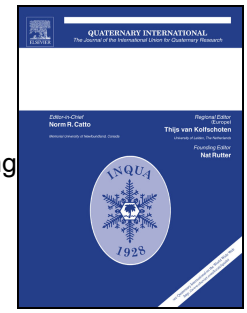
Accepted Manuscript



Title: Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel

Authors: M. Anzidei, F. Antonioli, A. Benini, K. Lambeck, D. Sivan, E. Serpelloni, P. Stocchi

PII: S1040-6182(10)00186-2

DOI: 10.1016/j.quaint.2010.05.005

Reference: JQI 2356

To appear in: *Quaternary International*

Received Date: 20 February 2010

Revised Date: 4 May 2010

Accepted Date: 11 May 2010

Please cite this article as: Anzidei, M., Antonioli, F., Benini, A., Lambeck, K., Sivan, D., Serpelloni, E., Stocchi, P. Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel, Quaternary International (2010), doi: 10.1016/j.quaint.2010.05.005

Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel

(1,2)Anzidei M., (3)Antonioli F., (4)Benini A., (5)Lambeck K., (6)Sivan D., (1)Serpelloni E., (7)Stocchi P.

(1) Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy
(2) Università della Calabria, Dipartimento di Fisica, Cosenza, Italy
(3)ENEA, Italy
(4) Università di Cosenza, Dipartimento di Scienze antiche, Cosenza, Italy
(5) Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia
(6) Department of Maritime Civilizations and the Leon Recanati Institute for Maritime Studies, School of Marine Studies, University of Haifa, Israel
(7) DEOS, Faculty of Aerospace Engineering, TU Delft, Delft, The Netherlands

Abstract

This paper provides new relative sea-level data inferred from coastal archaeological sites located along the Turkish coasts of the Gulf of Fethye (8 sites), and Israel, between Akziv and Caesarea (5 sites). The structures selected are those that, for effective functioning, can be accurately related to sea level at the time of their construction. Thus their positions with respect to present sea level provide a measure of the relative sea level change since their time of construction. Useful information was obtained from the investigated sites spanning an age range of ~2.3 to ~1.6 ka BP. The inferred changes in relative sea level for the two areas are distinctly different, from a rise of 2.41 to 4.50 m in Turkey and from 0 to 0.18 m in Israel. Sea level change is the combination of several processes, including vertical tectonics, glacio–hydro-isostatic signals associated with the last glacial cycle, and changes in ocean volume. For the Israel section, the present elevations of the MIS 5.5 Tyrrhenian terraces occur at a few meters above present sea level and vertical tectonic displacements are small. Data from GPS and tide gauge measurements also indicate that any recent vertical movements are small. The MIS-5.5 shorelines are absent from the investigated section of the Turkish coast, consistent with crustal subsidence associated with the Hellenic Arc. The isostatic signals for the Israel section of the coast are also small (ranging from -0.11 mm/year to 0.14 mm/year, depending on site and earth model) and the observed (eustatic) average sea level change, corrected for this contribution, is a rise of 13.5±2.6 cm during the past ~2 ka. This is attributed to the time-integrated contribution to sea level from a combination of thermal expansion and other increases in ocean volume. The observed sea levels from the Turkish sites, in contrast, indicate a much greater rise of up to 2.2 mm/yr since 2.3 ka BP occurring in a wide area between Knidos and Kekova. The isostatic signal here is also one of a rising sea level (of up to ~ 1mm/year and site and earth-model dependent) and the corrected tectonic rate of land subsidence is ~1.48 mm/year. This is the primary cause of dramatic relative sea level rise for this part of the coast.

1. Introduction

During past decades, sea level change within the Mediterranean has been estimated from instrumental measurements, as well as from archaeological, geological, and biological indicators (Flemming and Webb, 1986; Pirazzoli, 1976). This paper examines mainly archaeological and geological evidence for the late Holocene relative sea-level change along the coastline of Turkey and Israel (Fig.1). Geological indicators are a powerful source of information from which the relative sea level change can be estimated for selective periods back to the last interglacial (Ferranti et al., 2008), while the archaeological and instrumental data fill a gap between geological and

present time. A particularly good estimate of relative sea-level change can be obtained for the last ~2 ka from archaeological coastal installations (Lambeck et al., 2004b; Antonioli et al., 2007). The Mediterranean, with its small tidal range and continuous human settlement throughout historical times, has the most complete archaeological record relevant for sea level studies, with a large number of coastal archaeological sites that are often well dated and well preserved with functional features that can be precisely related to sea level at the time of their construction. Hence, they can be successfully used to constraint past local sea levels. Fish tanks, piers, docks, pools, quarries, harbors and slipways constructions, generally built around 2±0.3 ka BP are reliable indicators and provide a valuable insight of the regional variation in sea level during the last two millennia (Flemming, 1969; Schmiedt, 1974; Caputo and Pieri, 1976; Pirazzoli, 1976; Flemming and Webb, 1986; Lambeck et al., 2004a, 2004b; Antonioli et al., 2007; Lambeck et al., 2010, and references therein).

Local sea level change is a combination of various factors, including changes in ocean volume from the addition or subtraction of water. This includes contributions from temperature changes in the water column and contributions from changes in ice sheets and glaciers. The response of the ocean and the earth to changing ice and water loads, usually referred to as glacio-hydro-isostasy, is important, as are vertical tectonic movements of the land surface, local compaction of sediments or changes in meteorological forcing of the ocean surface. Of these, through the nature of the observational data used, subsidence arising from compaction of sediments or from the extraction of ground water is unlikely to be important and the dominant contributions considered here are tectonics and the isostatic factors. The latter have been previously evaluated for Mediterranean sites and the same models and parameters are used here as have previously been found satisfactory (Lambeck, 1995; Sivan et al., 2001; Lambeck et al., 2004a, 2004b; Antonioli et al. 2007; Anzidei et al., this issue). Geological evidence, in the form of the present elevation of the MIS-5e shoreline, along with instrumental data from GPS and tide gauge recordings, has been used to examine tectonic stability of the sites, relevant elements for the understanding of the recent geodynamic evolution of these areas of the Mediterranean basin. These isostatic and tectonic components are then compared with the observed sea levels to establish whether there have been additional changes in local and regional levels.

This paper examines archaeological evidence from the eastern Mediterranean coast of southeastern Turkey and Israel (Fig.1, Fig.2a,b), where the development of maritime constructions reached its greatest concentration in Hellenistic and Lycian times (~2.3 ka BP) and continued during the Roman and Byzantine ages (~2 ka and ~1.6 ka respectively). Particularly, the coasts of Israel contains many still very well-preserved remains The best preserved sites provide new information on constructional levels that can be accurately related to mean local sea levels between ~2300 and ~1600 BP.

2. Geodynamic setting of Eastern Mediterranean

The geological and geodynamic features of Israel and Turkey reflect those of the eastern Mediterranean region, which is subjected to the long-lasting plate convergence between Africa/Arabia and Eurasia (Dewey *et al*. 1973; Le Pichon *et al*. 1988; Dewey *et al*. 1989), active since the Late Cretaceous (DeMets *et al*. 1994; Calais *et al*. 2003). The current dynamics of the Africa-Eurasia plate boundary, as delineated by earthquake distribution, runs roughly east-west across the basin and is characterized by narrow to broad seismic belts of seismicity and deformation that result in a complex pattern of crustal stress and strain fields (Jackson and McKenzie, 1988; Rebai *et al*. 1992; Jiménez-Munt et al., 2003; Vannucci and Gasperini, 2004). The several lithospheric blocks 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). In this geodynamic framework, the Anatolia and the Levantine areas are both dominated by the northward motion of the Arabian plate

that produces the westward extrusion of the Anatolia peninsula and the two important and still active strike slip fault systems of the Dead Sea in Israel and the North Anatolia in Turkey along which large earthquakes have occurred throughout historical times (Boschi et al., 1995; Guidoboni et al., 1994; www.globalcmt.org; www.bo.ingv.it/RCMT; www.seismo.ethz.ch/mt) (Fig.1). In addition, the Gulf of Fethye will also be affected by the convergence along the Hellenic arc (McKenzie, 1970; Kalafat et al., 2004; Serpelloni et at., 2007 and references therein), as also reflected in previous estimates of the uplift of Rhodes and Karpathos and further to the north and with subsidence of the eastern part of the Gulf (see figure 17b of Lambeck 1995).

Of importance for the current investigation is the vertical land movement and one indicator of vertical stability is provided by the elevation of the Last Interglacial shoreline. From areas believed to be tectonically stable elsewhere within the Mediterranean, this shoreline usually occurs at ~5-7 m above mean sea level and its actual position can therefore be indicative of vertical movements on a time scale of 10^5 years. This shoreline feature, readily identified by sediments containing *Strombus bubonius* and other Senegalese fauna, has not been identified within the Fethye area, and its absence is consistent with a continuous broad subsidence of this region, in agreement with independent observations which estimate subsidence trends in the Gulf of Gökova (Uluğ et al., 2005) and at Gemile Island (Lambeck, 1995).

Previous research along the Israel coast has identified Last Interglacial fossil deposits at between 12 and 2 m above present sea level (Sivan et al., 1999; Galili et al., 2007), and this has used to argue for a tectonically stable coast (Sneh, 2000; Galili et al., 2007). The stratigraphic relationship of these particular deposits to coeval sea level is not well known, and tectonic stability can only be assumed to within ~±5 m over the past 120,000 years, yielding a vertical tectonic rate of ±0.04 mm/year. Inland from the coast, the vertical tectonics are likely to become increasingly dominated by deformation along the Dead Sea Fault.

3. Instrumental data

There are 6 tide gauge stations along the Mediterranean coast of Turkey but only the station of Antalya (Fig.2a) is located near the investigated archaeological sites. For Israel, there is the Hadera tide gauge station, south of Caesarea (Fig.2b). The data used from these sites are from the Permanent Service for Mean Sea Level (PSMSL) (Woodworth and Player, 2003; www.pol.ac.uk/psmsl/). The time series records for both Antalya and Hadera (Fig.3), are too short (< 20 years, with missing years for the former, and 11 years with two missing years for the latter) to provide significant estimates for long-term trends, although the record for Antalya points to a rising sea level, consistent with the subsidence noted for the Gulf of Fethye. The record from Hadera is consistent with the inference from the LIG elevations for vertical stability to within ±0.04 mm/year.

GPS position information also only provide limited constraints on the vertical motions because the record lengths are sub-decadal, and then only for the Israel coast (Fig.2b). The Israel network has been analysed together with about 500 stations belonging to several CGPS networks in the Euro-Mediterranean and African area, using GAMIT software (Herring et al., 2004) as well as regional and global solutions from SOPAC (http://sopac.ucsd.edu) using the ST_FILTER software (http://gipsy.jpl.nasa.gov/qoca). The final position time-series were computed in the IGS05 reference frame. Velocities were estimated from the time series after removing jumps due to stations' equipment changes (or co-seismic offsets) and the seasonal signals (with annual and semi-annual period). Uncertainties were computed adopting a white+colored error noise model (Williams et al., 2004), to produce a self-consistent and homogeneous three-dimensional velocity field and estimates of vertical land movements. The results are consistent with earlier inferences that this region is undergoing horizontal northwestern motion with an average velocity of ~1 cm/yr (McClusky et al 2000). The vertical displacements present a less systematic pattern (Fig. 2b). All coastal sites indicate an upwards displacement with a weighted average value that is barely significant in view of unresolved questions about the GPS reference frame stability (Altamimi et al.

2007). If the reference frame correction to the vertical rate of 1.8sin(latitude) mm/year proposed by these authors is applied, then the weighted mean vertical rate is 0.6±0.7 mm/year and consistent with tectonic stability for the coastal sites. Of greater significance is that larger vertical movements occur only in the inner regions, approaching the tectonic area dominated by the Dead Sea Fault zone (Fig.2b) and consistent with higher elevations of LIG sediments at these more inland sites.

4. Materials and methods

Thirteen archaeological sites were surveyed along the coasts of Turkey and Israel (Fig.1). Eight are located in Turkey (Fig. 2a) and five in Israel (Fig.2b), all of different ages and with multiple sea level indicators (Table 1). Analysis follows the procedures already applied in other areas of the Mediterranean (Lambeck et al., 2004b; Antonioli et al., 2007), and consisted of four sequential steps: 1) the measurements of the elevation of the significant archaeological markers of maritime structures with respect to the present sea level by simple optical or mechanical methods and during favorable meteorological conditions (calm sea, absence of wind); 2) correction of the elevation measurements for tide and atmospheric pressure affecting the level of the sea surface at the time of surveys, using the data and algorithms adopted by the Permanent Service for Mean Sea Level (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 derived from the measurements, corrections and estimates of the functional heights; and 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 geophysical model for each location. In the areas where the elevations of the markers are in agreement with the predicted sea-level curve, tectonic stability is hypothesized. Conversely, when the elevations of the markers are below or above that of the predicted sea-level curve, the area has experienced tectonic subsidence or uplift.

