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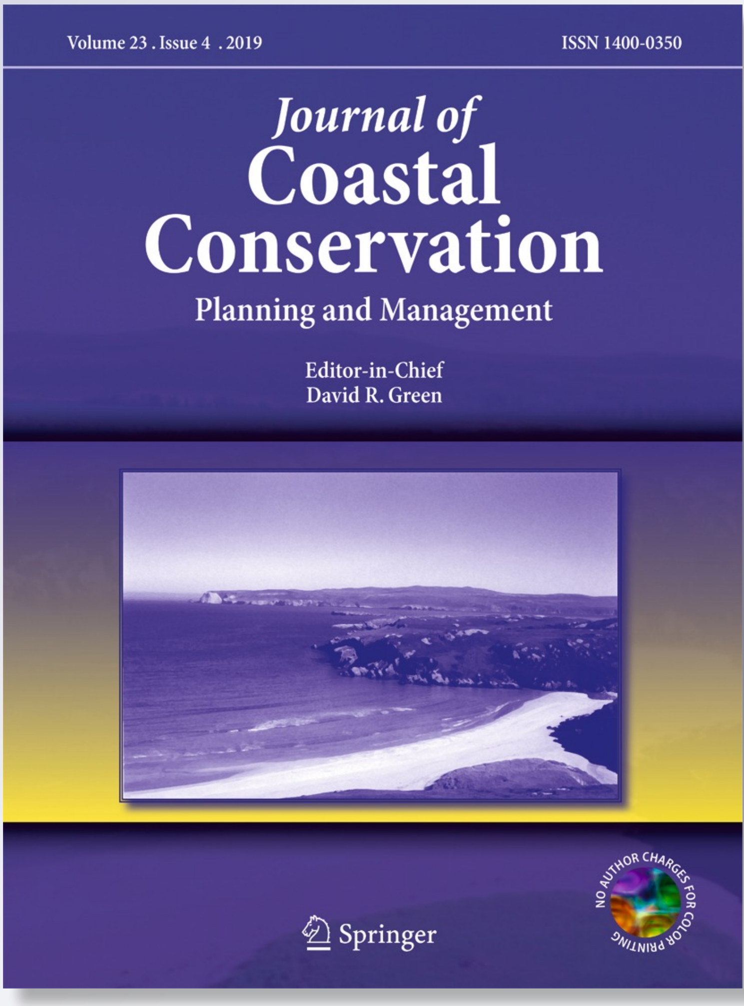

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Geo-archaeological markers reveal magnitude and rates of Israeli coastal cliff erosion and retreat

E. Galili [1] **· D. Zviely** [2]

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Abstract

Geo-archaeological studies along the Mediterranean coast of Israel and its seabed have revealed shipwrecks, anchorages, coastal installations and natural features that can act as markers to estimate the formation date and retreat rates of the coastal cliff of central Israel. The Sharon coastal ridge consists of alternating layers of kurkar (local term for aeolian carbonate-cemented, quartz sandstone) and poorly consolidated palaeosol deposits. The ridge was formed during the Late Pleistocene (about 70,000 to 10,000 yr. BP). At about 7,500 yr. BP, sea level reached the western edge of the present coastal ridge, currently located about 8 m below the present sea level, and a coastal cliff developed. Since then the cliff has continuously been eroded and retreated eastward by natural processes, as well as by anthropogenic impact. This article is an interdisciplinary geo-archaeological study of the extent and rates of retreat of the coastal cliff over the last 7,500 years. The findings suggest that overall the cliff has retreated about 730 m in this period, at an average rate of 9.7 cm/yr. However, the study shows that a considerably higher rate of cliff retreat occurred between about 7,500 and 3,900 yr. BP (about 650 m in about 3,600 years, at about 18 cm/yr). Sea level reached its present level at about 4,000 yr. BP (Middle Bronze Age) and has not changed significantly since. Since the Middle Bronze Age, the cliff has retreated about 80 m in 3,900 years (at about 2 cm/yr). Human activity and sea level rise during the last 100 years have significantly accelerated coastal erosion and cliff retreat.

