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SEA LEVEL CHANGES AND VERTICAL MOVEMENTS OF THE LAND IN THE MEDITERRANEAN REGION FROM INTEGRATED DATA

Marco Anzidei[1, 2], Fabrizio Antonioli[3], Kurt Lambeck[4], Dorit Sivan[5], Mohamed Soussi[6], Enrico Serpelloni[7], Silvia Pondrelli[7], Gianfranco Vannucci[7], Paolo Baldi[8], Rita Auriemma[9], Alessandra Benini[10] & Emanuela Solinas[11]

(1) Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
(2)Università della Calabria, Dipartimento di Fisica, Cosenza, Italy
(3) ENEA, Casaccia, Rome, Italy
(4) Research School of Earth Sciences, The Australian National University, Canberra 0200, Australia
(5) University of El Manar, Faculty of Sciences of Tunis, Department of Geology, Tunisia
(6) University of El Manar, Faculty of Sciences of Tunis, Department of Geology, Tunisia
(7) Istituto Nazionale di Geofisica e Vulcanologia,Bologna, Italy
(8) Università di Bologna, Dipartimento di Fisica, Bologna, Italy
(9) Dipartimento Beni Culturali, Universita` degli Studi di Lecce, Lecce, Italy
(10) Università della Calabria, Dipartimento di Archeologia e Storia delle Arti, Cosenza, Italy
(11) Civico Museo Archeologico Sa Domu Nosta, Cagliari, Italy
Corresponding author: M. Anzidei <marco.anzidei@ingv.it>

ABSTRACT: Anzidei M. *et al.,* Sea level changes and vertical movements of the land in the Mediterranean region from integrated data. (IT ISSN 0394-3356, 2011)
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Parole chiave: Mediterraneo, livello del mare, archeologia, geodesia, geofisica

Coastal settlements and maritime installations built in antiquity provide important insights into sea-level changes during past millennia, and reconstructions of historical sea-level change using archaeological coastal sites are particularly effective in the Mediterranean sea, whose coastlines still preserve remnants of human activity since the last glacial maximum. The first pioneering results on sea level changes from archaeological indicators in the Mediterranean were published during the '70s (FLEMMING, 1969; CAPUTO & PIERI, 1976; SCHMIEDT, 1974; PIRAZZOLI, 1976; FLEMMING & WEBB, 1986), but new and more detailed results arise for the Mediterranean during the last decade (ANTONIOLI *et al*., 2007; LAMBECK *et al*., 2010a & references therein; LAMBECK *et al.,* 2010b; ANZIDEI *et al.,* 2010a; ANZIDEI *et al*., 2010b;).
Unfortunately, despite the large number of archaeological remains in the Mediterranean, only a part of them can be used to obtain reliable information on their former relationship to sea level (AURIEMMA & SOLINAS, 2009). Limitations arise as a result of their uncertain use, poor preservation, or because they were built in geologically unstable areas which produce local disturbances. Although the oldest known archaeological site useful to constraints the sea-level change in the Mediterranean (LAMBECK & PURCELL, 2005) starts with the 22 ka flooded paintings of Cosquer cave (Southern France) today 37 m below sea level (CLOTTES *et al.,* 1997), particularly valuable are the roman age coastal sites. Fish tanks, piers and harbors constructions, generally dated between the 1st century BC and the 1st century AD, are very precise indicators (LAMBECK *et al.,* 2004b). Quarries carved along the coastlines and located nearby fish tanks and harbors or villas of similar age, can provide additional data on past water level, as well as information on their elevation above sea level, although these alone are less precise indicators.
We provide a data base of coastal archaeological sites with valid records dated back to 1.6-2.5 ka BP, using direct observations as well as archaeological, geophysical and geological literature. Particular attention was given to the elevation of the significant architectural features related with the sea level. These include the system of channels of the fish tanks, bollard and piers for harbors, lower cuttings for quarries, bottom end of slipways. In addition to those artifacts which provide precise data, other features can be classified as to whether they must have been dry (house pavements, roads, tombs),

partially in the water (piers, quays, moles, slipways, fish tanks), or completely submerged (floor of channels for water exchange in the fish tanks, floor of fish tanks, channels at the entrance of harbors, floor of harbors). When different class of structures exist at a single site, as for example at Ventotene island (Italy), we can obtain a very accurate estimation of the relative sea level change as well as understand the relationships between their elevations with respect to the mean sea level at the time of their construction. Moreover, structures from different ages can provide a relative sea level curve for that specific site.