As the investigated archaeological structures were originally used year round, it is assumed that the defining levels correspond to the annual mean conditions at the time of construction. Functional heights of the archaeological benchmarks were used to estimate relative sea-level change in each location. This parameter 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 amplitude (Lambeck et al., 2004b; Auriemma and Solinas, 2009). Functional heights also define the minimum elevation of the structure above the local highest tides (Lambeck et al., 2004b). This information can also be deduced from previous publications (Schmiedt, 1965, 1974; Flemming, 1969; Flemming and Webb, 1986), from historical documents (Hesnard, 2004), from the remnants of the Roman Age shipwrecks (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 (which is dependent on their conservation), the accuracy of the survey and the estimation of the functional heights were all used in considering the observational uncertainties at each site.

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 re-discussed in Lambeck et al. (2004a, b), Lambeck and Purcell (2005), and Antonioli et al. (2007). 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 sought parameters (Lambeck, 1995; Lambeck et al., 1998, Lambeck, 2002;

Lambeck et al., 2006; Antonioli et al., 2006). This paper uses the same iteration results for the ice and earth models as in Anzidei et al. (this issue). The isostatic signals will generally be earth-model dependent, as is illustrated in Table 1 for a number of Earth models that differ in their upper mantle viscosity (2 = $2x10^{20}$ Pa s; 3 = $3x10^{20}$ Pa s) and lower mantle viscosity (A = 10^{22} Pa s, C = $3x10^{22}$ Pa s) for lithosphere with an effective elastic thickness of 65 km. Models with other values for this last parameter between 50 and 80 km give very similar results. With this observational data set alone, particularly with the unknown tectonic contributions to the Turkey rates of sea-level change, it is not possible to establish optimum values from this analysis alone, although analyses from elsewhere in the Mediterranean indicate that this range of parameters provides a consistent description of the sea-level data for the region.

5. Archaeological data along the coast of Turkey

The Mediterranean coasts of Southeastern Turkey contain a number of archaeological sites, such as urban structures and harbors installations (Flemming et al., 1973) that are useful for sea level studies. Approximately 150 km of the Turkish coast along the Gulf of Fethye, from the northwestern site of the ancient harbour of Cnidos, located on the Datča peninsula, up to the southeastern site of Kekova was examined (Fig.2a). In this region, coastal installations such as buildings, docks, tombs, slipways and breakwaters built during the last 1.6 to 2.3 ka, can still be found. It is remarkable that all these sites are largely submerged, providing the dramatic evidence of the relative sea level change in this region during the last 2.3 ka (Fig.4a,b; Fig.6a; Tab.1). The harbour of Cnidos and the settlement of Kekova are the most important archaeological settlements in this area, and they display different types of sea level markers that include well preserved piers with bollards. The harbor of Cnidos was surveyed for the first time in 1968 by Flemming, who published the elevations of bollards, from which he estimated a minor sea level rise with respect to the other archaeological sites located south of this site followed by a possible tectonic uplift occurred during the last 2 ka. Other significant indicators include the stairs of a submerged harbor at Skopea Island (placed at -3.81 m), foundations of building walls at Cleopatra's bath (at -3.52 m), Domuz Island (at -2.41 m) and Kala Kapi (at -2.63 m), slipways at Tersane (at -3.52 m) and finally tombs, docks, slipways and other buildings at Kekova. All the markers are consistent with a relative sea level rise of 2.3 m, since the last 2.3 ka (Fig.4a,b; Fig.6a; Table 1). This inference of subsidence is consistent with the absence of coastal sediments that contain the characteristic Senegalese fauna that is indicative of MIS 5.5 highstands elsewhere in the Mediterranean.

6. Archaeological data along the coast of Israel

Abundant archaeological installations, whose ages may go back to the Bronze age, characterize the 100 km of the coast of Israel between Caesarea and Akziv, below the Lebanese border (Sivan et al., 2004 and references therein) (Fig.2b). The most precise archaeological sea level indicators are the coastal installations of Roman age that span a period of a few centuries around 2 ka BP. Previous research from the elevation of fish tanks, harbors, quarries and slipways indicates nearly no sea level change since Roman time. Some sites, such as the pool at Caesarea, provide an excellent example of almost unchanged relative sea level since its construction (Fig.5a,b; Fig.6b; Table 1). This rock-cut pool, located on the headland west of the Roman Theater at Caesarea, has also been also known as "Cleopatra's Bath". The architecture and technology of *piscina* was popular in Italy during the period of the late Republic and the Early Empire and were usually integrated with the maritime villas. They were designed to ensure a constant flow of sea-water during a tidal cycle by a series of channels leading to and from the sea with intermediate sluice gates, and sometimes with tunnels, providing very precise sea level indicators (Lambeck et al., 2004b).
Other significant sites are the pool and the docks of Dor, the fish tank of Akziv with its in situ sluice gate which dates the site to the Early Roman period (based on the technology similarity to the fish

tanks in Italy), and the small round pool of Shiqmona, near Haifa (this latter site, although it is of uncertain age, can be roughly attributed to the Roman age, as similar structures are present along the coasts of Italy and are dated at 2±0.1 ka). All these sites show values of local relative sea level rise within 0.01±0.2 and 0.18±0.2 m, since the last ~2 ka (Fig.6b; Table 1).

Data from the most submerged part of the harbour of Caesarea has not been used as it is presently collapsed (Fig.5a). The authors support the hypothesis, based on these investigations and previous studies (Raban, 1990 and references therein), that this installation was not destroyed during an earthquake, but that it collapsed due to the poor mechanical quality of the geological units beneath its foundations (Reinhardt, 1999).

7. Discussion

For the Israel sites, the isostatic contributions to the observed relative sea level change are small and not critically dependent on earth-model parameters (Table 1, columns K to N). This is a consequence of a near canceling out of the water-loading or hydro-isostatic component and the ice-loading or glacio-isostatic component of the deglaciation effect of the Late Pleistocene high-latitude ice sheets. These predicted corrections to sea level observations are also of very comparable amplitude to the observed values, and this indicates that any vertical tectonic displacements have been small at all the Israel sites during the past 2000 years. Thus, for the past two millennia relative sea levels here provide a quite direct estimate of the eustatic component of sea level: the changes due to ocean volume increases that have not been included in the ice models. The nominal ice model that has been used in these isostatic models has constant grounded ice volume for the past 2000 years and the difference between the observed and predicted sea levels provide a measure of any change in ice volume in this interval, including changes in mountain glaciers, and any other contributions such as thermal expansion of the oceans. The former contribution will be associated with its own loading and gravitational terms, but since the locations are far from any significant ice loads this additional contribution will be small.

While the data set is limited, an estimate of the eustatic correction and the optimum earth-model parameters within a restricted range of (2-4)x10^{20} Pa s for the upper mantle and (1-3) for the lower mantle can be attempted. This yields values of 2.5 x10^{20} and 2 x10^{22} Pa s for the two layers respectively and an eustatic rise in sea level during the past 2000 years of only 13.5±2.6 cm. For a present-day eustatic sea level rise of ~1.2-1.5 mm/year, this implies that if the present-day rise is extrapolated back in time the Roman epoch levels were reached only about 100 years ago, confirming the earlier result of Lambeck et al. (2004b) and consistent with the similar results from Roman sites in Tunisia and Libya (Anzidei et al., this issue).

Archaeological data from other periods, mainly from archaeological indicators such as coastal quarries, water wells and Roman and Byzantine installations (Fig.4a) (Nir and Eldar, 1987; Mart and Perecman, 1996; Nir, 1997; Galili and Sharvit, 1998; Sivan and Galili,1999; Sivan et al., 2004; Galili et al., 2007) have confirmed the generally good agreement between the observed and isostatic predicted values consistent with an absence of vertical tectonic deformation (within the observational limits) as far back as ~ 10,000 BP (Sivan et al., 2001), that the sea-level curve here reflects primarily the eustatic component, and that it can be used as a first-order reference for other eastern Mediterranean coasts to establish rates of tectonic uplift or subsidence. This can be effectively illustrated with the information discussed above for the section of the Turkish coast between Cnidos and Kekova that is dominated by diffuse tectonics (strike slip and normal faulting) at the eastern end of the Hellenic arc tectonic system (Altunel et al., 2003; Jackson and McKenzie, 1988). The archaeological sites provide evidence of major submergence of this region, of between 2.4 and 4.5 m, depending on site, over the past 2300 years (Fig.5).

The isostatic corrections for these sites are larger than for the Israel sites and also show a greater dependence on the Earth model (Table 1) although the range of the corrections lie within the uncertainties of the observations and the tectonic subsidence signal clearly dominates the other

contributions. Using the optimum earth and eustatic parameters established from the Israel data, the average tectonic rates of uplift for the past 1.6-2.3 ka can be calculated (column O in Table 1). The uncertainties of these estimated rates are ~0.2 mm/year and are dominated by the observational uncertainties. Within uncertainties, the sites within the Gulf of Fethye yield consistent rates of subsidence of 1.48 +/- 0.3 mm/year

The absence of elevated Last Interglacial shorelines is consistent with these rates of subsidence. If the above rates are representative of longer time intervals, then these shorelines can be expected at depths of up to ~200 m below present sea level. The subsidence recorded at the Antalya tide gauge, albeit of limited quality but independently confirmed by Burkay et al. (2007), indicate that the present rate may be higher than the longer-term average, but a longer record will be required before significance can be attached to this observation.

8. Conclusion

The evidence from archaeological data shows that the coasts of SW Turkey underwent a maximum relative sea level rise between 2.4 to 4.5±0.3 m over the last 2.3 ka. During about the same period, the coast of Israel shows a near constancy of sea level. The observed changes can be attributed to the glacio-hydro-isostatic signal, eustatsy and vertical tectonics. The glacio-hydro-isostatic contribution to the observed changes plays approximately a null role along the coasts of Israel and has a minor contribution in Turkey. The estimated eustatic change since 2 ka BP of 13.5±2.6 cm is in agreement with previous results for central Mediterranean and North Africa. If the present-day rise at ~1.2-1.5 mm/y shown by tide gauge data is extrapolated back in time to the Roman epoch, levels were reached ~100 years ago establishing that the onset of the modern sea level rise occurred in the late nineteenth or early twentieth century. The sea level prediction model fits the archaeological observation in Israel. In Turkey, which is one of the highest seismic regions of the Mediterranean, all the archaeological markers largely fall below the predictions due to intervening vertical tectonics. Recent sea level and crustal deformation trends inferred from the available geodetic data, although of short duration, are consistent with tectonic stability for the coast of Israel and a still active subsidence of SW Turkey.

Finally, this analysis show that the coast of Israel is tectonically stable since the last ~2.0 ka while a broad tectonic subsidence has affected the SW coast of Turkey between Cnidos and Kekova, at an average rate of 1.48±0.3 mm/y since the last ~2.3 ka. Estimates are in agreement with the elevation of the MIS-5.5 shorelines which are at normal elevation along the coast of Israel and absent along the Turkish coasts, consistent with the long term crustal subsidence associated with tectonics of the eastern ending of the Hellenic Arc which is the primary cause of dramatic relative sea level rise for this region.

Acknowledgments

We are thankful to Eng. Paolo Gaburro and Cap. Mustafà Yiltir for their skilled assistance during marine surveys in Turkey. The anonymous reviewers and Norm Catto and Sanja Faivre improved this paper with their suggestions. This study has been partially funded by INGV, ENEA, Leon Recanati Institute, Australian National University and MIUR – Prin 2006, Grant Project “Il ruolo del riaggiustamento isostatico post-glaciale nelle variazioni del livello marino globale e Mediterraneo: nuovi vincoli geofisici, geologici ed archeologici”, coordinator Prof. Giorgio Spada.

References

Altamimi, Z., Collilieux X., Legrand, J., Garayt, B., and Boucher, C., 2007. ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. Journal of Geophysical Research, 112, B09401, doi:10.1029/2007JB004949, 2007.

Altunel, E., Stewart, I., S., Barka, A., Piccardi, L., 2003. Earthquake faulting at ancient Cnidus, SW Turkey. Turkish Journal of Earth Sciences, 12, 137-151.

Antonioli, F., Ferranti, L., Lambeck, K., Kershaw, S., Verrubbi, V., Dai Pra, G., 2006. Late Pleistocene to Holocene record of changing uplift rates in southern Calabria and eastern Sicily (southern Italy, Central Mediterranean Sea). Tectonophysics. 422, 23–40.

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

Anzidei, M., Antonioli, F., Lambeck, K., Benini, A., Soussi, M., this issue. New insights on the relative sea level change during Holocene along the coasts of Tunisia and western Libya from archaeological and geomorphological markers. Quaternary International, this issue.