Keywords Marine archaeology · Stone anchors · Coastal change · Coastal erosion · Sea level change

Introduction

The unique cultural heritage of Israel reflects important chapters and events in the history of humanity, starting with the Neolithic revolution, the first Near Eastern Empires, the foundation stones of the major monotheistic religions, and other major historical events (Galili et al. 2002; Galili and Rosen 2010).

Coastal erosion due to sea-level rise and human activity along the Mediterranean coast of Israel endangers the ancient coastal cities and sites of Ashkelon, Yavne-Yam, Jaffa, Apollonia, Caesarea, Dor, Atlit, Akko (Acre) and Achziv, as well as other assets of cultural, natural and economic value (Fig. 1a). Several laws and policy documents are used in Israel to control development and its impact on the coastal environment. Among them are: The Law of Antiquities, the law of Planning and Building, the Nature and Parks Law, the Law for the Protection of the Coastal Environment, and the Policy Document for the Coastal Waters of Israel (Galili and Arenson 2014, 2015). About five million of Israel's population of eight million are situated in the coastal plain, and the majority are concentrated along the Sharon coast which stretches about 50 km from Giv'at Olga (Hadera) in the north to Bat Yam (south of Tel Aviv) in the south. This coast is mostly characterised by sandy narrow (less than 30 m wide) beaches backed by a coastal cliff 10 to 50 m high, termed the Sharon cliff or escarpment (Perath and Almagor 2000). The coastal cliff is generally poorly consolidated and is retreating, mainly due to storm wave action, surface runoff and anthropogenic impact (Perath 1982; Perath and Almagor 2000; Gill and Almagor 2002). The morphology of the Sharon coastal cliff has a significant effect on access to the beaches and the marine environment. Its retreat has crucial consequences on

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Fig. 1 Location map: **a** The Mediterranean coast of Israel: locations of sea-level markers off the Carmel coast and location of Byblos-type stone anchors recovered off the Israeli coast; **b** Location of Byblos-type stone anchors recovered onshore in the Red Sea and eastern Mediterranean (EG)

national, public and private assets, including urban centres, cultural heritage, natural values and infrastructures. To ensure proper integral coastal zone management, sustainability and protection of valuable resources, it is important to understand the time span and rates of coastal cliff formation and erosion.

Previous studies used aerial photographs and geodetic measurement to measure the Sharon coastal cliff erosion during the last century, and estimated retreat rates of 20 to 30 cm/yr. on average (Perath 1982; Perath and Almagor 2000; Gill and Almagor 2002; Zviely and Klein 2004 and references therein). A recent study measured the cliff erosion characteristics associated with high-energy winter storms (10 to 20-year return period) at five locations along the Sharon coastal cliff. The study used LIDAR measurements of storm-induced landslide scars and remains of previous landslides seen in aerial photographs (Katz et al. 2007). Based on archaeological features studied by Z. Herzog in Tell Michal, Neev et al. (1987: 57, Fig. 17) suggested a rate of 20 cm/yr. for the Middle/Late Bronze Age (3,600 to 3,300 yr. BP). A more recent research project studied the destruction of archaeological features and estimated coastal cliff retreat over the last 3,650 years using archaeological structures (Barkai et al. 2017). The 2007 and 2017 studies proposed considerably lower retreat rates - about 10 cm/yr. and 2 to 3 cm/yr. respectively - than those proposed previously. These significant differences in retreat rates demand discussion. By applying interdisciplinary archaeological, geological and geomorphological studies the present article evaluates the magnitude and rates of post-glacial, Holocene, sea-level rise and the resulting coastal cliff retreat in Apollonia, some 10 km north of Tel Aviv.

