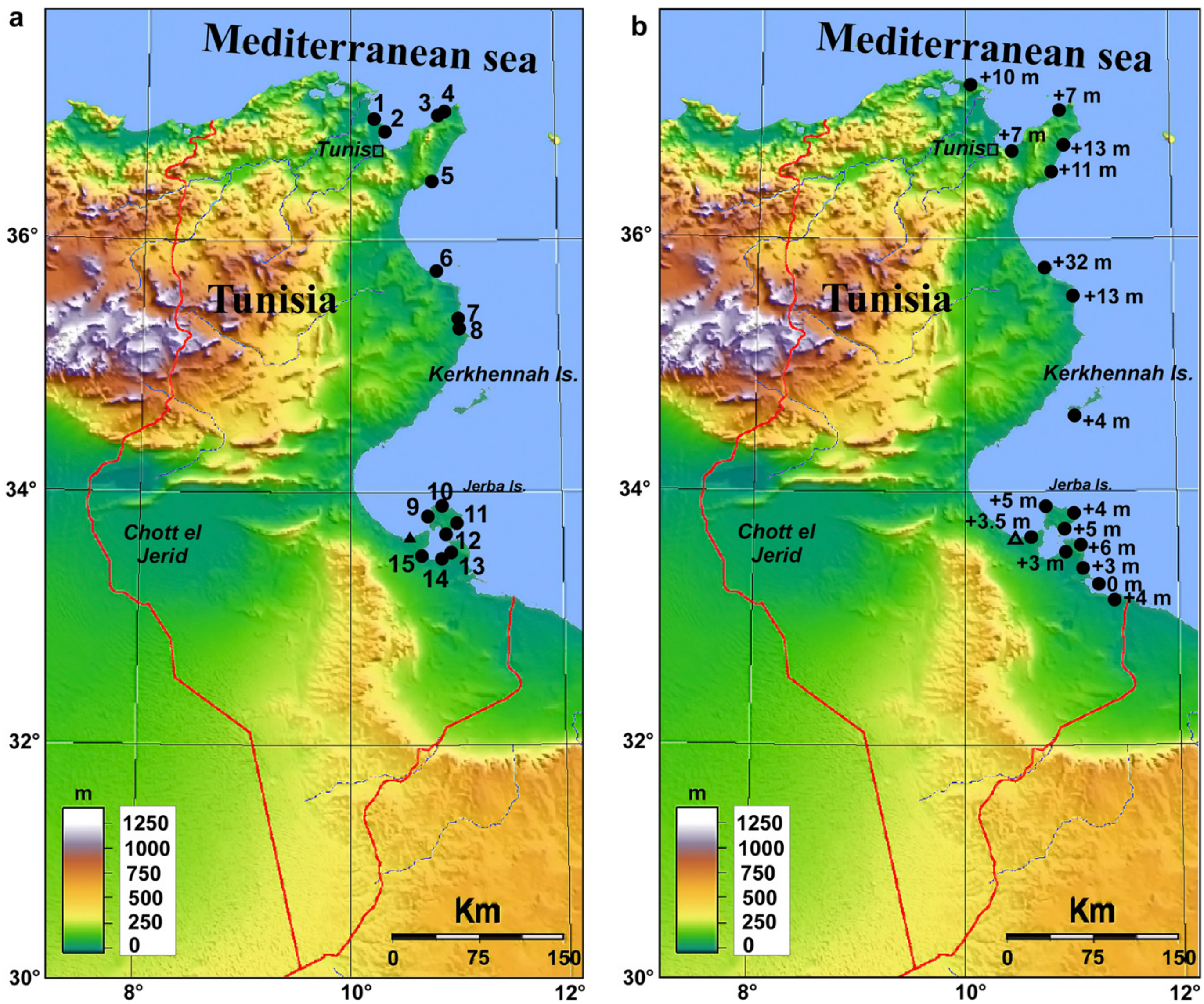

Fig. 1. (a) Map of the investigated archaeological sites in Tunisia; (b) elevation of the MIS 5.5 (modified from Bouaziz et al., 2003). The black triangle is the position of the *Lithophaga* sampled at El Grine.