Auriemma, R., Solinas, E., 2009. Archaeological remains as sea level change markers: A review. Quaternary International 206, 134-146.

Boschi, E., Guidoboni, E., Ferrari, G., Valensise, G., Gasperini, P., 1995. Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980,. ING SGA, Bologna.

Burkay, S., Ebru, E., Ercan, K., 2007. Trend analysis of sea levels along Turkish coasts. Hydrology days 2007, 152-160.

Calais, E., DeMets, C. & Nocquet, J.M., 2003. Evidence for a post-3.16-Ma change in Nubia-Eurasia-North America plate motions? Earth and Planetary Sciences Letters., 216, 8-92.

Caputo, M., L., Pieri, 1976. Eustatic variation in the last 2000 years in the Mediterranean, Journal of Geophysical Research 81, 5787– 5790.

Charlin, G., Gassend, J.M., Lequèment, R., 1978. L'èpave antique de la baie de cavalière – Le Levandou, Var. Archeonautica, 2.

DeMets, C., Gordon, R.G., Argus, D.F.,Stein, S., 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophysical Research Letters **21**, 2191-2194.

Dewey, J.F., Pitman, W. C., Ryan, W. B. F. Bonnin, J., 1973. Plate tectonics and the evolution of the Alpine system. Geological Society of America Bulletin, 84, 3137–3180.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W. & Knott, S.D., 1989. Kinematics of the Western Mediterranean, In: M.P. Coward, D. Dietrich, and R.G. Park (eds), Alpine Tectonics, Geological Society Special Publication 45, 265-283.

Faccenna, C., Thorsten, W., Becker, L., Lucente, F., Jolivet, L., Rossetti, F., 2001. History of subduction and back-arc extension in the Central Mediterranean. Geophysical Journal

International., 145, 809-820.

Ferranti, L, Monaco, C., Antonioli, F., Maschio, L., Kershaw, S., Verrubbi, V., 2008. Alternating steady and stick-slip uplift in the Messina straits, southern Italy: evidence from raised late Holocene shorelines. Journal of Geophysical Research 112, B06401, doi:10.1029/2006JB004473 .

Flemming, N.C., 1969. Archaeological evidence for eustatic changes of sea level and earth movements in the Western Mediterranean in the last 2000 years. Geological Society of America, Special Paper 109.

Flemming, N.C., Webb, C.O., 1986. Tectonic and eustatic coastal changes during the last 10,000 years derived from archaeological data. Zeitschrift für Geomorphologie N.F., 62, 1 –29.

Flemming, N. C., Czartoryska, N. M. G., Hunter, P. M., 1973. Archaeological evidence for eustatic and tectonic components of relative sea level change in the South Aegean. in Blackman D.J. (Ed), Marine archaeology. Butterworths, London, pp. 1-16

Galili, E., Zviely, D., Ronen, A., Mienis, H.K., 2007. Beach deposits of MIS 5e high sea stand as indicators for tectonic stability of the Carmel coastal plain, Israel. Quaternary Science Reviews 26 2544 –2557.

Galili, E., Sharvit, J., 1998. Ancient coastal installations and the tectonic stability of the Israeli coast in historical times. In: Stewart, I. S. and Vita-Finzi, C., ed., Coastal Tectonics, Geological Society, London, Special Publications, 146, 147-163.

Guidoboni, E., Comastri, A, Traina, G., 1994. Catalogne of ancient earthquakes in the Mediterranean area up to the 10th century. Eds. Istituto Nazionale di Geofisica Rome, Societa Geofisica e Ambiente, Bologna, 504 pp.

Herring, T.H., 2004. GLOBK : Global Kalman Filter VLBI and GPS Analysis Program Version 10.0, Massachussetts Institute of Technology, Cambridge.

Hesnard, A., 2004. Vitruve, De architectura, V 12, et le port romaine de Marseille. In: Le strutture dei porti e degli approdi antichi. ANSER, 175-204.

Jackson, J., Mckenzie, D., 1988. The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East. Geophysical Journal International 93, 45–73.

Jiménez-Munt, I., Sabadini, R., Gardi, A., 2003. Active deformation in the Mediterranean from Gibraltar to Anatolia inferred from numerical modeling and geodetic and seismological data. Journal of Geophysical Research 108, No. B1, 2006, doi:10.1029/2001JB001544.

Jolivet, L., Faccenna, C., 2000. Mediterranean extension and the Africa-Eurasia collision. Tectonics, 19, 1095–1106.

Kalafat, D., Günes, Y., Kekovali, K., Berberoğlu, M., 2004. Earthquake activity of the gulf of Gökova. Report Kandili Observatory & ERI, National earthquake monitoring center, Cengelkoy/Istanbul, Turkey. http://www.emsc-csem.org/Doc/Gokova_0804.pdf

Lambeck, K., 1995. Late Pleistocene and Holocene sea-level change in Greece and south-western

Turkey: a separation of eustatic, isostatic and tectonic contributions. Geophysical Journal International , 122, 1022-1044.

Lambeck, K., Smither, C., Johnston, P., 1998. Sea-level change, glacial rebound and mantle viscosity for northern Europe. Geophysical Journal International, 134, 102-144.

Lambeck, K., 2002. Sea-level change from mid-Holocene to recent time: an Australian example with global implications. In: Mitrovica, J.X., Vermeersen, B. (Eds.), Glacial Isostatic Adjustment and the Earth System. American Geophysical Union, Washington, DC, pp. 33–50.

Lambeck, K., Purcell, A., Johnston, P., Nakada, M., Yokoyama, Y., 2003. Water-load definition in the glacio-hydro-isostatic sea-level equation. Quaternary Science Reviews, 22, 309-318.

Lambeck, K., Antonioli, F., Purcell, A., Silenzi, S., 2004a. Sea level change along the Italian coast for the past 10,000 yrs. Quaternary, Science Reviews 23, 1567–1598.

Lambeck, K., Anzidei, M., Antonioli, F., Benini, A., Esposito, E., 2004b. Sea level in Roman time in the central Mediterranean and implications for modern sea level rise. Earth and Planetary Science Letters, 224, 563-575.

Lambeck, K., Purcell, A., 2005. Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. Quaternary Science Reviews 24, 1969–1988.

Lambeck, K., Purcell, A., Funder, S., Kjær, K., Larsen, E., Möller, P., 2006. Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from field data and rebound modelling. Boreas, 35, 539-575.

Lambeck, K., Woodroffe, C.D., Anzidei, M., Antonioli, F., Gehrels, W.R., Plassche, O. van de., Wright, A.J., 2010. Palaeoenvironmental records, geophysical modelling and reconstruction of sea-level trends and variability on centennial and longer time scales. In Church JA, Woodworth PL, Aarup T, Wilson, WS, eds., Understanding Sea-level Rise and Variability. Blackwell Publishing, London. (In press).

Le Pichon, X., Bergerat, F., Roulet, M. J., 1988. Plate kinematics and tectonics leading to the Alpine belt formation: a new analysis. Geological Society of America Special Paper 218, 111–131.

Mantovani, E., Cenni, N., Albarello, D., Viti, M., Babbucci, D., Tamburelli, C., D'Onza, F., 2001. Numerical simulation of the observed strain field in the central-eastern Mediterranean region. Journal of Geodynamics 31(5), 519 - 556.

McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintasv, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradisssis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksoz, M. N. and Veis, G., 2000. Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. Journal of Geophysical Research 105(B3), 5695–5719.

McKenzie, D. P., 1970. Plate tectonics of the Mediterranean region, Nature, 226, 239– 243.

Mart, Y., Perecman, I., 1996. Neotectonic activity in Caesarea, the Mediterranean coast of central Israel. Tectonophysics 254, 139– 153.

Medas, S., 2003. The Late-Roman Parco di Teodorico Wreck, Ravenna, Italy: preliminary remarks on the hull and the shipbuilding. In: Beltrame, C., Boats, Ships and Shipyards. Proceedings of the Ninth International Symposium on Boat and Ship Archaeology, Venice 2000.Oxford, 42-48.

Nir, Y., 1997. Middle and late Holocene sea-levels along the Israel Mediterranean coast – evidence from ancient water wells. Journal of Quaternary Science 12 (2), 143–151.

Nir, Y., and Eldar, I., 1987. Ancient wells and their geoarchaeological significance in detecting tectonics of the Israel Mediterranean coastline region. Geology, 15, 3-6.

Pirazzoli, P.A., 1976. Sea level variations in the northwest Mediterranean during Roman times. Science 194, 519– 521.

Pomey, P., 2003. Reconstruction of Marseilles 6th century BC Greek ships. In Beltrame, C., Boats, Ships and Shipyards. Proceedings of the Ninth International Symposium on Boat and Ship Archaeology, Venice 2000. Oxford pp. 57-65.

Raban, A., 1990. Oceanographic understanding of ancient harbour engineers of the Levant. Proc. 4th international congress on the history of oceanography, Deutsch Hydrographie Zietschrift 22, 257-271.

Rebai, S., Philip, H., Taboada, A., 1992. Modern tectonic stress field in the mediterranean region: evidence For variation in stress directions at different scale. Geophysical Journal International **110**, 106–140.

Reinhardt, E., 1999. Destruction of Herod the Great's harbour at Caesarea Maritima, Israel, Geoarcheological evidence. Geology, 27, 811-814.

Schmiedt, G., 1965. Antichi porti d'Italia. L'Universo, 45, 234-238.

Schmiedt, G., 1974. Il livello antico del mar Tirreno. Testimonianze da resti archeologici. E. Olschki Eds., Firenze, 323 pp.

Serpelloni, E., Vannucci, G., Pondrelli, S., Argnani, A., Casula, G., Anzidei, M., Baldi, P., Gasperini, P., 2007. Kinematics of the Western Africa-Eurasia plate boundary from focal mechanisms and GPS data Geophysical Journal International. doi: 10.1111/j.1365-246X.2007.03367.x

Sivan, D., Gvirtzman, G. Sass, E., 1999. Quaternary Stratigraphy and Paleogeography of the Galilee Coastal Plain, Israel. Quaternary Research 51, 280–294.

Sivan, D., and Galili, E., 1999. Holocene tectonic activity in the Galilee coast and shallow shelf, Israel, A geological and archaeological study. Israel Journal of Earth Science, 48:47-61.

Sivan, D., Wdowinski, S., Lambeck, K., Galili, E., Raban, A. 2001. Holocene sea-level changes along the Mediterranean coast of Israel, based on archaeological observations and Numerical model. Palaeogeography, Palaeoclimatology, Palaeoecology 167, 101-117.

Sivan, D., Lambeck, K., Toueg, R., Raban, A., Porat, Y., Shirman, B. 2004 .Ancient coastal wells of Caesarea Maritima, Israel, an indicator for sea level changes during the last 2000 years. Earth and Planetary Science Letters 222, 315-330.

Sneh, A., 2000. Faulting in the coastal plain of Israel during the Late Quaternary, re-examined. Israel Journal of Earth Sciences, 49,1, 21-29.

Steffy, J.R., 1990. The boat: A preliminary study of its construction. In S. Wachsmann et al. The Excavation of an Ancient Boat in the Sea of Galilee (Lake Kinneret).Israel Antiquities Authority, Jerusalem, 29-47.

Uluğ, A., Duman, M., Ersoy, X., Özel, E., Avci, M., 2005. Late Quaternary sea-level change, sedimentation and neotectonics of the Gulf of Gfkova: Southeastern Aegean Sea. Marine Geology 221, 381– 395.

Vannucci, G., Gasperini, P., 2004. The new release of the database of Earthquake Mechanisms of the Mediterranean Area (EMMA Version 2), Annals of Geophysics, supplement to Vol. 47, n. 1, 307-334.

Williams, S. D. P., Bock, Y., Fang, P., Jamason, P., Nikolaidis, R.M., Prawirodirdjo, L., Miller, M., Johnson, D.J., 2004. Error analysis of continuous GPS position time series. Journal of Geophysical Research., 109, B03412, doi:10.1029/2003JB002741.

Woodworth, P.L., 1991. The permanent service for mean sea-level and global sea-level observing system. Journal of Coastal Research 7, 699–710.

Woodworth, P.L., Player, R., 2003. The permanent service for mean sea-level: an update to the 21st century. Journal of Coastal Research 19, 287–295 http://www.pol.ac.uk/PSMSL/

Figure captions

Fig.1 Current seismicity and focal mechanisms of the studied region (CMT catalogues from: www.globalcmt.org; www.bo.ingv.it/RCMT; www.seismo.ethz.ch/mt). Main faults, the North Anatolian Fault (NAF) and the Dead Sea Fault are shown on the map. The detailed maps of Figure 2 are identified by the red rectangles.

