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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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Abstract

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 Tunisi 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÷0.5m 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.

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 harbors constructions generally built around 2±0.3 ka B.P. 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; Felici, 2000; Lambeck et al., 2004a, 2004b; Antonioli et al., 2007; Lambeck et al., in press, 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).

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 B.P. 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 last 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. Geodynamic setting of Tunisia and Libya

Tunisia and Libya are located on the foreland of the African plate, facing the southern Mediterranean basin. The geological and geodynamic features of this region are driven by several lithospheric blocks that move according to their different structural and kinematic features including subduction, back-arc spreading, rifting, thrusting, normal and strike slip faulting (Mantovani et al., 2001; Jolivet and Faccenna, 2000; Faccenna et al., 2001). The region is dominated by subduction in the Hellenic and Calabrian Arc and by collision between the African and Arabian plates with Eurasia (McKenzie, 1970; Jackson and McKenzie, 1988). Various processes, from continental collision to escape tectonics with major continental strike-slip faults, subduction of continental and oceanic lithosphere and associated back arc spreading, are still acting in this region. Convergence and extension in the Mediterranean basin is a matter of debate to delineate the features of this area. Recently, new geological and geophysical data have been integrated into tectonic reconstructions (Bishop, 1975; Piqué, 2001; Faccenna et al., 2004; Jime´nez-Munt et al., 2003; Serpelloni et al., 2007). Earthquake distribution outlines the current dynamics of the region, its plate boundaries and the quasi-aseismic domains as part of the North African areas of Libya and Tunisia. Unfortunately, these two countries are still lacking in adequate geophysical infrastructure such as geodetic (GPS) and seismological networks, preventing observation of the detailed current crustal activity in this part of the Mediterranean.

3. Materials and methods

Nineteen archaeological markers were 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 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 is a 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.

4 Data along the coast of Tunisia

The ~1,300 km coastlines of Tunisia is abundant with archaeological installations whose age goes back to the Punic age (Slim et al., 2004), although the best preserved sites are of the roman age of ~2 ka B.P. (Fig.1a). Since 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 the Roman age, from the elevation of urban structures, fish tanks, harbors, 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 channels systems of fish tanks), provide an excellent estimation of the intervening relative sea level rise since its construction 0.28±0.10 m (Fig.4b). Other significant sites are the harbors of Gigtis and Rass Segala (Fig. 4c) that provide relative sea level rise values of 0.37±0.30 m and 0.34±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±0.20 m and 0.46±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. More data arise 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) provided a relative sea level rise of 0.30±0.20 m and 0.48 ±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 archeological markers that show a relative sea level rise ranging between 0.58±0.50 m and 0.28±0.3 m. These sites have been included in the analysis, although 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 ~2 ka, in the range of 0.18±0.2 m and 0.43±0.3 m, with the exception of the less constrained markers as the slipway of Carthage (0.24 ± 0.5 m). The most precise data are from the fish tank of Sidi Daoud (0.05±0.1 m) (Tab.1).

Besides the archeological remains, fossils of *Lithophaga* and *Strombus bubonius* were found. The first, placed at a corrected elevation of +0.31±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; Morahange and Pirazzoli, 2005 and references therein). As regards the geological evidence of the Last Interglagial, a deposit containg *Strombus bubonius* at Monastir (Fig. 4g) occurs at 14 m above sea level. Its elevation varies between 0 and 32 m above current sea level, as also reported in Richards (1996) and Bouaziz et al. (2003).

5. Data along the coast of Libya

The Mediterranean coasts of western Libya show several coastal archaeological installations, such as urban structures, pools, harbors 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 harbor 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 (Tab.1).

The harbor 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 harbor, 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 harbor 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±0.2 m since the 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 harbor, 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).

6. The isostatic model

The theory used here for describing the glacio–hydroisostatic process has been previously discussed in Lambeck et al., 2003 and its 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 are 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: data from Scandinavia to constrain the northern European and Eurasian ice models (Lambeck et al., 1998, 2006), a re-evaluation of the North American data for improved Laurentide ice models (Lambeck et al., unpublished) and data from far-field sites to improve the ice-volume esl function (Lambeck, 2002). Iterative procedures are used in which far-field data are used to establish the global changes in ice volume and mantle rheology and near-field data are used to 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 this analysis mainly to establish constraints on regional mantle parameters and the eustatic sea-level function (Lambeck, 2002) and on rates of tectonic vertical movements (Lambeck, 1995; Antonioli et al., 2007). This paper uses the most recent iteration results for the ice models (Lambeck et al., 2006) 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, 2002). The Italian data discussed in Lambeck et al. (2004a) have not been used in arriving at the new model parameters.

The adopted earth-model parameters are those that have provided a consistent description of the sea-level data for the Mediterranean region. The Mediterranean data alone have so far not yet yielded solutions in which a complete separation of earth-model parameters is 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. Also, the eustatic parameters determined from the Mediterranean region are consistent with those obtained from other regions of the world (Lambeck, 2002). The solutions indicate that three-layer rheological models largely suffice for the region: an effective elastic lithosphere with thickness 65 km, an upper mantle from the base of this lithosphere to the 670 km seismic discontinuity with an effective viscosity of $3x10^{20}$ Pa s and a lower mantle with an average effective viscosity of 10^{22} Pa s (earth model m-3) (Lambeck et al., 2004a).

The new parameters yield better agreement with the observations than before: the terrestrial indicators lie on or above the prediction, the marine indicators lie mostly below the expected results and the transitional data points are also close to the predicted function (Antonioli et al., 2007). Of the earth-model parameters, the parameter most sensitive to the predictions is the upper mantle viscosity (model m-2 for which the effective upper mantle viscosity is $2x10^{20}$ Pa/s, while the other parameters are unchanged). These comparisons indicate some of the trade-offs between parameters that occur. Model m-3 with the new ice model leads to very similar results as model m-2 with the old ice parameters. However, the old ice model is less consistent with the sea-level data from North America than the new model, and so the former is adopted here. The predictions recently estimated for Sardinia (Antonioli et al., 2007) are characteristic of the sea-level rise in most parts of the Mediterranean: an initially rapid rise as eustasy dominates isostasy, but after ~6500 a, a much slower rate of increase as isostasy dominates eustasy right up to the present time. The rates of rise are dependent on the rheology as is illustrated for the comparison of the two model results m-2 and m-3 with a difference of ~1.5m at 7000 BP (Antonioli et al., 2007).