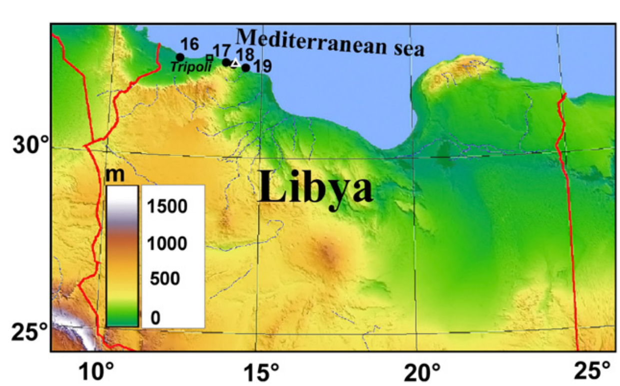

Fig. 2. Map of the investigated archaeological sites in Libya. The elevation of the MIS 5.5 at is also reported in the map. The white triangle is the position of the MIS 5.5 at +6 m above sea level (C. Faccenna, personal communication).

last 2 ka is estimated. This value is in agreement with the observation performed by Bartoccini in 1958. Other indicators include stairs and bollards, and reflect the commercial use of the harbour, planned for large commercial ships.

At Sabratha, the pools of the thermal area, equipped with channels opening toward the sea, indicate a sea level change of 0.48 ± 0.2 m (Fig. 5b). Minor relative sea level values are inferred from the coastal quarries of Villa Silin (Fig. 5c) as well as the fish tanks of Wadi Jabrum (Fig. 5d) and Foundoug en Nagazza. A tidal notch of 40 cm height is also present at Villa Silin, at an elevation corresponding to the current sea level.

Concerning the elevation of the MIS 5.5 transgression, fossil beaches are located between 5 and 10 m a.s.l., close to the fish tank of Fondoug En Nagazza (Claudio Faccenna, personal communication). Based on the elevation of the MIS 5.5 highstand this outcrop is assigned to the Last Interglacial (LIG).

5. The Isostatic model

The theory used here for describing the glacio-hydroisostatic process has been previously discussed in Lambeck et al., 2003 and its

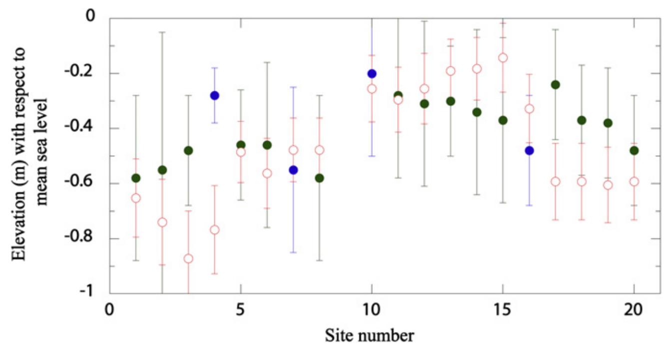

Fig. 3. Elevation (m) of the observed upper (green) and lower (blue) limits to sea level estimates from the archaeological sites compared with the predicted levels for the epoch of construction (open red circles). The predictions include the glacio-hydro isostatic contributions based on the mean of earth models discussed in the text and a contribution of recent increase in ocean volume at an equivalent sea level rate of 1.5 mm/year for the past 100 years (see Table 1 for data and Figures 1 and 2 for site location and numbering).