Fig. 2 Investigated sites (white dots with numbers as in Table 1) along the coast of a) Turkey and b) Israel. Yellow lines identify the principal faults. CF is the Carmel Fault. In b) the locations of the tide gauge of Hadera and the GPS network are also shown. Vertical GPS velocities (in mm/y) are estimated for the time span 1998-2008. See also Table.1 for site data.

Fig.3 Annual mean sea level trends estimated from the tide gauges of Hadera (top) and Antalya (bottom), located along the coast of Israel and SW Turkey, respectively. Although the duration of recordings are too short at both stations (time span 1996-2003 at Hadera and 1985-2005 at Antalya) to provide a reliable secular sea level trend, their data are in agreement with archaeological sea level indicators and models. Note the anomalous oscillations in Antalya compared with Hadera (valid data from the PMSLS data base, www.pol.ac.uk).

Fig.4a The archaeological evidence of the relative sea live rise in Turkey. Cnidos: a) the coastline out of the northern harbour with a Greek age pier (marked by the white arrows), b) the Hellenic age submerged pier in the southern harbour, c) the Roman age bollard in the southern harbour, d)

submerged Byzantine age buildings at Cala Kapi, e-f) Byzantine age buildings of Cleopatra's bath at Twelve Islands. (Gulf of Fethye)

Fig.4b The archaeological and geomorphological evidence of the relative sea live rise in Turkey: a) Byzantine age building at Domuz Island, (b) the Hellenic age pier of Tersane island, c-g) the Byzantine age pier of Gemile Island with bollards; h) a submerged stalactite (unknown age) along the coast of Fethye; i) Lycian age tombs and j) harbour installations at Kekova. See Figures 1 and 2a for site location and Table 1 for data.

Fig.5a The archaeological evidence of relative sea level rise in Israel: a) the submerged remnants of the collapsed Herod's harbour of Caesarea; b) the roman age pool of Caesarea, equipped with c) channels tidally controlled for the exchange of water in the basin; d) the acqueduct of Caesarea. This structure is still in situ and indicates that major seismic disturbances since its construction are unlikely, e) the bollard in the inner harbour of Caesarea. See Figures 1 and 2b for site location and Table 1 for data.

Fig.5b The archaeological evidence of relative sea level rise in Israel: a) the Roman age dock and b) the pools connected with sea level at Dor; c) the sluice gate raised in its original position in the Roman age fish tank of Akziv (d), equipped with tidally channels controlled for water exchange in the basin (e); f) the small round pool of Shiqmona, near Haifa with channels equipped with grooves for the sluice gates (g). See Figures 1 and 2b for site location and Table 1 for data.

Fig.6 a) Relative sea level change along the coast of SW Turkey observed from archaeological data and from predictions based on different parameters of the glacio-hydro-isostatic model (see text); b) relative sea level change along the coast of Israel from archaeological data and isostatic predictions based on different parameters of the glacio-hydro-isostatic model (see text).

Tables

Tab.1 Elevation of archaeological data versus sea level prediction models.
(A) Site numbers (number in brackets according to database list); (B) names as indicated in Figures 2a,b, 4a,b and 5a,b; (C) country; (D) type of archaeological remain; (E) and (F) are the WGS84 coordinates of the sites; (G) age estimates based on historical documentation and archaeological data; (H) observed relative sea level change (corrected for tide and pressure values at the time of measurements) estimated from the functional elevation of the significant markers; (I) elevation error estimates; (J) limiting value of survey data: UL= upper limit, LL= lower limit of the archeological markers; (K-N) are the predicted sea levels at 2 ka according to different parameters used in the model; (O) estimate of average rate of vertical tectonic movement.
Architectural features used to define sea level: B=buildings, BR=breakwater, CH=channels, D=docks, H=harbor; FT=fish tank, P=pools, PV=pavement, SW=slipways, T=tombs. For pools and fish tanks we considered a minimum functional elevation corresponding to at least 0.3 m above the maximum local high tide. 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 this part of the Mediterranean is ~0.40 m. Tidal corrections have been performed used the algorithms of the PSMSL (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. The tectonic rates assume uniform uplift since the time of

construction of the archaeological markers. The uncertainty estimates include observational and model uncertainties.

Figures

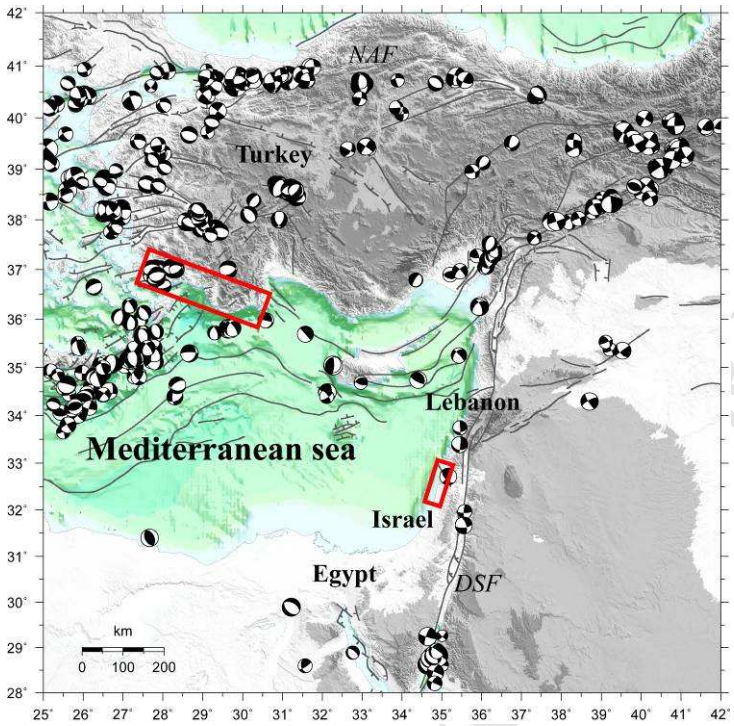


Fig.1

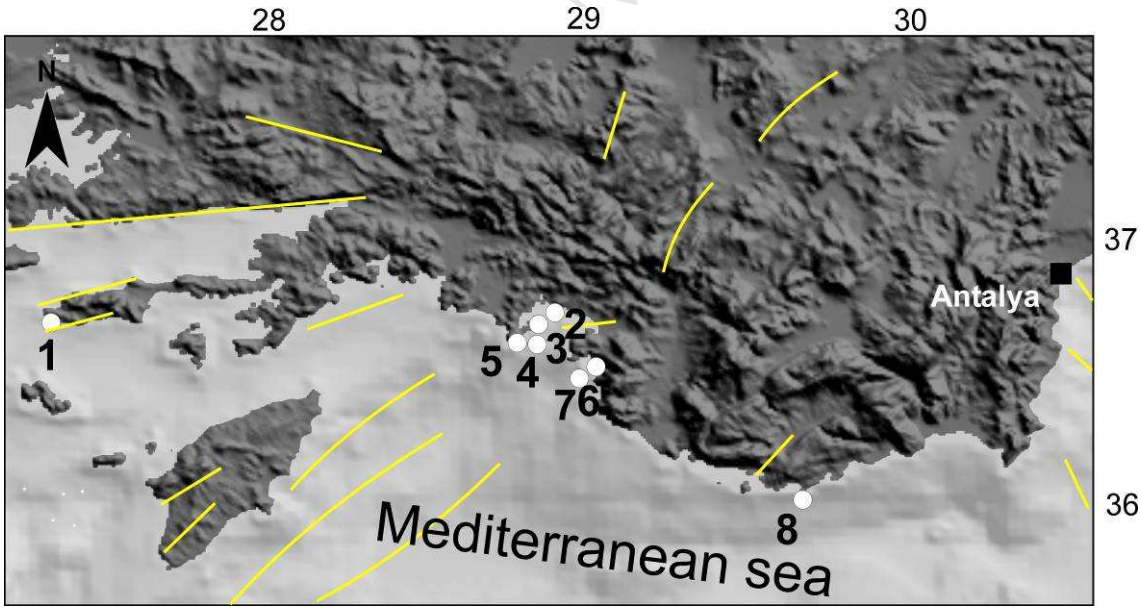


Fig.2a

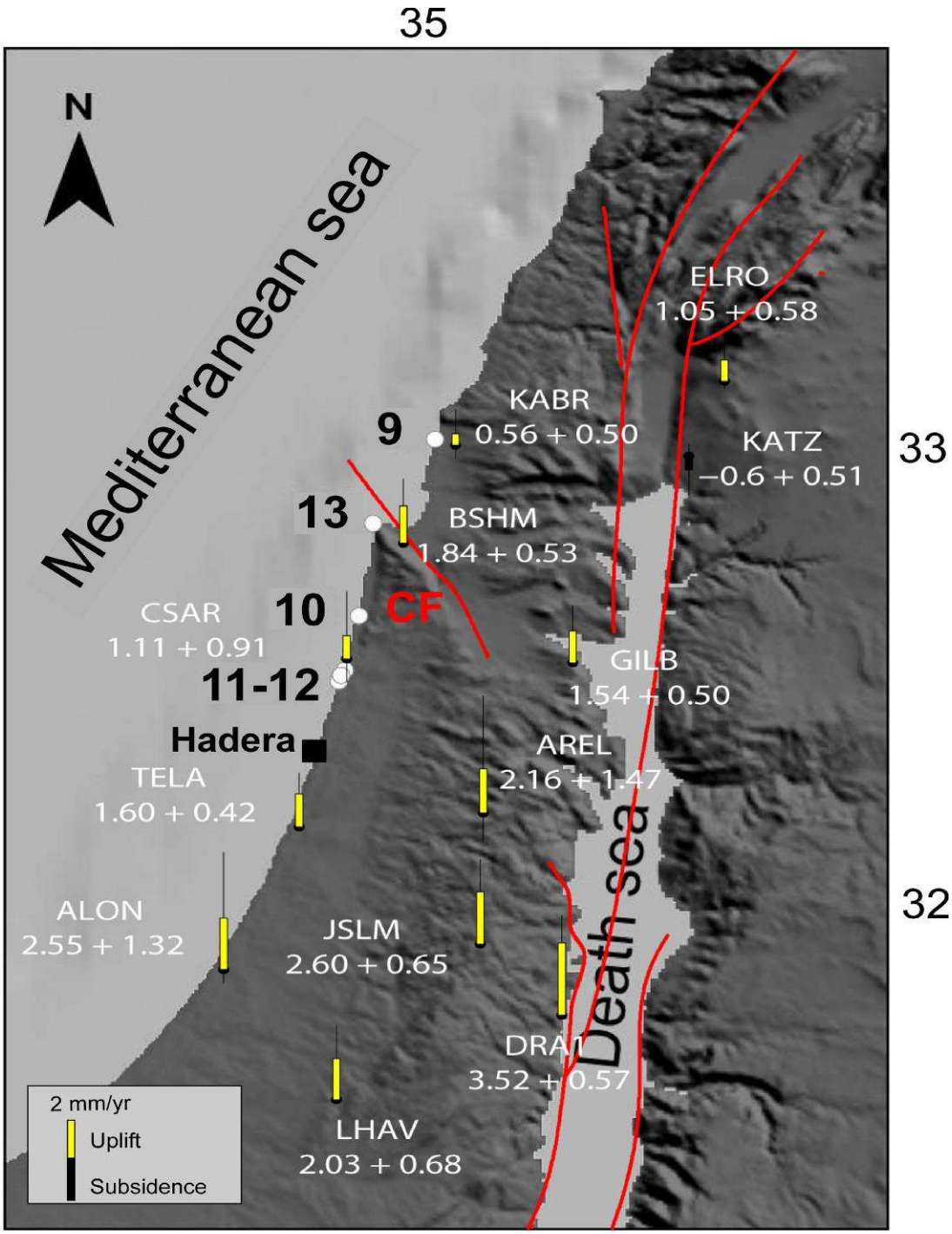

35
N
Mediterranean sea
ELRO
1.05 + 0.58
KABR
0.56 + 0.50
9
KATZ
−0.6 + 0.51
33
13
BSHM
1.84 + 0.53
CSAR
1.11 + 0.91
10
CF
GILB
1.54 + 0.50
11-12
Hadera
AREL
2.16 + 1.47
TELA
1.60 + 0.42
Death sea
32
ALON
2.55 + 1.32
JSLM
2.60 + 0.65
DRAI
3.52 + 0.57
LHAV
2.03 + 0.68
2 mm/yr
Uplift
Subsidence