7. Discussion

The coastal archaeological sites of Punic-Roman age located along the coasts of Tunisia and Libya show that sea level has changed at 0.3-0.5 m since the last ~2 ka and that the region shows a vertical tectonic stability. The comparison between the elevation of the archaeological sites together with their uncertainties, and the predicted values of the sea levels for the different parameters used in the models, show that they always fall between the maximum and the minimum values of the predicted sea levels. Using a eustatic change of 13 cm during the last 2 ka (Lambeck et al., 2004b), produces a glacio-hydro-isostatic contribution in the range of 0.2-0.4 m. This value is of minor amplitude with respect to those estimated in the central and northern Mediterranean (Lambeck et al., 2004b; Antonioli et al., 2007; Scicchitano et al., 2008);

Besides the archaeological evidence of the relative sea level change along the coast of Tunisia and Lybia, biological data can be considered, as Tunisia has placed a key role in Quaternary sea level change studies in the Mediterranean, since the work of Flick and Pervinquiére (1904). Fossils of *Lithophaga* were found at El Grine (Southeastern Tunisia) and the most elevated samples were collected at an elevation of +0.3 m above sea level (corrected for barometric pressure and tides). This value implies crustal uplift or complex behavior of the sea level changes during the Holocene in this region.

Jedoui et al. (1998) propose that, for this area, postglacial melting should not be responsible for the change. Moreover the elevation of the palaeo-beach deposit is regularly distributed in southern Tunisia and does not suggest any intervening tectonics in this area, and the vertical movements can be addressed only to isostatic rebound (Lambeck et al., 2003). Similar conclusions are suggested by Mohrange and Pirazzoli (2006). They estimate that the movements cannot be ascribed to tectonics but are likely related to post-glacial hydro-isostatic effects.

In this region, the elevation of the LIG is shown by *Strombus bubonius.* At Monastir these fossils are found between 0 and 32 m above sea level, indicating in this coastal area the occurrence of vertical movements related to the Sknes-Krniss fault activity (Richards, 1986). Along the coast of Southern Tunisia and at the Sabkha el Melah, south of Jerba island, LIG is placed at 2÷6 m asl, inferring vertical tectonic stability (Jedoui et al., 2003).

Results of U\Th analyses on biological data suggest that the LIG was characterized by at least two sea level high-stands. Owing to the uncertainties on estimated ages, the exact duration of each cannot be determined. It is reasonable to doubt the existence of these two cycles as they are not displayed in any other part of the Mediterranean coast. Conversely, on the basis of the elevation of the MIS 5.5 placed between 0 and 32 m in the Gulf of Hammamet (Monastir): i) the coasts of Tunisia in the gulfs of Hammamet and Gabes and at Cape Bon are subjected to minor vertical tectonic movements, as shown by the quasi normal elevation of the MIS 5.5 (up to 32 m, corresponding to a max uplift tectonic rate of ~0.26 mm/y in 124 ka and to an uplift rate of ~1.5 m over 5.7 ka); ii) the two supposed Tyrrhenian cycles are cut by discontinuities that could be interpreted as the result of a tectonic movement during the transgression; iii) the elevation of the submerged archaeological sites at -0.3 to -0.5 m, when compared with the sea level prediction model (Lambeck and Purcell, 2005) show tectonic stability for the last 2 ka cal B.P., thus not indicating crustal uplift (Fig.3). Hence, the relative sea level rise of ~4 m since the last 5.7 ka, is neither eustatic nor isostatic. Excluding critical events (coseismic uplift, tsunami or large sea storms) as responsible for the location of the fossil of *Lithophaga* at 0.3 m asl at El Grine, and excluding tectonic influences on its position, a different explanation must be invoked for its elevation. The predicted sea level for this area (Lambeck and Purcell, 2005) at 5700 B.P. is 2.5 m lower than today. As the sample is currently at +0.3 m asl and as *Lithophaga* lives only underwater even during the lowest tides (assuming a minimum value of about -1 m), a minimum sea level rise of nearly 4 m is indicated. 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. On the other hand, this elevation is consistent with a Holocene sea level highstand. The latter has been recently re-estimated for this region by Stocchi et al. (2009), showing that the area of SE Tunisia is sensible to the time-history of the remote ice sheet of Antarctica.

8. Conclusions

The archaeological sites in this region of the Mediterranean provided good quality data that fill a gap on sea level change estimations for recent times. Particularly they are the best indicators of the relative sea level changes intervening during the last two millennia and allow calibration and improvement of the glacio-hydro-isostatic models for this region.

The coastal archaeological data show that the coast of Libya underwent a relative sea level change in the range of 0.24±0.10 m and 0.48±0.10 m since the last 2 ka. During the same period, in Tunisia the relative sea level change is in the range 0.20±0.10 m and 0.58±0.30 m. These changes can be addressed to the eustatic contribution and the glacio-hydro-isostatic signal. As the former has been recently estimated in 0.13 m for the central Mediterranean (Lambeck et al., 2004b), the glacio-hydro-isostatic contribution is about 75% less than in the central and northern Mediterranean (Lambeck et al., 2005; Antonioli et al., 2007; Lambeck et al., 2004; Scicchitano et al., 2007). The glacio-hydro-isostatic sea level predictions satisfactory fits all the archaeological data but the ma2a, ma2c, ma3a are the model parameters that are in better agreement with archaeological observations. Discrepancies are of a few cm and generally within the error estimation of the used technique. The largest discrepancies are ~0.7 m and arise only from the comparison with ma3c model parameter, while the best fitting model parameter is ma2c. The comparison with this model parameter infer an estimated esl for the past ~2 ka of 0.15±0.04 m, which is in good agreement with the results obtained for the central Mediterranean (Lambeck et al., 2004b) and with earlier conclusion that the eustatic sea level change is recent.