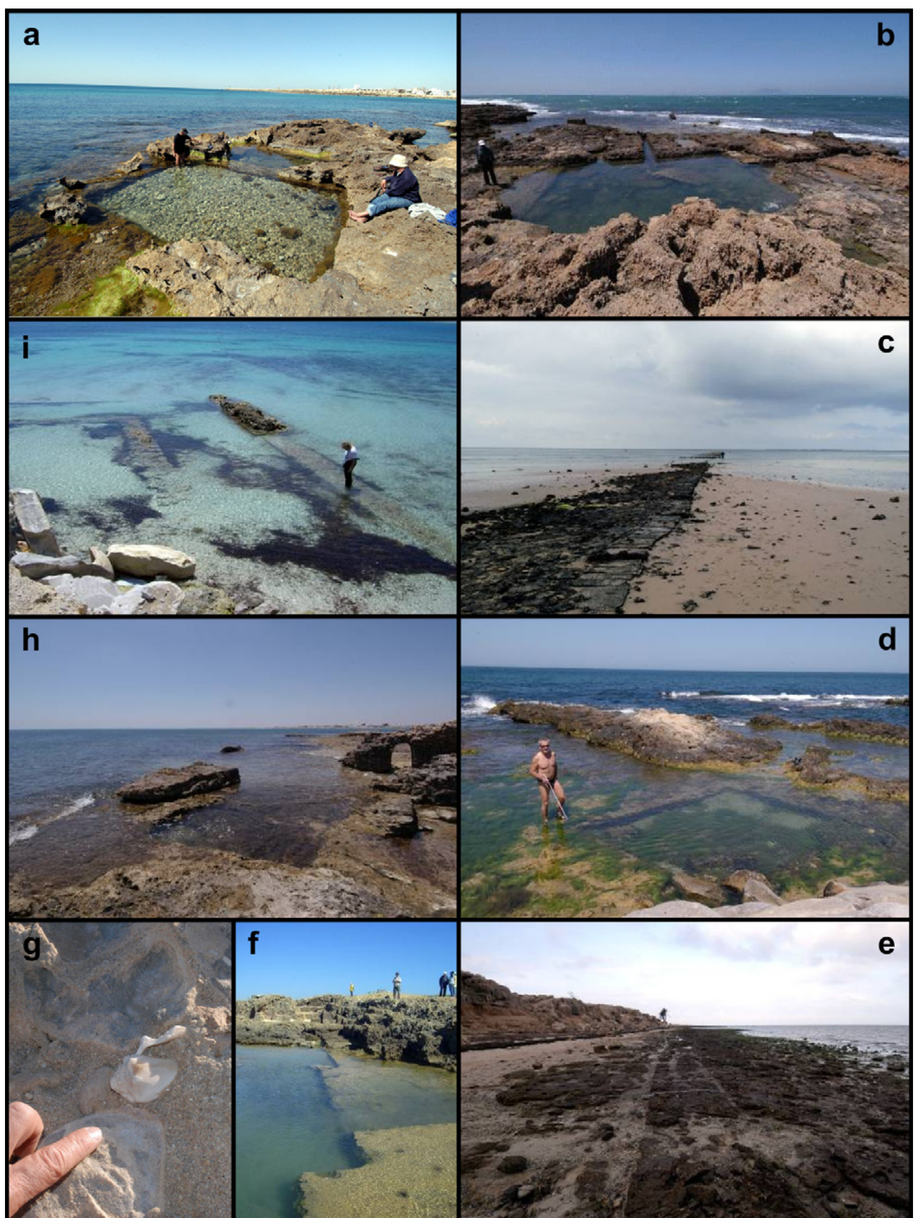

Fig. 4. The investigated archaeological sites in Tunisia: a) The pools of Sidi Mansour; b) the fish tank of Sidi Daoud. Note the two channels (front and right) for the exchange of water; c) the Roman age pier of Rass Segala; d) the pools at Maamoura, e) the roman road of Sidi Salem; f) the quarries at Mraissa; g) the MIS 5.5 fossil of Strombus Bubonius elevated at +5 m above sea level near Monastir; h) the submerged buildings and pools at Salakta; i) the submerged ruins of maritime installations at Salakta.