Fig.2b

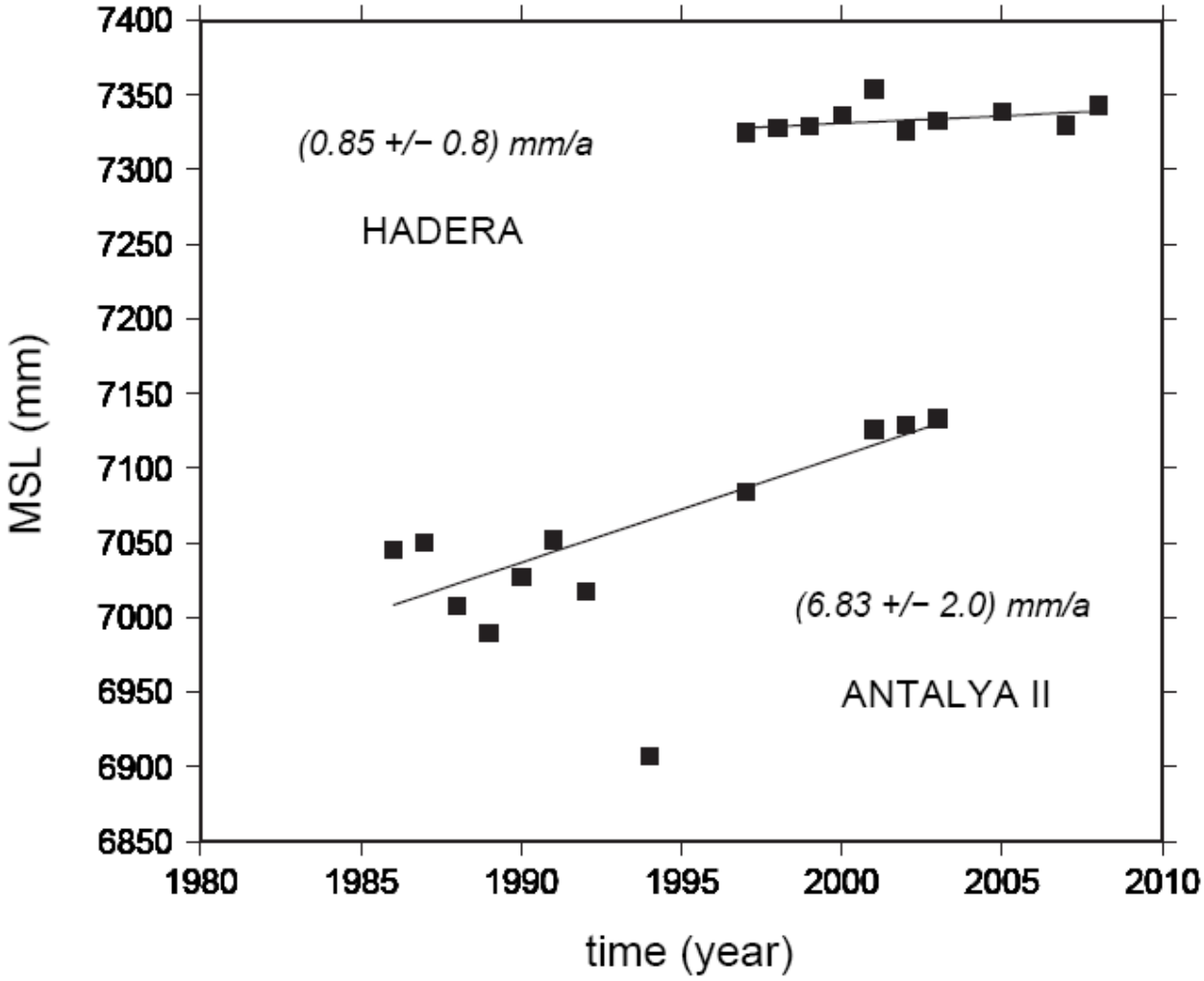


Fig. 3

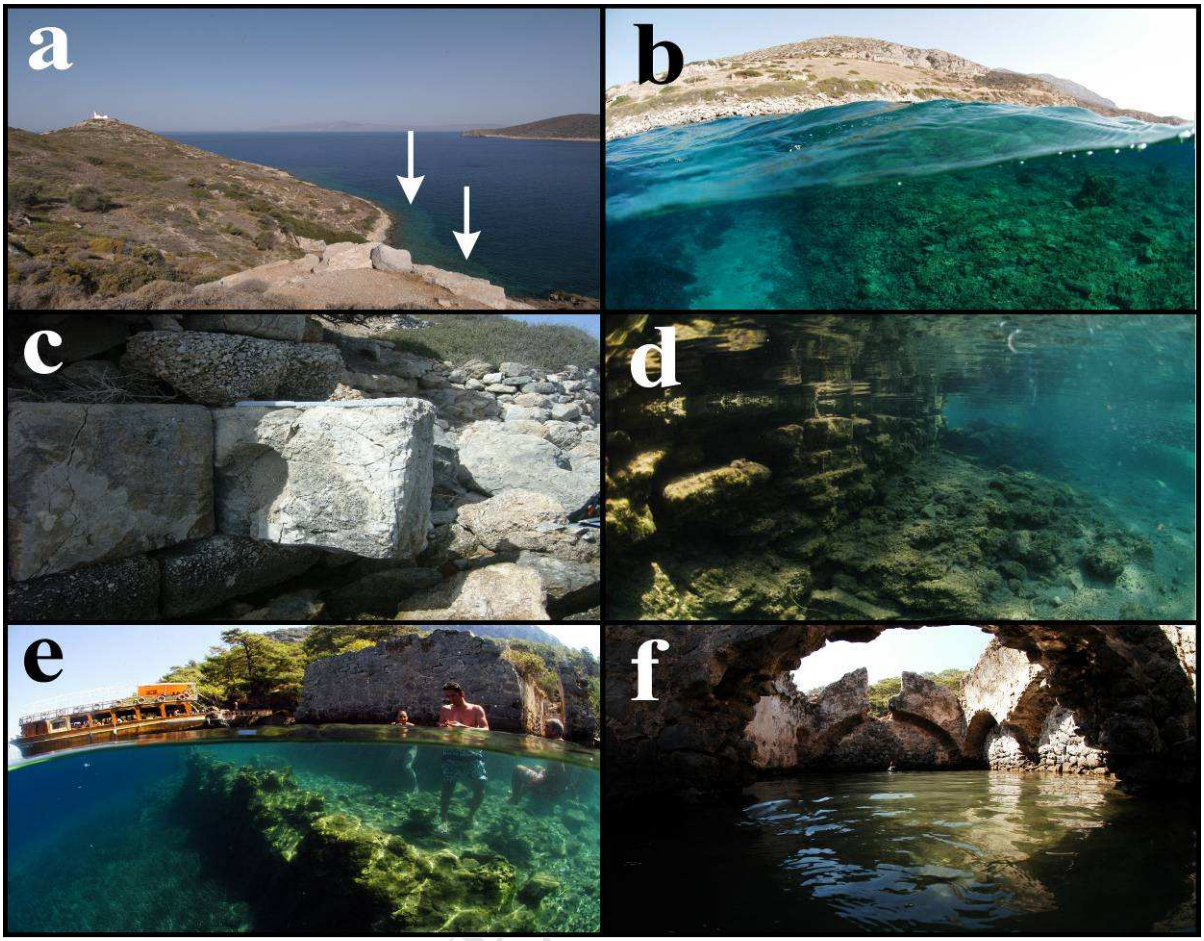


Fig.4a

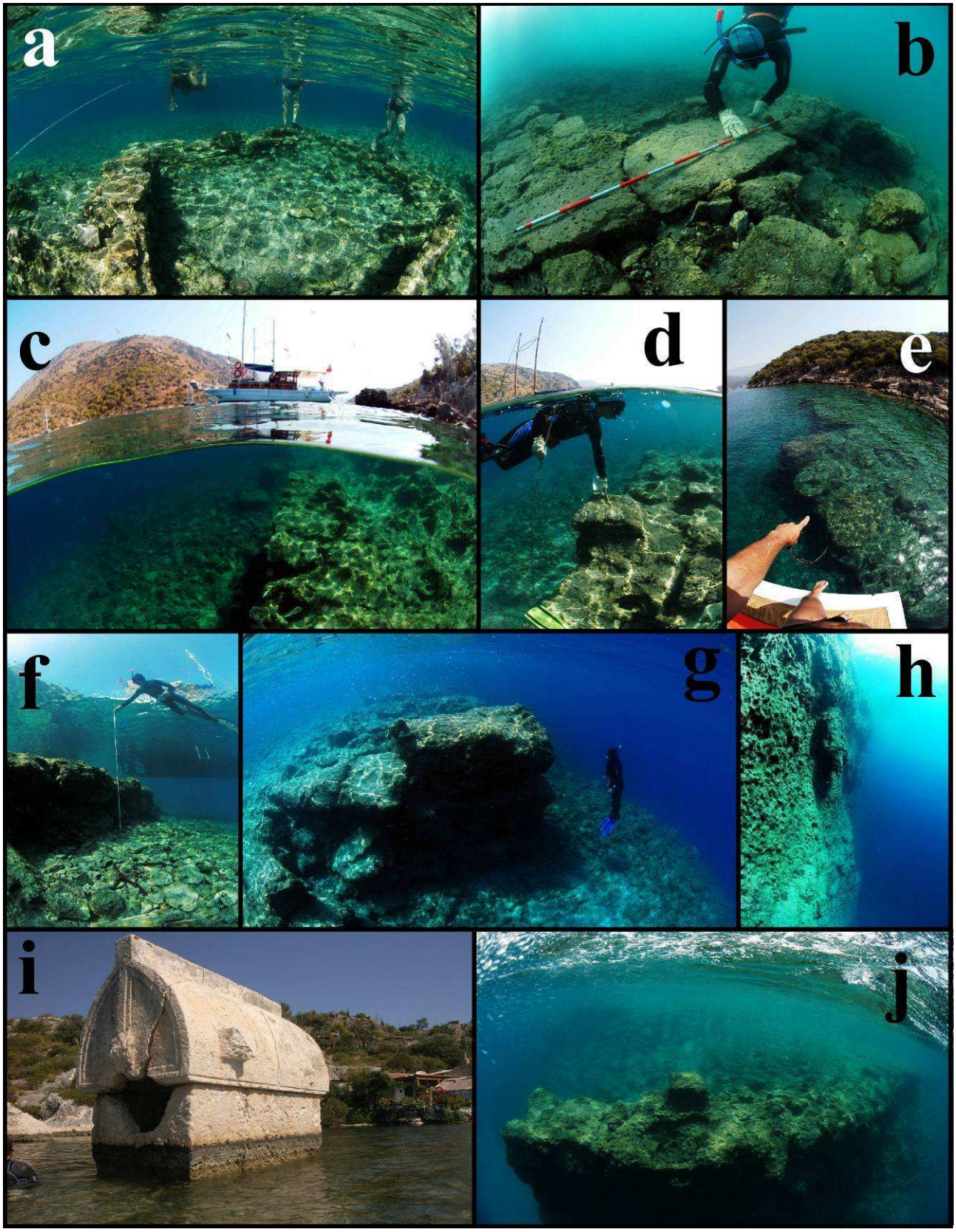


Fig.4b

Fig.5a

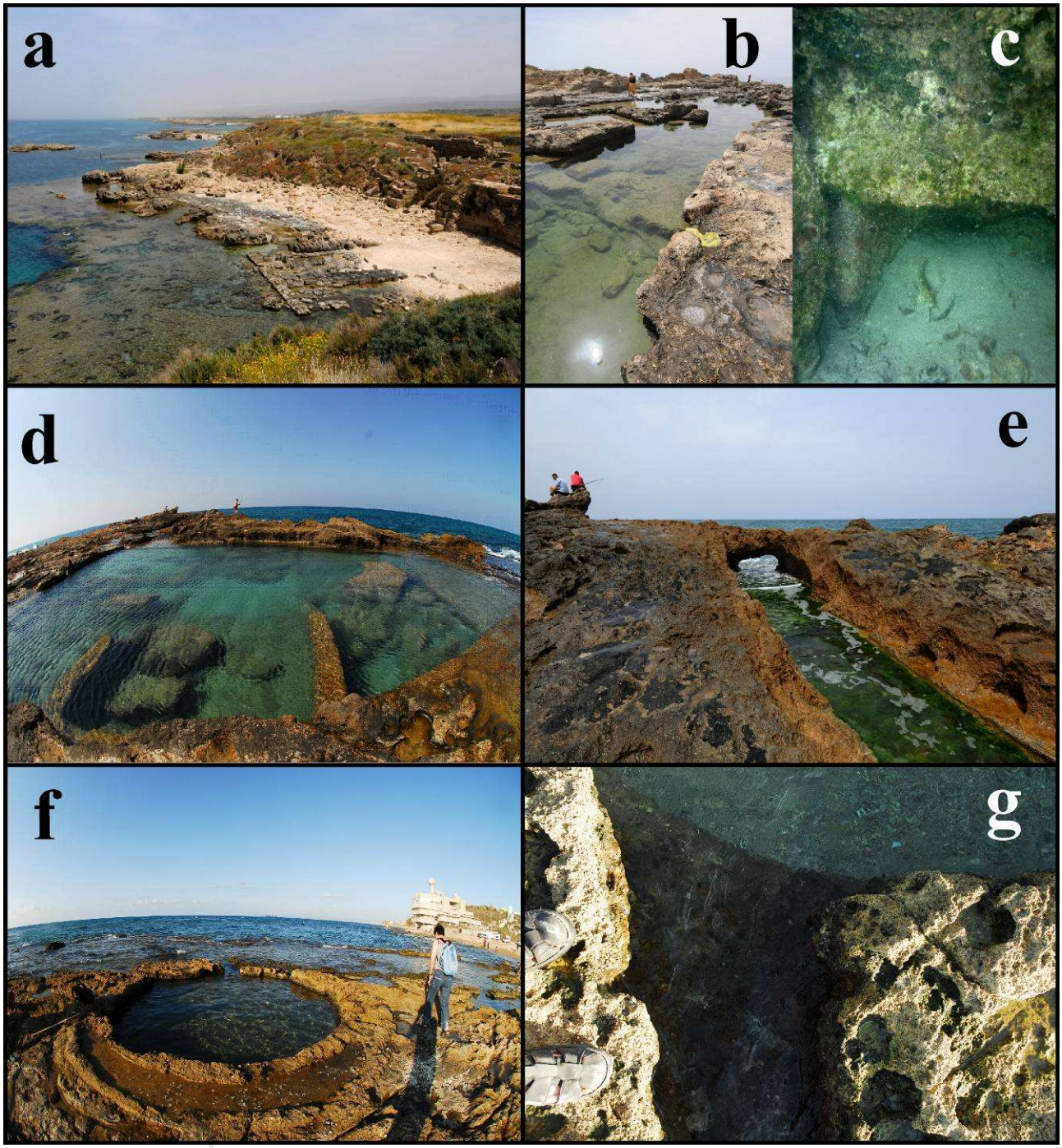


Fig.5b

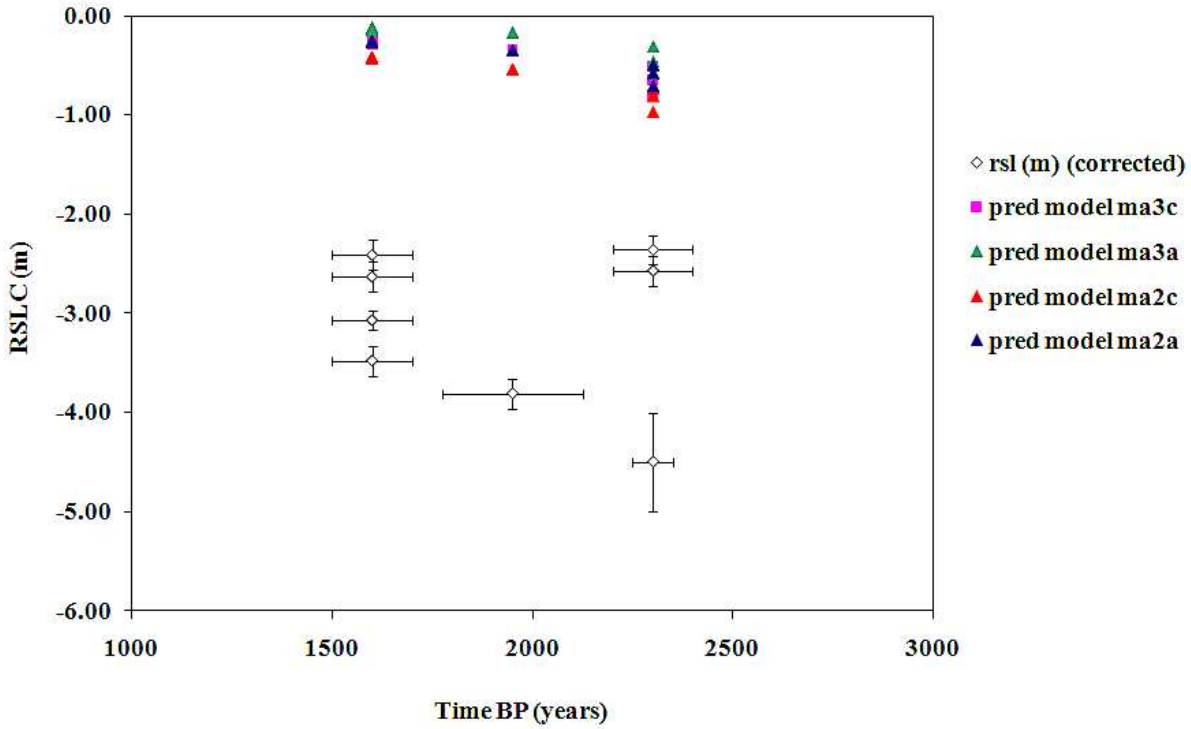

0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