Finally, the data show an overall vertical tectonic stability of the investigated coasts of Libya and Tunisia with the exceptions of Sidi Daoud and Mraissa, both located in northern Tunisa, along the coast of Cape Bon. Excluding the prediction of provided by model ma3c, the discrepancies between predictions and field observations for these sites, infer tectonic uplift at average rates of 0.22 mm/y at Sidi Daoud and 0.14 mm/y at Mraissa, in agreement with independent data (Burollet, 1991; Bouaziz et al., 2003)**.**

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Figure captions

Fig.1a Map of the investigated archaeological sites in Tunisia; b) elevation of the MIS 5.5 (modified from Jedoui et al 1998). 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).

Fig. 3 Relative sea level change inferred from archaological sites in Tunisia and Libya. Archaeological elevations are compared against glacio hydro isostatic model with different Earth parameters (Lambeck and Purcell, 2005). Triangles are the sea level predictions from Lambeck and Purcell (2005) estimated at each location.

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.

Table caption

Table 1. (A) Site numbers (in brackets are listed according to the CAB data base); (B) names as indicated in Figures 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=harbor; 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 (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 www.metoffice.com.

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Figures

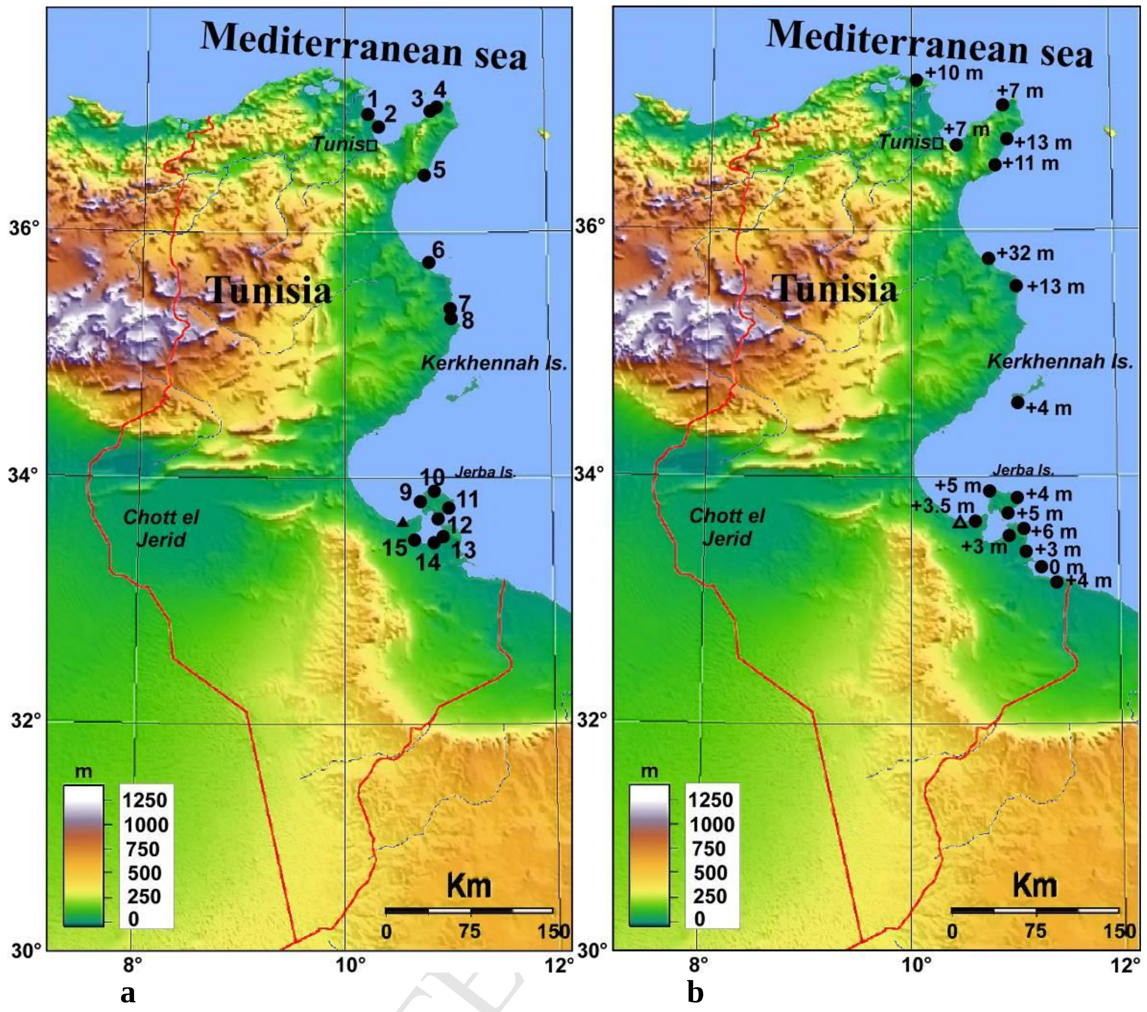


Fig. 1

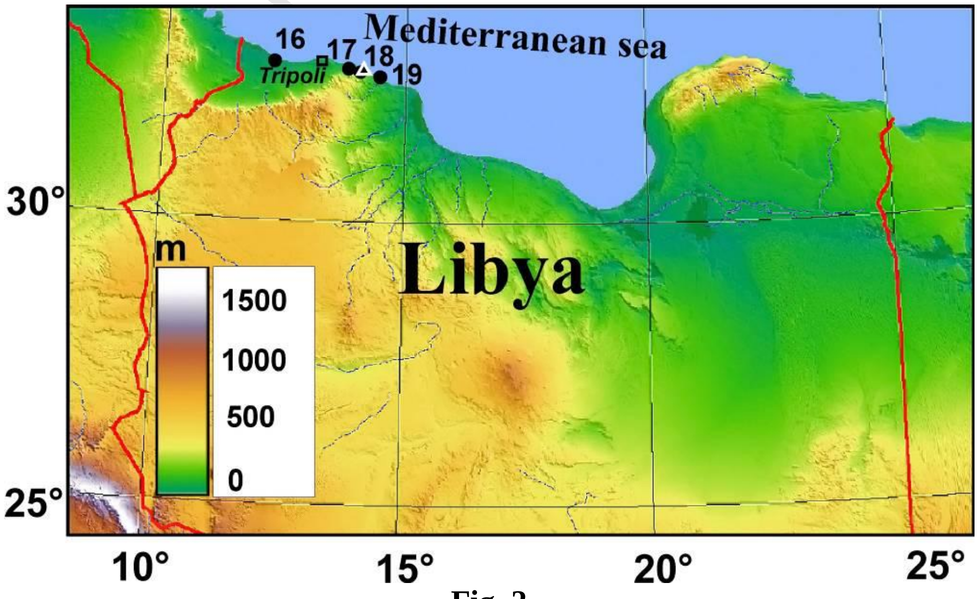


Fig. 2

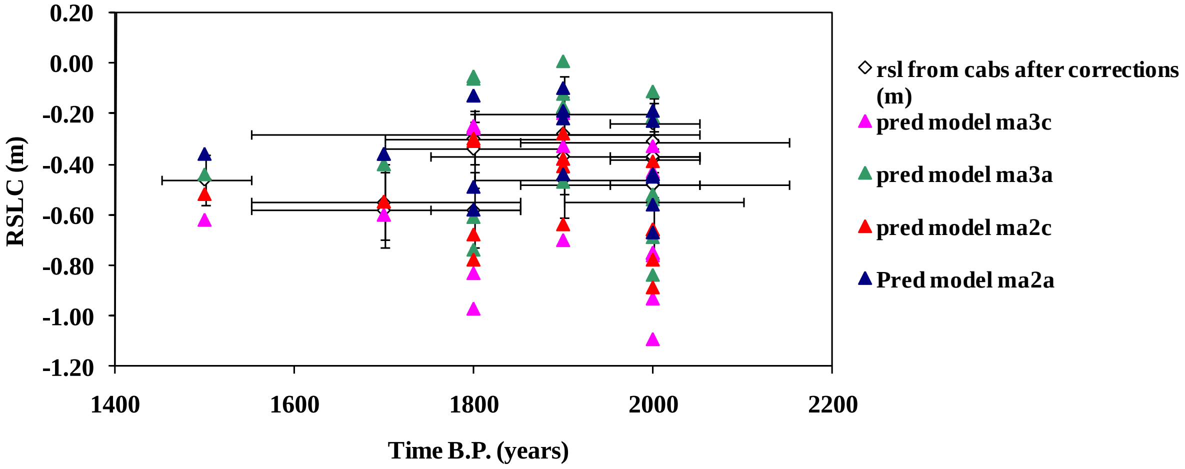

0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
RSLC (m)
1400
1600
1800
2000
2200
Time B.P. (years)
◇ rsl from cabs after corrections (m)
▲ pred model ma3c
▲ pred model ma3a
▲ pred model ma2c
▲ Pred model ma2a