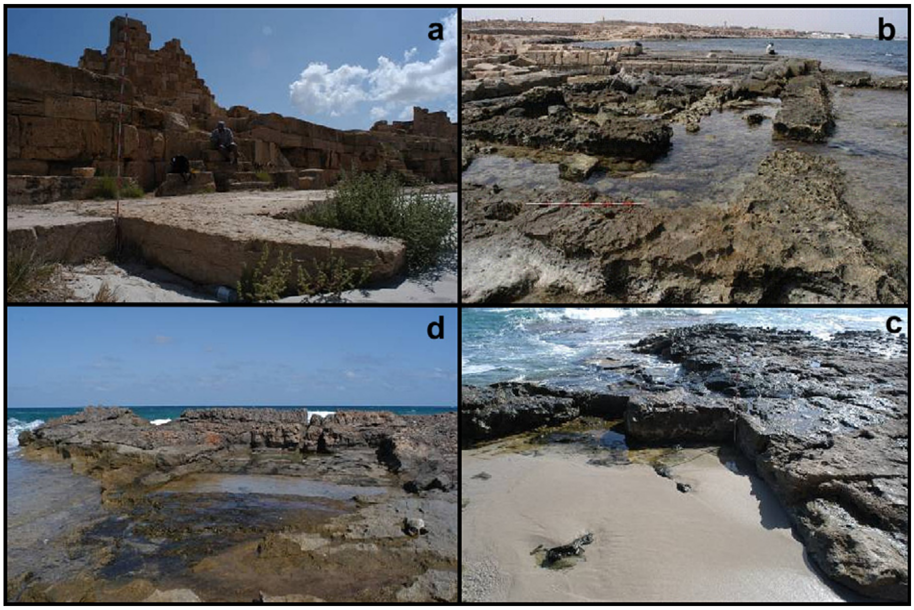

Fig. 5. The investigated archaeological sites in Libya: a) The Harbour of Leptis Magna. Front: the pier at 1.2 ± 0.2 m above current sea level. Back: the bollards and the stairways leading to the warehouses; b) the pools of the Baths of Oceanus (thermal installation) at Sabratha; c) the roman age coastal quarry at Villa Silin; d) the roman age fish tank at Wadi Jabrum.

applications to the Mediterranean region have been most recently discussed in Lambeck et al. (2004a, b) and Lambeck and Purcell (2005). The input parameters into these models are the ice models from the time of the Last Interglacial to the present and the earth rheology parameters.These have been established by calibrating the model against sea-level data from tectonically stable regions and from regions that are sensitive to particular subsets of the parameters: for example, data from Scandinavia to constrain the northern European and Eurasian ice models and data from far-field sites to improve the ice-volume equivalent sea-level function. Iterative procedures are used in which far-field data establish the global changes in ice volume and mantle rheology and near-field data constrain the local ice sheets and mantle rheology. The procedure is then re-iterated, using the near-field derived ice models to improve the isostatic corrections for the far-field analysis. The Mediterranean data, from the intermediate field, have been previously included in these analyses to establish constraints on regional mantle parameters and the eustatic sea-level function (Lambeck et al., 2004b) and on rates of tectonic vertical movements (Lambeck, 1995; Antonioli et al., 2006). This paper uses the most recent iteration results for the ice models (Lambeck et al., 2006; 2010) which include improved ice models for the major ice sheets of Europe, North America, Antarctica and Greenland back to the penultimate Interglacial, as well as mountain glaciation models including the Alps (Lambeck and Purcell, 2005). This last addition impacts primarily on the sea-level predictions for northern Italy and Slovenia. The time-integrated ice volumes are consistent with the ice-volume esl function previously established (Lambeck et al., 2002).

The solutions here and for other regions have indicated that three-layer rheological models largely suffice to provide a consistent description of the sea-level change due to the growth and decay of ice sheets. This comprises a high viscosity or elastic lithosphere defined by an effective elastic thickness of between 65 and 80 km, an upper mantle from the base of the lithosphere down to the 670 km seismic discontinuity with an average effective viscosity of between $(2–3) \times 10^{20}$ Pa s, and a lower mantle with an average effective viscosity of $(1–3) \times 10^{22}$ Pa s.

