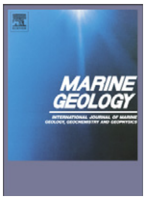
Marine Geology 376 (2016) 26–38

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo



# Impact of eustatic and tectonic processes on the southeastern Mediterranean shelf during the last one million years: Quantitative reconstructions using a foraminiferal transfer function

Simona Avnaim-Katav [a,b,*], Yvonne Milker [c], Gerhard Schmiedl [d], Dorit Sivan [a], Orit Hyams-Kaphzan [e], Amir Sandler [e], Ahuva Almogi-Labin [e]

[a] Department of Maritime Civilizations, Leon Charney School of Marine Sciences and the Leon Recanati Institute for Maritime Studies (RIMS), University of Haifa, Mount Carmel, Haifa 31905, Israel
[b] University of California, Los Angeles, Institute of the Environment and Sustainability, La Kretz Hall, Suite 300, Box 951496, Los Angeles, CA 90095-1496, USA
[c] University of Leipzig, Institute for Geophysics and Geology, Talstrasse 35, 04103 Leipzig, Germany
[d] University of Hamburg, Center for Earth System Research and Sustainability, Institute for Geology, Bundesstrasse 55, 20146 Hamburg, Germany
[e] Geological Survey of Israel, 30 Malkhe Yisrael, Jerusalem 95501, Israel

## ARTICLE INFO

*Article history:*
Received 26 November 2015
Received in revised form 7 March 2016
Accepted 16 March 2016
Available online 6 April 2016

*Keywords:*
Southeastern Mediterranean shelf
Transfer function
Weighted averaging-partial least squares
Benthic foraminifera
Relative sea level reconstruction
Pleistocene

## ABSTRACT

Benthic foraminifera-based transfer function models provide accurate sea-level reconstructions for shelf and coastal environments around the world. This study presents for the first time results of a foraminiferal transfer function aiming at the reconstruction of relative sea-level in the southeastern Mediterranean shelf during the past one million years. A Weighted Averaging-Partial Least Squares (WA-PLS) regression method was used for the development of the transfer function based on an extensive set of surface samples (modern training data set) from the study area. The transfer function was applied to three shelf sediment successions retrieved from Haifa Bay, Israel. The Modern Analog Technique (MAT) and the random TF test were used to investigate similarity between modern and fossil foraminiferal faunas, testing the reliability and significance of our model for paleowater depth reconstruction. The performance of the WA-PLS transfer functions suggests a strong relationship between the observed and estimated water depths in the modern data set with relatively precise reconstructions of 7.0 m (Root Mean Squared error of Prediction) over a water depth range of 3 to 80 m. The deepest paleo water depths were reconstructed for the earliest sea-level highstands recorded in the sediment records (MIS 27? and MIS 29?) in the down-faulted boreholes due to tectonic movements, whereas the younger interglacial sedimentary units (MIS 25?, 13, 11, 7, 5.5 and 1) were mostly deposited at <15 m water depths or slightly deeper during MIS 7. The relative sea-level history of the southeastern Mediterranean shelf reveals deviations from the global sea-level trend during MIS 5.5, which may have resulted from minor tectonic movements in the study area and/or un-representation of the phase of maximum sea-level in the sediment succession. Our paleowater depth estimates demonstrate a shallowing trend during the Holocene, generally matching other regional Mediterranean sea-level records.

## 1. Introduction

Quaternary sea-level fluctuations in the southeastern Mediterranean Sea were mainly controlled by global eustatic processes and have affected the environmental conditions and depositional processes at the sea-land transition zone. Accordingly, sediment archives from these environments provide detailed insights into sea-level changes on glacial/interglacial time-scales. Sea-level low-stands are commonly documented in form of hiatuses while shallow-neritic sediments represent sea-level high-stands (e.g., Avital, 2002; Porat et al., 2003; Avnaim-Katav et al., 2012, 2013).