Fig. 3

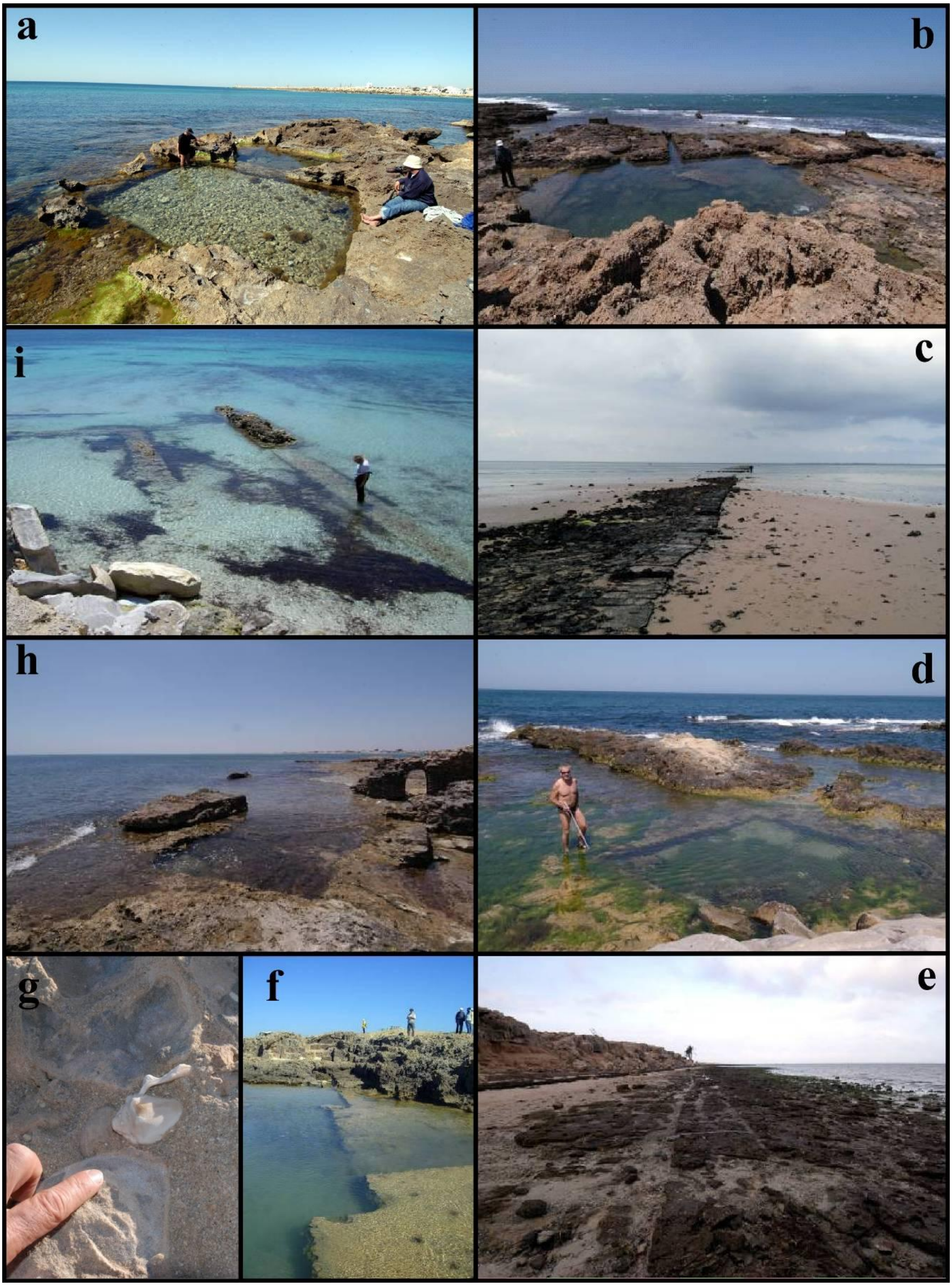