RSLC (m)
1000
1500
2000
2500
3000
Time BP (years)
rsl (m) (corrected)
pred model ma3c
pred model ma3a
pred model ma2c
pred model ma2a

Fig.6a

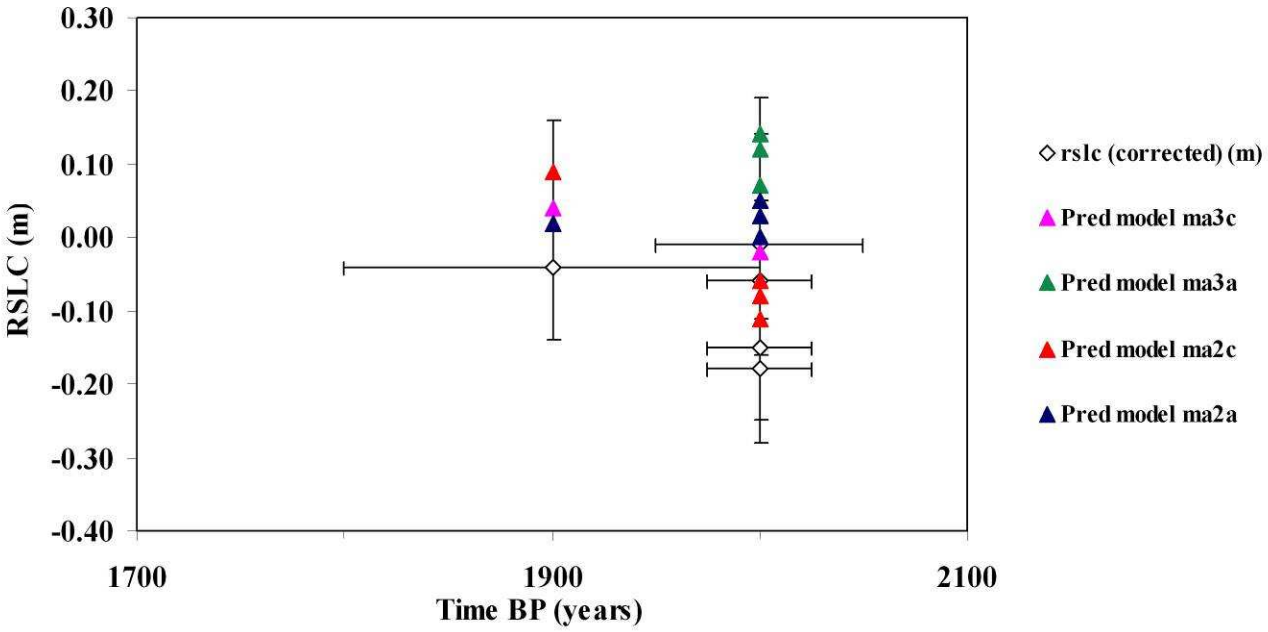
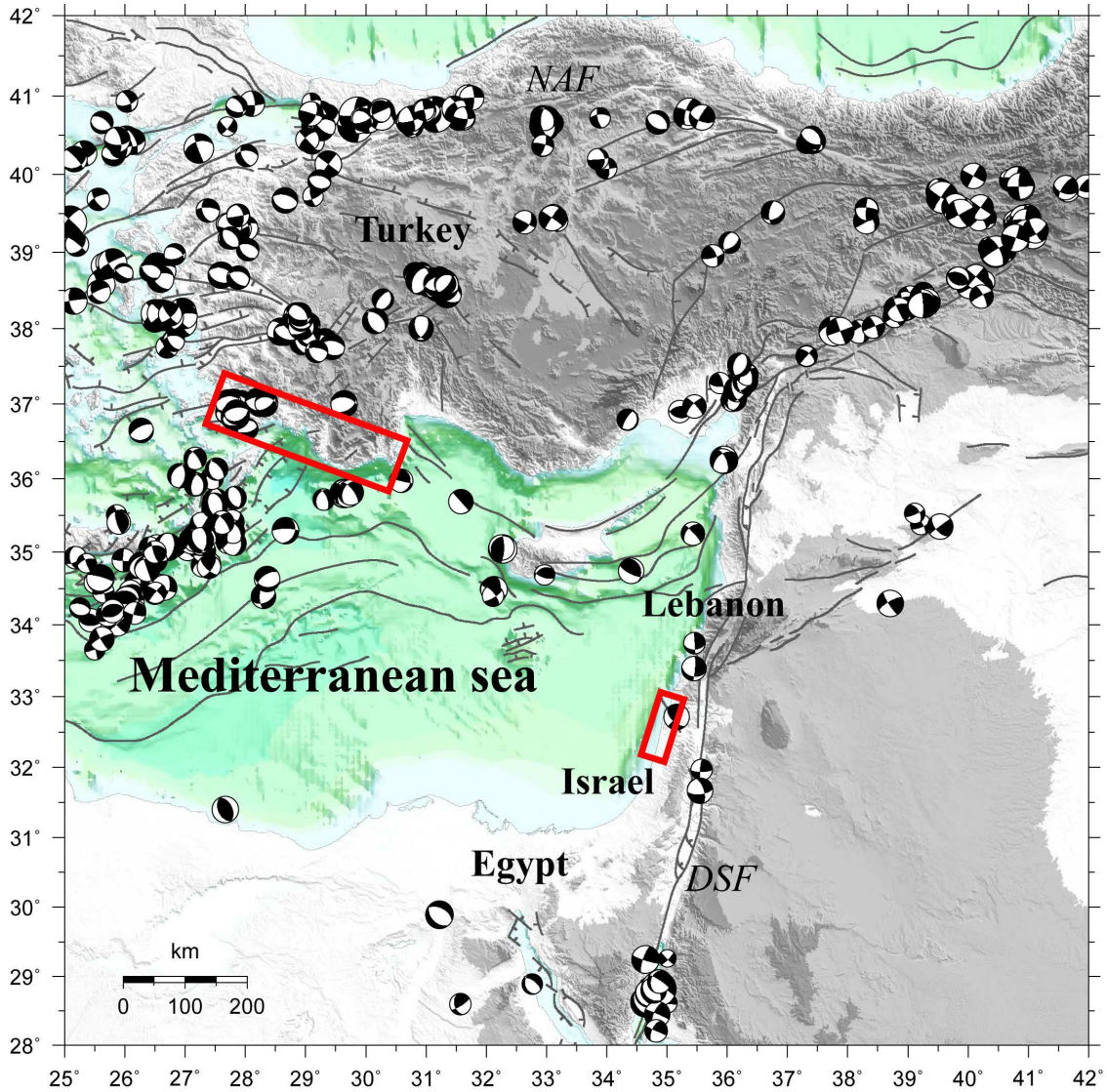
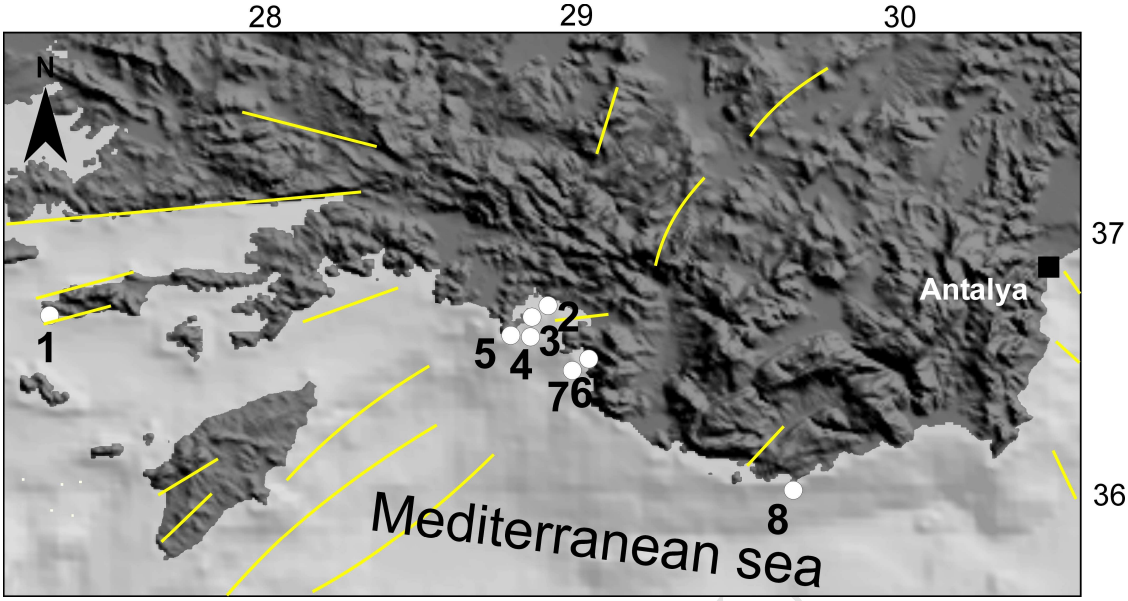