Sea-level reconstructions vary in elevation and accuracy when using different methodological approaches but may also deviate when comparing different adjacent sites. For continuous relatively long records of up to ~0.5 Ma obtained by transferring deep sea foraminifera $\delta^{18}O$ values to sea level, uncertainties commonly vary between ±13 m (Waelbroeck et al., 2002), ±12 m (Siddall et al., 2003), ±6 m (Rohling et al., 2008) and ±3 m when using statistical calculations (Kopp et al., 2009, 2013). Coastal morphological structures, such as notches, offer relative accurate indicators for past sea level elevations (Hearty et al., 2007), yet its greatest problem is the lack of accurate dating. Unlike the above mentioned long-term sea-level records, the longest record from the (western) Mediterranean Sea covers the last

---

[*] Corresponding author at: Department of Maritime Civilizations, Leon Charney School of Marine Sciences and the Leon Recanati Institute for Maritime Studies (RIMS), University of Haifa, Mount Carmel, Haifa 31905, Israel.

*E-mail addresses:* savnaim-k@univ.haifa.ac.il, simona100@ucla.edu (S. Avnaim-Katav).

http://dx.doi.org/10.1016/j.margeo.2016.03.010
0025-3227/© 2016 Elsevier B.V. All rights reserved.

30 ka and is based on archeological data (Lambeck and Bard, 2000). The Holocene sea-level history of the southeastern Mediterranean Sea has been relatively widely studied, also mainly based on archeological data (Sivan et al., 2001, 2004; Anzidei et al., 2010). Further information is provided by bio-indicators, such as reef-building organisms at the edges of abrasion platforms of rocky shorelines (Sivan et al., 2010 and refs therein). These observations have been compared to numerical models (Sivan et al., 2001, 2004; Lambeck and Purcell, 2005; Stocchi and Spada, 2009) aiming to fill in data from periods of low data availability and for extracting the local tectonic component. Sea-level changes in the southeastern Mediterranean Sea have also been documented by semi-quantitative micropaleontological data (Avital, 2002; Lazar, 2007; Avnaim-Katav et al., 2013). In shelf environments of the western Mediterranean Sea, benthic foraminifera have been used as proxy for quantitative paleo-depth estimates (Rossi and Horton, 2009; Milker et al., 2011).

Several ecological studies have demonstrated that the environmental variables controlling the spatial distribution pattern of shallow-water to deep-sea benthic foraminiferal assemblages often correlate with water depth (e.g., Bandy and Chierici, 1966; Cita and Zocchi, 1978; Murray, 1991; De Rijk et al., 2000; Mendes et al., 2004; Horton et al., 2007; Pascual et al., 2008; Rossi and Horton, 2009). Many species show bathymetric zonations in areas where water depth influences the environmental variables controlling their distribution pattern (e.g., Jorissen et al., 1995; De Rijk et al., 2000; Rossi and Horton, 2009, and references therein; Milker et al., 2011; Avnaim-Katav et al., 2013). A depth zonation of benthic foraminifera is reported from numerous shallow-marine environments worldwide (e.g., Morigi et al., 2005; Rossi and Horton, 2009; Milker et al., 2009). Van der Zwaan et al. (1999) concluded that the bathymetric zonation of benthic foraminifera is primarily controlled by organic matter flux (food availability) and oxygen content. In the Mediterranean Sea, this bathymetric zonation displays general contrasts between the western and eastern basins, reflecting the W–E decrease of surface water productivity and related food fluxes to the sea floor (De Rijk et al., 1999, 2000). The recent benthic foraminiferal faunas on the shelves off southwestern Iberia and the northern Tyrrhenian Sea show a depth zonation related to sediment type, organic matter content, and hydrodynamic conditions (Mendes et al., 2004; Frezza and Carboni, 2009). In the northern Adriatic Sea, this bathymetric zonation is interrelated with environmental parameters such as grain-size distribution and organic matter content (Jorissen, 1987; Morigi et al., 2005). De Stigter et al. (1998) and Milker et al. (2009) showed a distinct bathymetric zonation of foraminifera linked to substrate, water turbulence and food availability at the Adriatic Sea floor and on shelf environments of the western Mediterranean, respectively. Hyams-Kaphzan et al. (2008) showed that the distribution of recent benthic foraminiferal assemblages on the southeastern Mediterranean inner-shelf depends primarily on substrate type, which is linked to its position along the Nile littoral cell, and to bathymetry. Avnaim-Katav et al. (2015) reinforced this earlier observation by using multivariate statistical analyses, identifying a distinct bathymetric zonation of foraminifera related to TOC content and grain size of the substrate. Hence, the benthic foraminiferal distribution pattern in these modern environments provides a useful basis for paleo-bathymetric estimates.