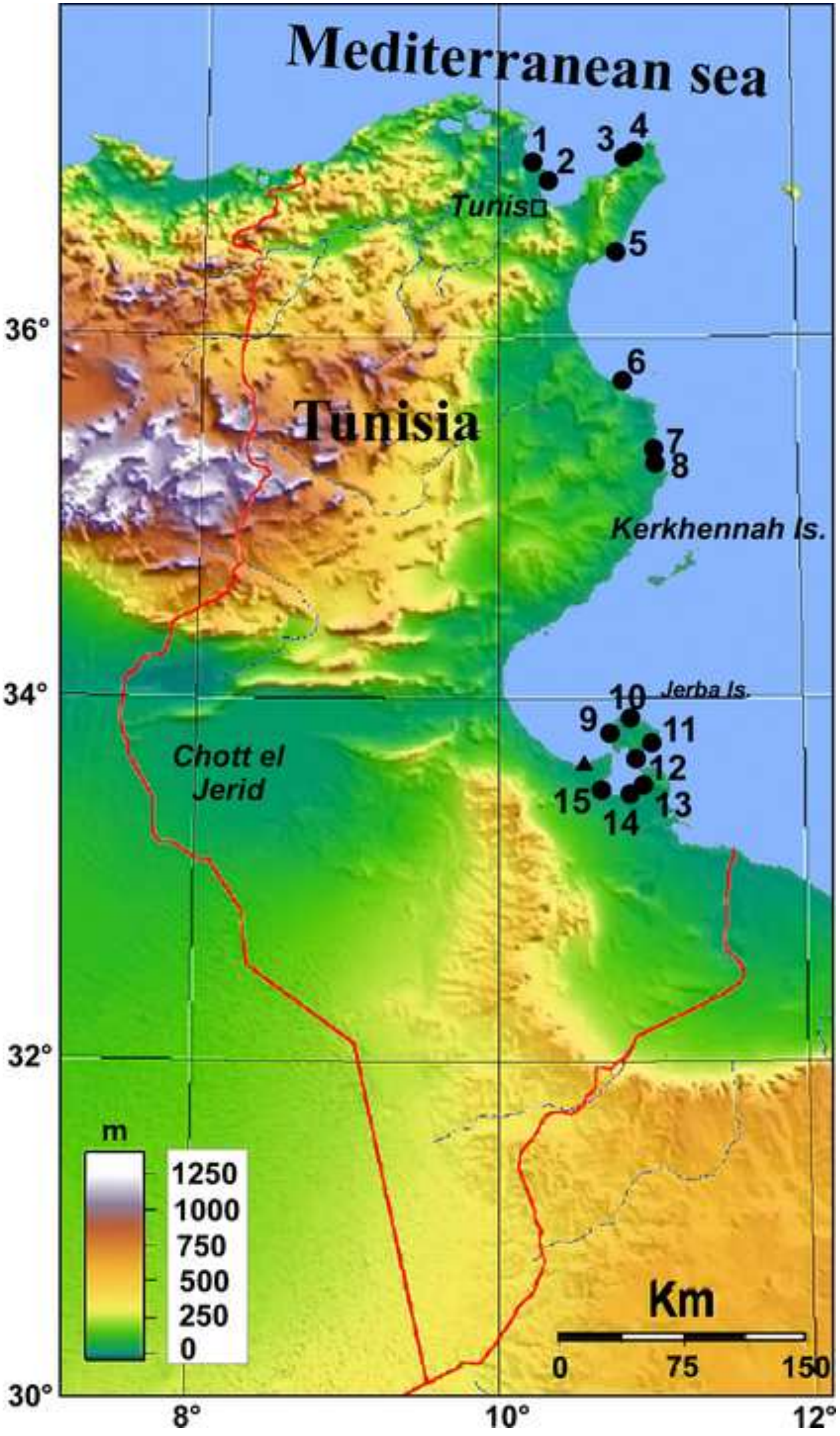
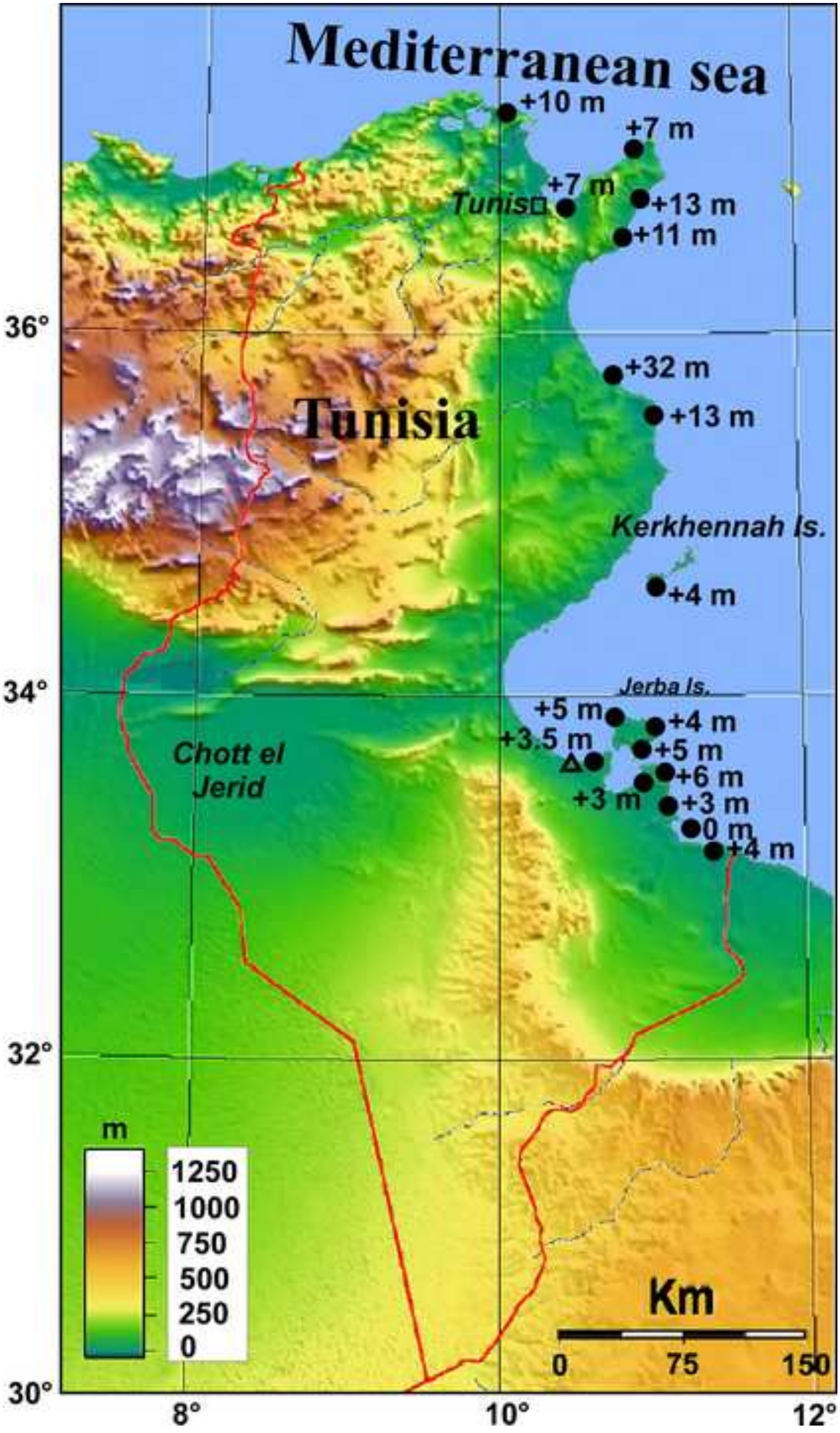