To obtain precise measurements of the relative sea level change at the archaeological sites, we defined the "functional elevation" as the elevation of specific architectural parts of an archaeological structure with respect to the local mean sea level at that location and at the time of its construction. It depends on the type of structure, its use and the local tide amplitudes. The minimum elevation of particular structures above the local highest tides can also be defined.

Field data from more than 150 sites of valid archaeological markers were used in our study. Field measurements were performed by invar rod, optical or electronic methods, during calm sea with null wave action. Elevations are related to the sea-level position at that moment. Data accuracy with their uncertainties for age and elevation at each site, are estimated on the basis of the type of indicator used and of the historical literature, based on the artifacts or on the architectural features. Observations of geomorphological indicators, such as beachrocks and solution notches, are used to integrate and reinforce the archaeological interpretations as in ANTONIOLI *et al*. (2007).

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. Accuracy of the elevations of the data set is within 0.5-0.2 m, although some limitations occurs, as for quarries or slipways, which are less precise indicators in comparison with fish tanks (LAMBECK *et al*., 2004b).

The analysis was performed during four different steps: 1) the elevation of the valid sites were measured (average value of multiple measurements of the best preserved parts of the investigated structures) with respect to the sea level at the time of surveys; 2) measurements were reduced to mean sea level of the site itself, applying tidal corrections at the surveyed sites, using the data of the nearby tide gauges (www.idromare.it; www.psmsl.ac.uk). In the cases of the unavailability of tide gauge data were we used the predicted tide estimation, corrected for local pressure values. We estimate errors for the elevations and ages of the archaeological markers and evaluate their functional elevations on the basis of archaeological interpretations. Since the investigated archaeological structures were originally used year round, we assume that the defining levels correspond to the annual mean conditions at the time of construction. Age errors are estimated from the architectural features and historical documents, while elevation errors derive from the measurements of the functional heights (for example, the lower limiting values for the quarries and slipways); 4) finally, we examined 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 proposed glacio-hydro-isostatic model for each location. We hypothesize tectonic stability at the sites where the elevations of the markers are in agreement with the predicted sea-level curve. Conversely, we hypothesize that the area has experienced tectonic or volcanic subsidence or uplift when the elevations of the markers are below or above that of the predicted sea-level curve, respectively.

The archaeological evidences is providing a new picture of the spatial distribution of the sea level changes in Mediterranean since the last ~2.3 ka. Despite the limitations and resolution of the available data with respect to the known tectonic complexity of the study region, an integrated use of historical data, geological observations of the elevation of MIS 5.5, instrumental data of tide gauges and vertical GPS can provide, together with an accurate modelling of the glacio-hydro-isostatic contribution for vertical land movements and amount of water in the basin, to a more comprehensive description of the causes that are driving the sea level change since ~2.5 ka and their current rates at different locations, as reported in FERRANTI *et al*., 2010. We use the calibrated model results to separate out the tectonic contribution, widely diffused in the Mediterranean, from the vertical movements related to the glacio–hydro-isostatic changes. Our analysis are consistent with model predictions as well as trends inferred from seismic strain analysis of earthquakes occurred during the last 30-40 years and tide gauge data for the last ~100 yr. This indicates that besides the glacio–hydro-isostatic effect, also the tectonic contribution can affects the relative sea level changes along the coastlines of the Mediterranean, since the last ~2.5 ka.

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