The Mediterranean data alone have so far not yet yielded solutions in which a complete separation of earth-model parameters have been possible, nor in which these parameters can be separated fully from eustatic or ice-model unknowns. However, the combination used here provides a set of very effective interpolation parameters that describe well the observational data and that allow for an effective separation of tectonic and isostatic–eustatic contributions to sea level.

Table 1 gives the isostatic predictions for a subset of parameters within this model space. The second letter in the model name denotes lithospheric thickness but this parameter is not critical for these sites and the results are for a = 65 km lithosphere. The third character in the name refers to the upper mantle viscosity in units of 10^{20} Pa s, and the fourth character refers to the lower mantle viscosity with $A = 10^{22}$ and $C = 3 \times 10^{22}$ Pa s. A comparison between these model predictions and observations indicates that within the uncertainties of the latter agreement is satisfactory across this range of parameters and a mean model with uncertainties established from the spread of predictions at each site was adopted. To this a modern eustatic sea-level rise of 1.5 mm/year for the past 100 years was added, consistent with the inference previously drawn from the Roman period fish-tanks in Italy that the this rise started about 100 years ago (Lambeck et al., 2004b). Fig. 3 illustrates the comparison.

For most sites the predicted and observed values agree to within their respective uncertainties. Sidi Daoud (site 4) is one exception where the observed lower limit estimate lies well above the predicted value and is indicative of tectonic uplift. Table 1 gives the vertical rates inferred from the discrepancies between the observed and the mean-predicted (including the modern esl correction) values, with the estimate of the uncertainty taking into consideration the uncertainties of the observed and model values as well as an uncertainty of 0.09 m for the modern eustatic contribution (Lambeck et al., 2004b).

6. Discussion

The coastal archaeological sites of Punic-Roman age located along the coasts of Tunisia and Libya show that locally sea level has risen between 0.2 and 0.6 m during the last ~2 ka and that much of the region is consistent with vertical tectonic stability on this time scale. Most of the variation observed from site to site appears to be a consequence of the glacio-hydro-isostatic response. In this part of the Mediterranean quite substantial changes in this response can be expected because of the coastal geometry which effectively provides a north-south section across the predominantly east-west trending contours of equal sea-level change (see Fig. 2 of Lambeck and Purcell, 2005). Thus these data can be expected to have some resolving power for mantle structure if the observational data is sufficiently accurate, and some of the regional differences that can be seen in Fig. 3 suggest that the isostatic model may overestimate this variability and that models with higher lithospheric thickness may be appropriate for what is effectively a continental lithosphere here. But since all of the observations are only limiting values this data alone is inadequate to establish the earth parameters from this data set alone.

As noted above, the only site with a systematic difference between the observed and predicted values occurs for Sidi Daoud (site 4) on the northwest side of Cap Bon. At the nearby site of Mraissa (site 3) the observed elevation is also above the predicted level and the average tectonic uplift rate for these two sites is ∼ 0.3 mm/y and significant at 2 sigma level (Table 1). Both Burollet (1991) and Sebei et al. (2003) have previously suggested that faults on this peninsula may be active.

Sites 10–15 are all from the closely clustered area of Jerba Island and the eastern side of the Gabes Gulf and show very considerable consistency, although the upper limit estimates from the last three sites lie above (but within uncertainties) the predicted values. None of the indicators here have the intrinsic accuracy of fish tanks that are complete with their channels and sluice gates but their internal agreement indicates that the relative functional heights used are appropriate. Of note is that the *Lithophaga* sample, dated at ∼5 ka BP, from nearby El Grine yielded an elevation of 0.3 m above sea level (corrected for barometric pressure and tides). This is a lower limit value since *Lithophaga* lives only underwater even during the lowest tides. Thus local sea level here was above present sea level whereas all isostatic predictions that are consistent with the results for the later periods indicate that highstands were not reached at this site and at this time. Hence, the current elevation of + 0.3 m asl is not consistent with the sea level prediction valid for this stable region of the Mediterranean.