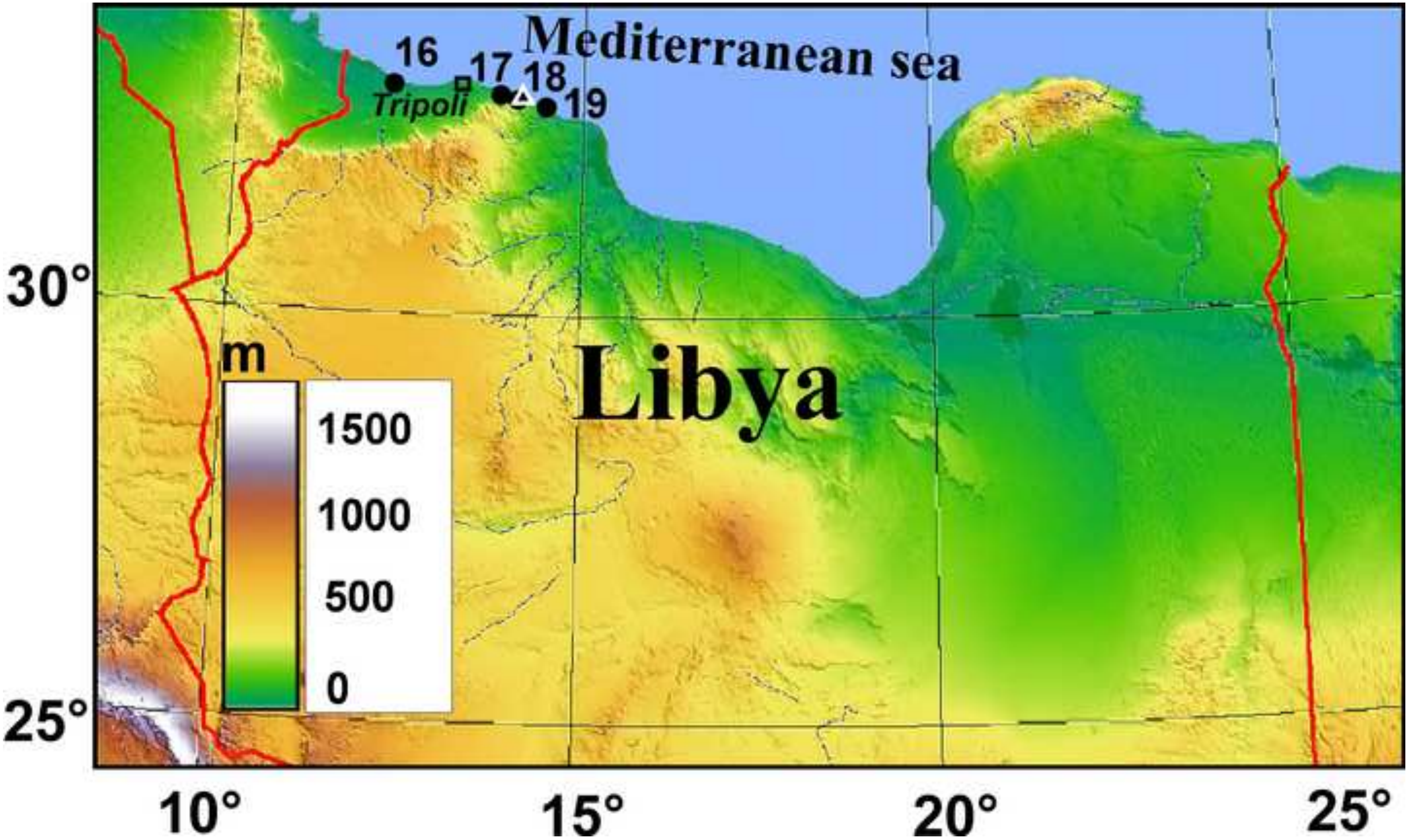