Various recent studies use advanced and accurate regression methods relying on the recent foraminiferal zonation with respect to water depth (or sea-level in salt marsh environments). This information was used to develop predictive transfer functions, capable of inferring the paleowater depth from a fossil foraminiferal content (e.g., Kemp and Telford, 2015; Barlow et al., 2013). These methods, including Weighted Averaging (WA) and Weighted Averaging-Partial Least Squares (WA-PLS) have been applied over a wide bathymetric range covering intertidal to subtidal environments and provide precise sea-level estimates mainly for the Holocene (e.g., Horton et al., 1999; Gehrels, 2000; Boomer and Horton, 2006; Horton and Edwards, 2006; Horton et al., 2007; Leorri et al., 2008; Woodroffe, 2009; Kemp et al., 2013). In the subtidal environments of the Mediterranean Sea, quantitative water depth estimates using WA-PLS reveal a close relationship between the observed and estimated water depths (Rossi and Horton, 2009; Milker et al., 2011). The developed transfer functions applied to Holocene successions have a precision of ±5 m within water depths ranging from 8 to 100 m for the northern Adriatic (Rossi and Horton, 2009) and ~±11 m within water depths ranging from 38 to 130 m for the western Mediterranean Sea (Milker et al., 2011).

To date, no transfer functions for sea-level reconstructions have yet been applied to older than Holocene (i.e., Pleistocene) records. In order to fill this gap, we here develop a foraminifera-based transfer function for water depth and apply it to three sediment records from the land-sea transition zone of the southeastern Mediterranean shelf, Haifa Bay, Israel. So far, these sediment records have been investigated for their chronostratigraphy and paleoenvironmental aspects (Avnaim-Katav et al., 2012, 2013; Tsatskin et al., 2015; Sandler and Avnaim-Katav, 2015). We aim to better constrain and refine the earlier qualitative paleo-water depth estimates that were based on foraminiferal distribution and their paleoecological parameters (species richness, dominance) integrated with the sedimentary facies characterization (Avnaim-Katav et al., 2013). The depositional environments of the study area represent a dynamic siliciclastic system, which is part of the Nile littoral cell, and prone to frequent sea-level fluctuations during the last ~1 Ma. The bathymetric reconstructions will be compared with the global sea-level history in order to extract local vertical components driven by tectonic movements.

## 2. Study area

### 2.1. Oceanographic settings

The coast of Israel along the southeastern Mediterranean shelf extends 180 km in a nearly straight NE–NNE line (Fig. 1). The Israeli shelf is 25–30 km wide in the south, narrowing northward to less than 10 km (Neev, 1965; Almagor and Hall, 1984). Most of the inner shelf sediments up to Haifa Bay are Nile-derived siliciclastics with a minor contribution from local sources (e.g., Zviely et al., 2007). Sand is extending from the foreshore to ~35 m water depth, the approximate position of the fair-weather wave base (Hyams-Kaphzan et al., 2008), and transported predominantly northward by wave-induced longshore currents (Emery and Neev, 1960; Golik, 1993, 1997). In the most distal part of the Nile littoral cell (Haifa Bay) and further north (Akhziv), carbonate-rich sediments replace the siliciclastic quartz sediments, forming rocky, sandy and silty–clayey substrates (Almagor et al., 2000, and references therein; Almogi-Labin et al., 2012). At depths between 40 m and the shelf edge, at ~100 to 120 m, sand is progressively diluted by silt and clay that comprise ~85% of the sediment at >60 water depths (Nir, 1984; Almagor et al., 2000; Zviely et al., 2007; Almogi-Labin et al., 2012). Pleistocene submerged calcareous sandstone (locally termed “kurkar”) ridges occur parallel to the shoreline along the continental shelf between 10 and ~100 m water depths, forming carbonate-rich hard substrates (Almagor et al., 2000; Sade et al., 2006). Carbonate coarse sand and gravel, mostly of biogenic marine origin, fill the gullies and channels between the ridges (Almagor et al., 2000, and references therein).

### 2.2. Tectonic setting

Haifa Bay, the largest inlet in the southeastern Mediterranean Sea is the marine extension of a larger graben (Qishon Graben) bordered by the Ahihud and Carmel normal faults to the north and to the south, respectively (Fig. 1). The Carmel fault is one of the main branches of the Dead Sea Transform (Schattner, 2006). Tectonic activity has led to subsidence of the Qishon Graben and uplift of the Carmel structure starting in the Miocene, with an estimated total vertical displacement of 1500 m.