The sites from Libya also yield good agreement, with the lower limit value from Sabratha occurring below the predicted values and the upper limit observations from the other sites occurring above the predicted positions. It should be noted that the two fish-tanks are much less complete than those usually found along the coast of Italy and that their functions remain unclear, it having been suggested that they may have served as basins for the preparation of *garum* sauce or purple dye (reference) in which case the reference level may have been near the high tide level rather than mean sea level.

As illustrated in Figure 1b there is considerable evidence for raised shorelines during the last Interglacial, MIS 5.5 (Bouaziz et al., 2003; Jedoui et al., 2003; Elmejdoub and Jedoui, 2009) with reported elevations ranging from near zero to 45 m. Much of this evidence is in the form of successions of Aeolian and beach ridge deposits that are assigned Last Interglacial age because they contain the fossil Strombus bubonius. The more precise markers such as tidal notches and inner margins that are prevalent on the Italian coast (Ferranti et al., 2006) are not present here and it is generally not possible to relate these deposits with any accuracy to mean sea level.

For Jerba Island and the eastern end of the Gulf of Gabes (Sebkha el Melah), MIS 5.5 deposits are reported at elevations between 0 and 6 m above mean sea level (Jedouy et al., 2003) and the inference is that this is an area of long-term stability, consistent with the archaeological evidence from sites 10–15 but not with the mid-Holocene result from site 9.

At the southern end of the Gulf of Hammamet (Monastir) MIS 5.5 deposits occur between 0 and 32 m above sea level, and it has been suggested that this is indicative of vertical movements on the Sknes-Krniss fault (Richards, 1986). If the higher value of 32 m reflects true uplift then the average rate for the past 125,000 years is ~2.5 mm/year, compared with an effectively zero rate indicated for the past 2000 years at Sidi Mansour (site 6 of figure 1a), near Monastir.

7. Conclusions

Earlier work has shown the complex pattern of sea level change within the Mediterranean region as a result of the decay of the last ice sheets, with long wavelength variations resulting from mantle deformation induced by the unloading of the northern hemisphere ice sheets and shorter wavelength variations from the loading of the ocean basins, including the Mediterranean, by the melt water (Lambeck and Purcell, 2005). This pattern is diagnostic of mantle rheology as well as of the former ice sheets themselves and observations of sea level change provide constraints on this rheology and on the time history of the ice melt. In the presence of tectonics the predicted isostatic pattern can be significantly disrupted and the challenge is to develop an accurate sea-level data base that is representative of both stable and unstable sites. The epoch ∼ 2 ka BP is particular significant because of the large amount of archaeological information around the Mediterranean shore line that can be precisely related to the position of sea level at that time, relative to the present. The significance of the new Tunisia-Libya data is that it fills a gap in the spatial pattern in an area where the sea-level response is particularly sensitive to mantle rheology. This is in contrast to the coast of Israel where this dependence is low (Anzidei et al., this volume) and, to a lesser degree, to the Thyrranean coast of Italy (Lambeck et al., 2004b). The present analysis is indicative of the potential of the coastal archaeological structures to constrain past sea level, thereby providing constraints on mantle rheology as well as a reference surface for quantifying rates of vertical tectonic motions.

This first analysis of archaeological data from a large section of coast from Tunis to the east of Tripoli reflects the spatial variability in sea level that is expected from the glacio-hydro-isostatic process as well as from superimposed tectonic signals. The archaeological data shows that the coast of Libya experienced a relative sea level rise in the past 2000 years of between 0.24±0.10 m and 0.48±0.10 m similar to the range seen along the coast of Tunisia of between 0.20±0.10 m and 0.58±0.30 m. Most of this signal is explained by the isostatic-eustatic process that also defines sea level in other parts of the Mediterranean. Thus estimates for the tectonic rates for this interval are mostly insignificant with the exception of the northwestern side of Cap Bon in Tunisia where the uplift rate of ∼ 0.15mm/year appears to be significant at the 2 sigma level in agreement with independent data (Burollet, 1991; Bouaziz et al., 2003).

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