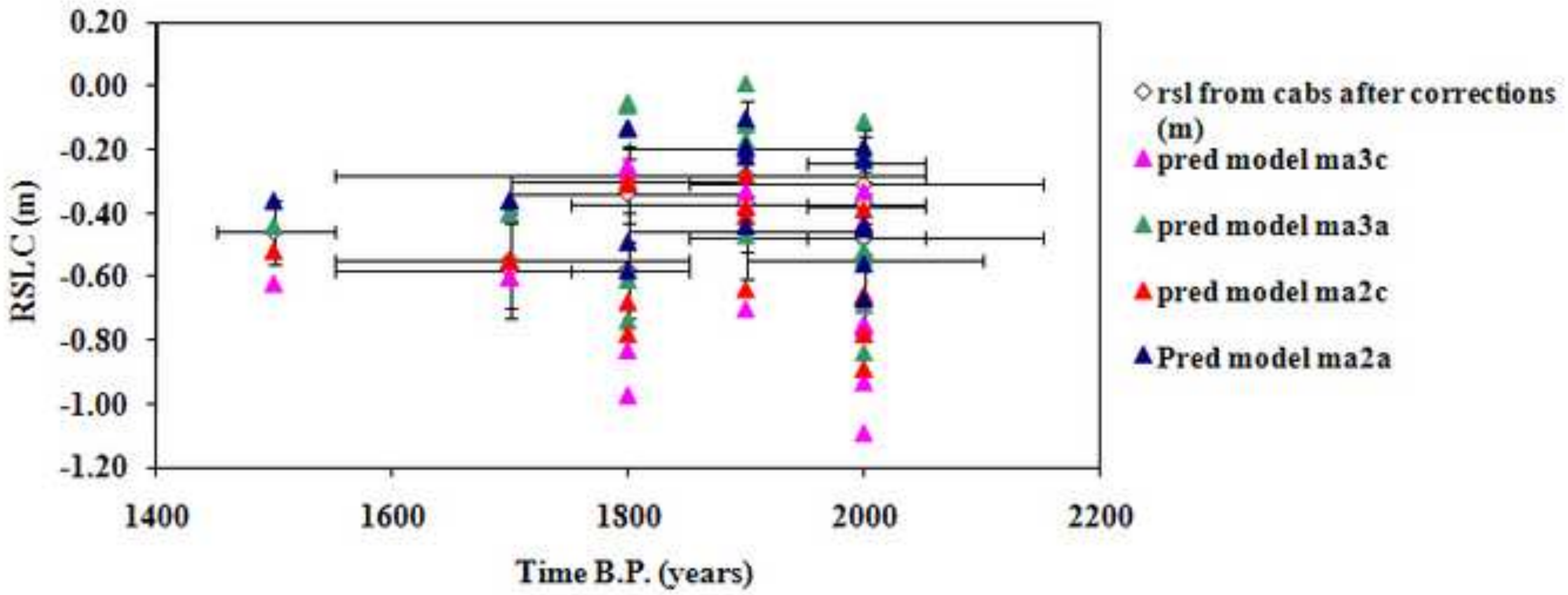
Fig.4

Fig.5

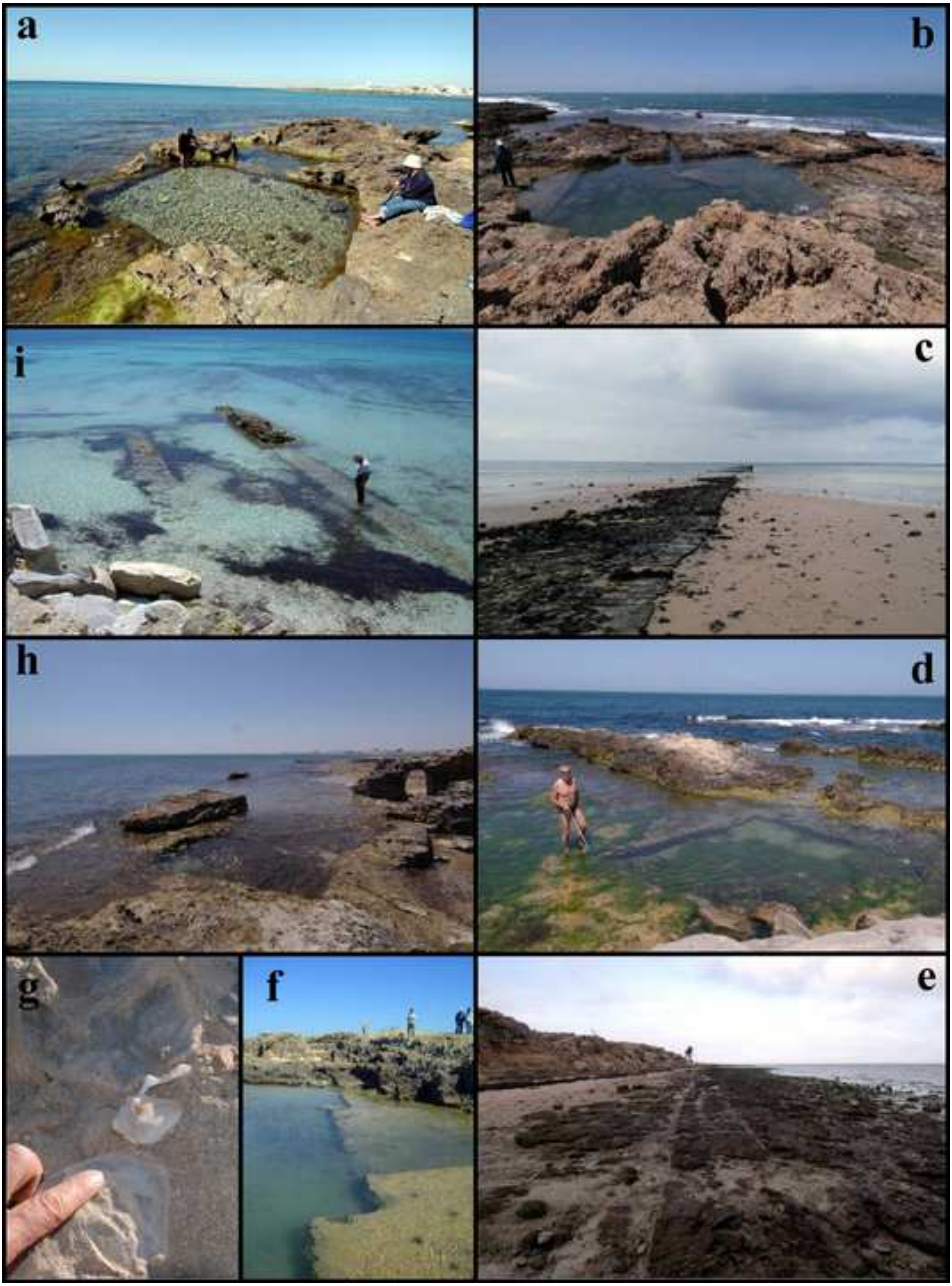

Mediterranean sea
1
2
3
4
Tunis
5
6
Tunisia
7
8
Kerkhennah Is.
10
Jerba Is.
9
11
12
13
14
15
Chott el Jerid
36°
34°
32°
30°
8°
10°
12°
m
1250
1000
750
500
250
0
Km
0
75
150


Mediterranean sea
+10 m
+7 m
+7 m
Tunis
+13 m
+11 m
36°
+32 m
+13 m
Tunisia
Kerkhennah Is.
+4 m
34°
Jerba Is.
+5 m
+4 m
+3.5 m
+5 m
Chott el Jerid
+6 m
+3 m
+3 m
0 m
+4 m
32°
m
1250
1000
750
500
250
0
Km
0
75
150
30°
8°
10°
12°


Mediterranean sea
16
17
18
19
Tripoli
Libya
m
1500
1000
500
0
30°
25°
10°
15°
20°
25°


0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
RSLC (m)
1400
1600
1800
2000
2200
Time B.P. (years)
◇ rsl from cabs after corrections (m)
▲ pred model ma3c
▲ pred model ma3a
▲ pred model ma2c
▲ Pred model ma2a

Figure




a
b
d
e

Table

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	Tectonics
1 (9)	Gammarth	Tunisia	S	36.921	10.296	1.8	-0.58	0.3	UL	-0.83	-0.61	-0.68	-0.49	stable
2 (8)	Carthage	Tunisia	SW	36.845	10.327	2	-0.55	0.5	UL	-0.93	-0.69	-0.78	-0.56	stable
3 (10)	Mraissa	Tunisia	Q	36.976	10.868	2	-0.48	0.1	LL	-1.09	-0.84	-0.89	-0.67	uplifting
4 (7)	Sidi Daoud	Tunisia	FT	37.002	10.894	1.8	-0.28	0.1	LL	-0.97	-0.74	-0.78	-0.58	uplifting
5 (6)	Maamoura	Tunisia	P	36.455	10.804	1.5	-0.46	0.2	LL	-0.62	-0.44	-0.52	-0.36	stable