0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
RSLC (m)
1700
1900
2100
Time BP (years)
rslc (corrected) (m)
Pred model ma3c
Pred model ma3a
Pred model ma2c
Pred model ma2a

Fig.6b

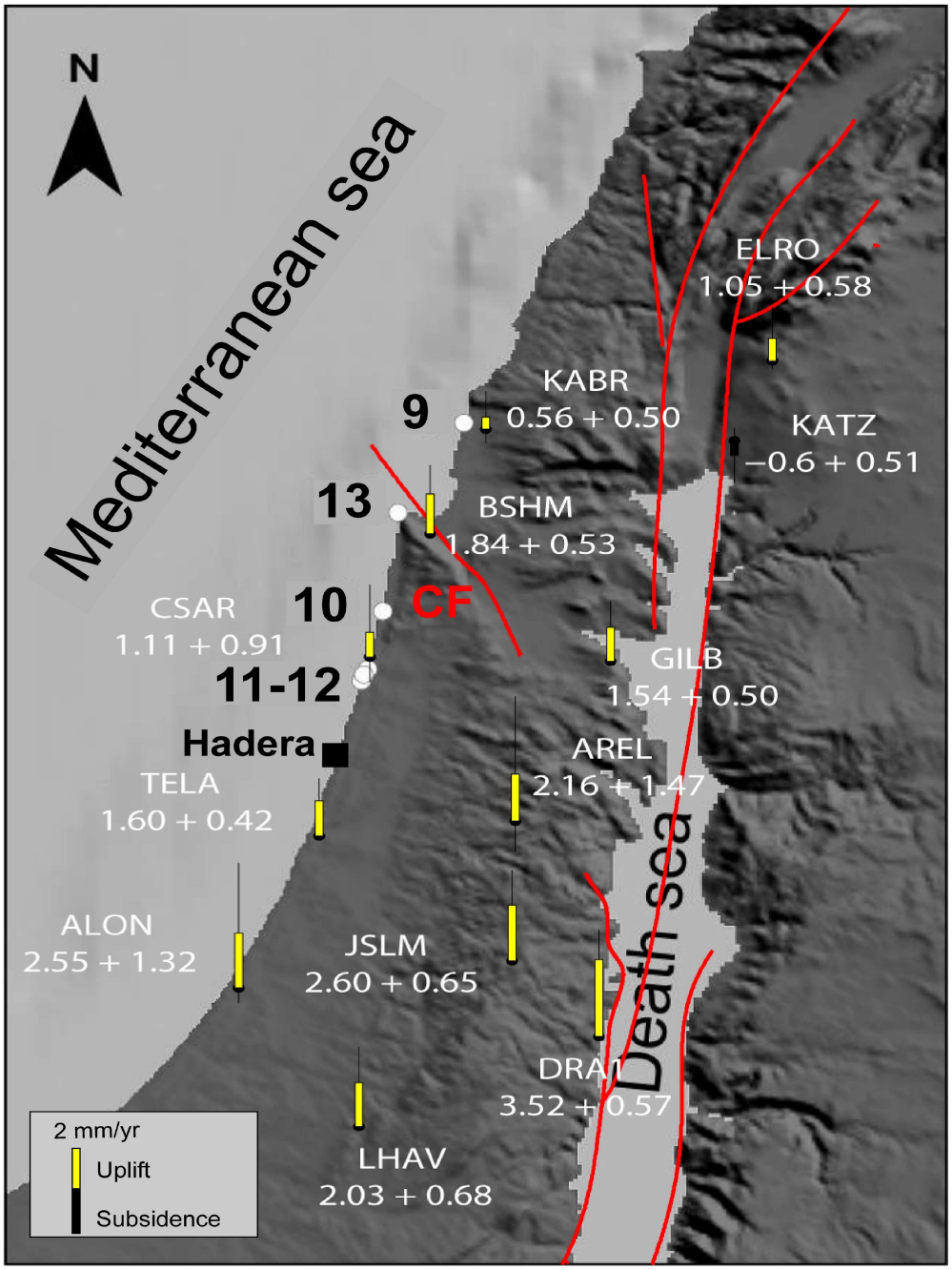
A Site No	B Site name	C Country	D Marker	E Latitude	F Longitude	G Age (ka)	H Obs rslc. (m)	I σ obs (m)	J Limit	K ma3C (m)	L ma3A (m)	M ma2C (m)	N ma2A (m)	O Up tectonic rate (mm/yr)
1 (8)	Cnidos	Turkey	BR,H	36.685	27.373	2.3±100	-2.57	0.3	UL	-0.8	-0.58	-0.97	-0.71	-0.73±0.23
2 (6)	Scopea_Bay	Turkey	D	36.675	28.915	1.95±175	-3.81	0.3	UL	-0.34	-0.17	-0.54	-0.35	-1.71±0.25
3 (4)	Domuz_Is.	Turkey	B	36.667	28.905	1.6±100	-2.41	0.3	UL	-0.26	-0.12	-0.42	-0.26	-1.26±0.26
4 (5)	Kala_Kapi	Turkey	B	36.643	28.893	1.6±100	-2.63	0.3	UL	-0.27	-0.13	-0.42	-0.26	-1.40±0.26
5 (3)	Cleopathras_bath	Turkey	B, PV	36.640	28.855	1.6±100	-3.52	0.3	UL	-0.27	-0.14	-0.42	-0.27	-1.95±0.26
6 (1)	Gemile_Is.	Turkey	D	36.555	29.064	1.6±100	-3.07	0.2	LL	-0.29	-0.15	-0.43	-0.27	-1.66±0.19
7 (2)	Tersane_bay	Turkey	SW	36.541	29.051	2.3±100	-4.50	1	LL	-0.5	-0.31	-0.73	-0.5	-1.68±0.67
8 (7)	Kekova	Turkey	T,D,B,PV	36.189	29.860	2.3±100	-2.36	0.3	UL	-0.65	-0.46	-0.81	-0.58	-0.70±0.23
9 (13)	Akziv	Israel	FT	33.049	35.100	2±25	-0.06	0.2	UL,LL	-0.02	0.07	-0.11	0.00	0.06±0.14
10 (12)	Dor	Israel	CH,P	32.620	34.917	2±50	-0.01	0.2	UL	0.03	0.12	-0.08	0.03	0.09±0.14
11 (9)	Caesarea_1	Israel	D	32.503	34.889	2±25	-0.15	0.2	UL	0.05	0.14	-0.06	0.05	0.02±0.14
12 (10)	Caesarea_2	Israel	P	32.497	34.889	2±25	-0.18	0.2	UL,LL	0.05	0.14	-0.06	0.05	0.01±0.14
13 (206)	Shiqmona	Israel	P	32.825	34.955	2±100	-0.04	0.2	UL	0.04	0.09	0.09	0.02	0.07±0.14

Table 1


NAF
Turkey
Mediterranean sea
Lebanon
Israel
Egypt
DSF
km
0 100 200
42°
41°
40°
39°
38°
37°
36°
35°
34°
33°
32°
31°
30°
29°
28°
25° 26° 27° 28° 29° 30° 31° 32° 33° 34° 35° 36° 37° 38° 39° 40° 41° 42°