6 (13)	Sidi Mansour	Tunisia	P	35.771	10.843	1.9	-0,46	0.3	UL	-0.7	-0.47	-0.64	-0.44	Stable
7 (11)	Salakta 1	Tunisia	P	35.388	11.042	1.7	-0,55	0.3	LL	-0.6	-0.4	-0.55	-0.36	stable
8 (12)	Salakta 2	Tunisia	BW,P	35.388	11.041	1.7	-0,58	0.3	UL	-0.6	-0.4	-0.55	-0.36	stable
9 (20)	El Grine	Tunisia	G	33.655	10.568	5.0	0.31	0.05	LL					stable
10 (18)	Sidi Salem 1	Tunisia	RD	33.895	10.829	1.9	-0,20	0.3	LL	-0.33	-0.12	-0.38	-0.19	Stable
11 (14)	Lalla Hadria	Tunisia	PV	33.789	11.059	1.9	-0,28	0.3	UL	-0.38	-0.17	-0.41	-0.22	stable
12 (16)	El Kantara (Meninx)	Tunisia	BW	33.683	10.920	2	-0,31	0.3	UL	-0.33	-0.11	-0.39	-0.19	stable
13 (19)	Ersifet	Tunisia	Q	33.559	10.944	1.8	-0,30	0.2	LL	-0.26	-0.06	-0.31	-0.13	stable
14 (17)	Rass Segala	Tunisia	H	33.532	10.925	1.8	-0,34	0.3	UL	-0.25	-0.05	-0.30	-0.13	Stable
15 (15)	Gigtis	Tunisia	H	33.533	10.680	1.9	-0,37	0.3	UL	-0.2	0.01	-0.28	-0.10	stable
16 (1)	Sabratha	Lybia	P	32.808	12.486	2	-0.48	0.2	LL	-0.43	-0.21	-0.44	-0.23	stable
17 (5)	Fondough en Naggaza	Lybia	FT	32.717	14.100	2	-0.24	0.2	LL	-0.75	-0.52	-0.66	-0.44	stable
18 (4)	Wadi Jabrum	Lybia	FT	32.717	14.105	2	-0.37	0.2	LL	-0.75	-0.52	-0.66	-0.44	stable
19 (3)	Villa Silin	Lybia	Q,N	32.709	14.178	2	-0.38	0.2	LL	-0.76	-0.54	-0.67	-0.45	stable
20 (2)	Leptis Magna	Lybia	H	32.638	14.300	2	-0.48	0.2	UL	-0.75	-0.52	-0.66	-0.44	stable

Table 1