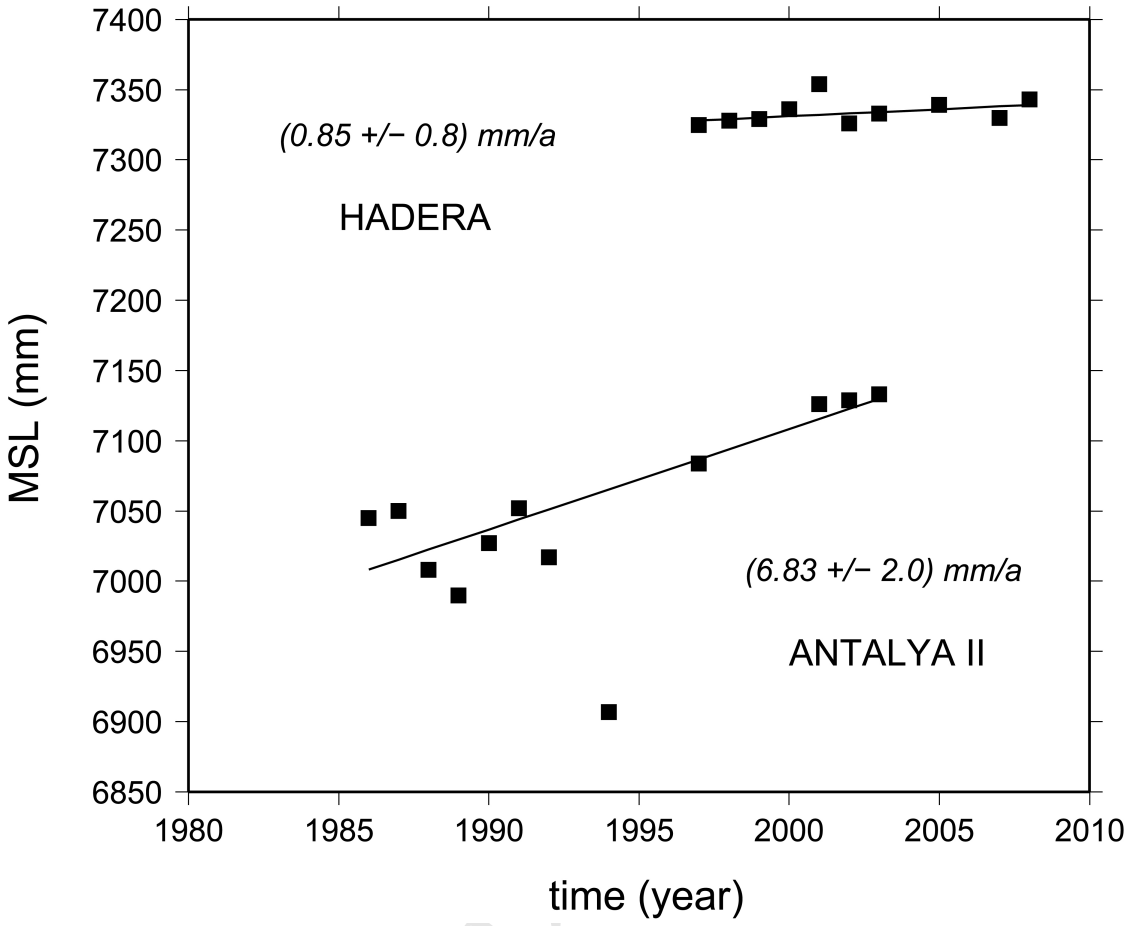


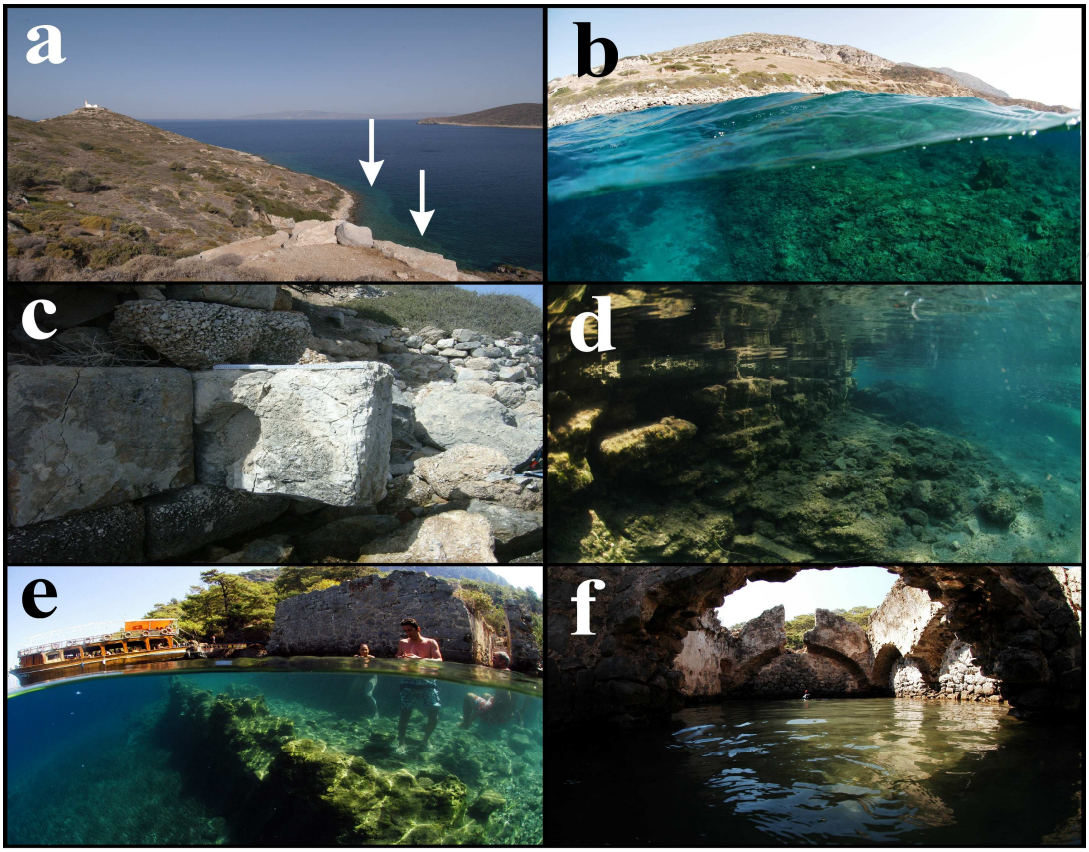
35

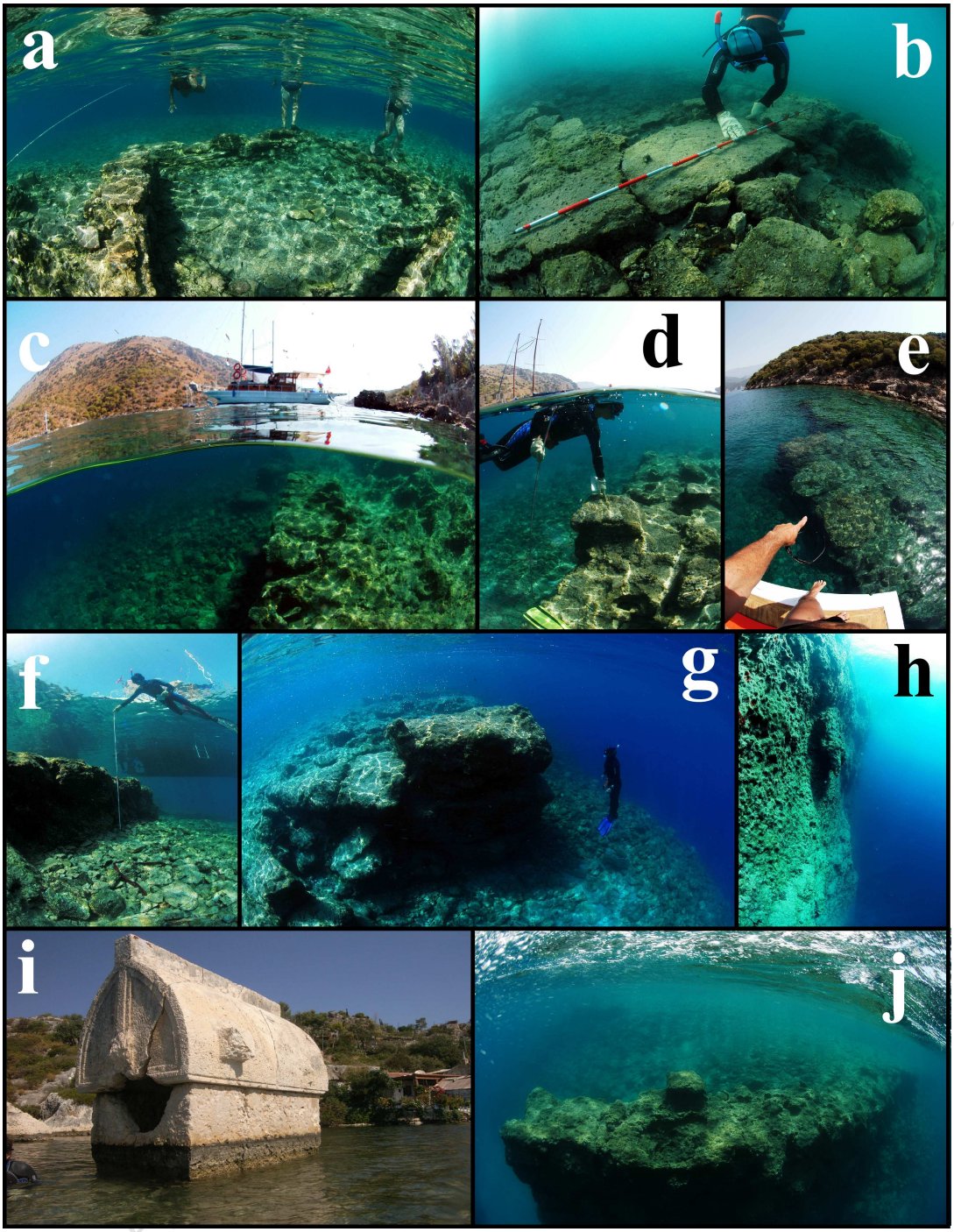

N
Mediterranean sea
ELRO
1.05 + 0.58
KABR
0.56 + 0.50
9
KATZ
−0.6 + 0.51
13
BSHM
1.84 + 0.53
CSAR
1.11 + 0.91
10
CF
11-12
GILB
1.54 + 0.50
Hadera
AREL
2.16 + 1.47
TELA
1.60 + 0.42
Death sea
ALON
2.55 + 1.32
JSLM
2.60 + 0.65
DRAI
3.52 + 0.57
LHAV
2.03 + 0.68
2 mm/yr
Uplift
Subsidence

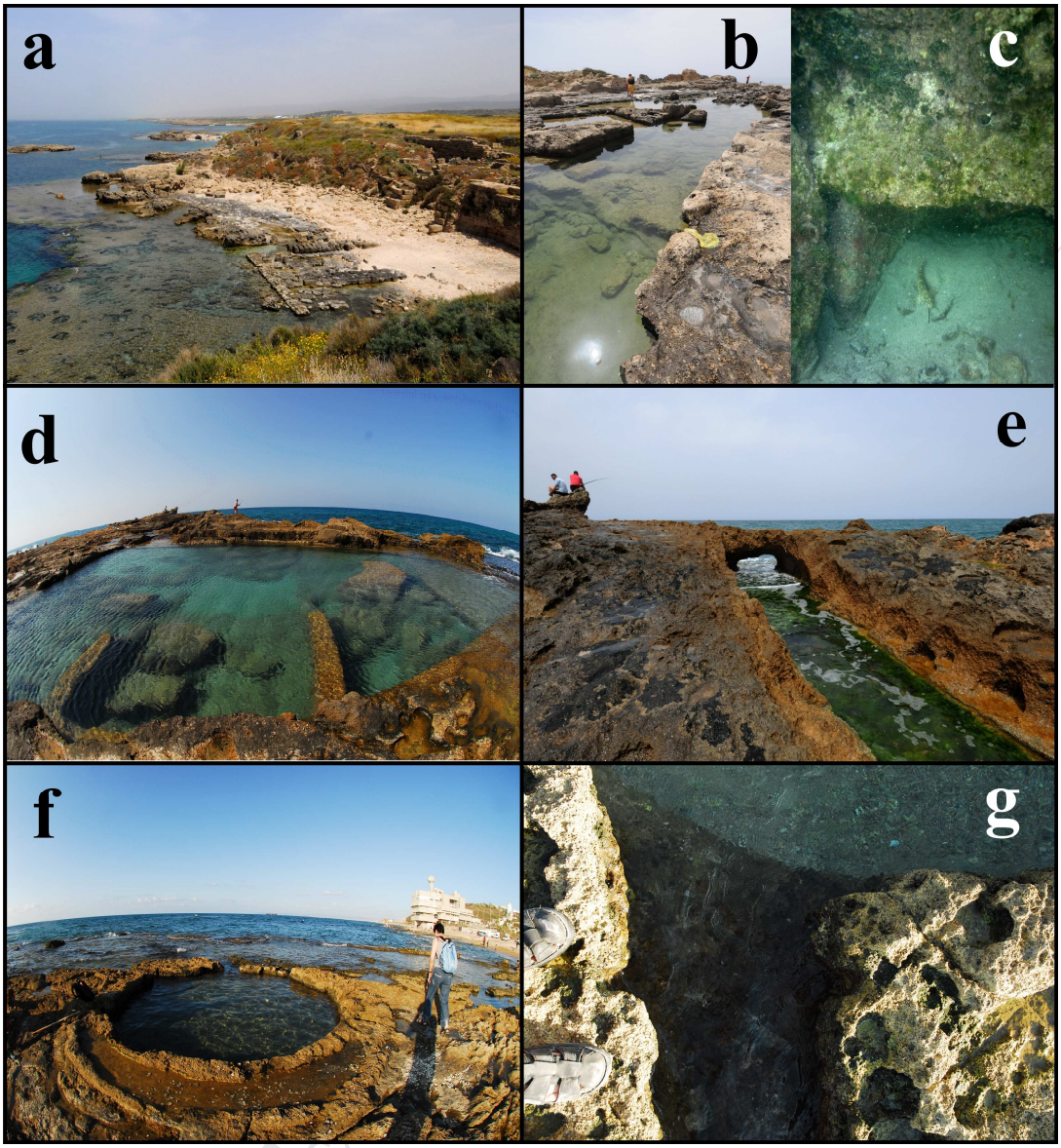
33

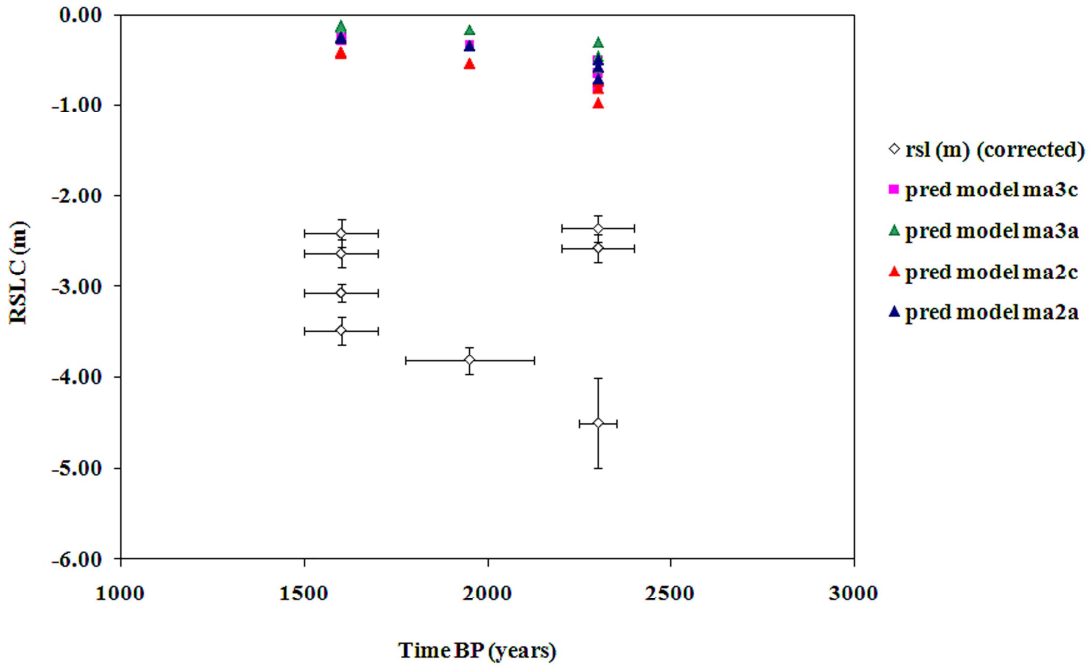
32


7400
7350
7300
7250
7200
7150
7100
7050
7000
6950
6900
6850
MSL (mm)
(0.85 +/− 0.8) mm/a
HADERA
(6.83 +/− 2.0) mm/a
ANTALYA II
1980
1985
1990
1995
2000
2005
2010
time (year)


a
b
c
d
e
f


a
b
c
d
e
f
g
h
i
j




0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
RSLC (m)
1000
1500
2000
2500
3000
Time BP (years)
rsl (m) (corrected)
pred model ma3c
pred model ma3a
pred model ma2c
pred model ma2a