Palaeo-morphological setting

Sea-level changes

Coastal and marine archaeological, geological and geomorphological features provide valuable information on sea-level changes and tectonics. By comparing a feature's elevation relative to the present mean sea level and defining its function and age, it may potentially be used as a sea-level marker (Galili et al. 2015b and references therein):

a) Global sea-level changes from LGM to the beginning of the Holocene

Based on global sea-level curves it can be assessed that from the Last Glacial Maximum (about 20 kyr BP) until the beginning of the Holocene (10 kyr ± 200 yr. BP), the sea level offshore Israel rose from about 120 ± 5 m to about 40 m below the present sea level (bsl) at a rate of about 8 mm/yr. (Fairbanks 1989; Bard et al. 1990, 1996; Flemming et al. 1978; Pirazzoli 1991; Rohling et al. 1998; Lambeck and Bard 2000; Lambeck et al. 2002, 2004; Lambeck and Purcell 2005). During that period the coastline shifted eastward from the current continental shelf edge to about 4 km offshore the Apollonia site.

b) Local sea-level changes during the first half of the Holocene

To draw the sea-level curve for the Israeli coast during the last 10,000 years, the current study relied on archaeological and geomorphological evidence from the Carmel coast (Fig. 2): A borehole located a few kilometres offshore Caesarea revealed organic terrestrial clay at a depth of 35 m bsl and dated to 8,900 yr. BP (uncalibrated) (Neev et al. 1987: 21). The peat (of terrestrial origin, Bakler pers. comm.) was embedded at the beginning of the Holocene in coastal swamps that were slightly elevated above the ancient sea level. Thus, sea level at that time was about 37 m bsl (Fig. 2: 1). The Pre-Pottery Neolithic C site of Atlit-Yam (Fig. 1a) is submerged some 200 m to 400 m offshore, at a depth of 8 m to 12 m bsl. Radiocarbon dates of wood remains from the site are dated to 9,180 to 8,550 yr. BP (Galili et al. 1993b, 2015a). The bottom of a stone-walled well (Galili and Nir 1993; Galili and Sharvit 1998) exposed in the site suggests that sea level was about16 m below sea level at that period. Five Pottery Neolithic sites are currently submerged at depths of 0.5 to 5.5 m bsl (Fig. 2: 2, 3) (Galili et al. 2005, 2015a, 2017). Wells excavated in the Kfar Samir site were dated by c14 to 7,000 to 7,790 yr. BP, indicating that sea level was about 8 to 9 m bsl at the time when they were constructed (Fig. 2: 4).

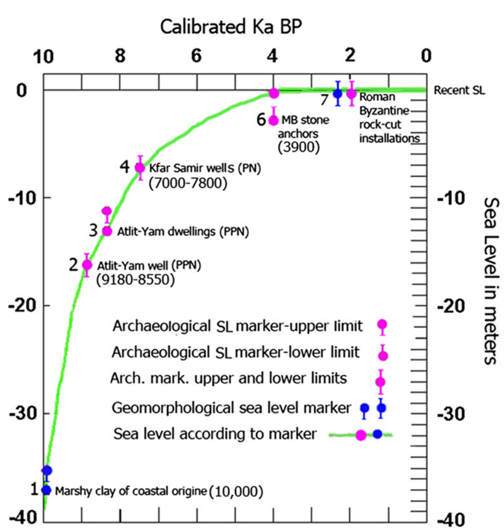


Fig. 2 Reconstruction of the sea-level changes along the Mediterranean coast of Israel based on archaeological and geological markers (EG)

c) Local sea-level changes during the second half of the Holocene

Geo-archaeological studies conducted on the eastern Mediterranean coast suggest that at 6,000 yr. BP, sea level was about 3 m bsl (Morhange et al. 2001, 2006; Lambeck et al. 2004; Marriner et al. 2005). Concentrations of Middle Bronze Age anchors originating from grounded ships (Fig. 2: 6) and Roman and Byzantine rock-cut coastal installations (Fig. 2: 7) suggest that sea level reached its present level about 4,000 yr. BP and has been relatively stable until recently (± 0.5 m) (Fig. 2: 6,7) (Galili et al. 1988, 2005; Sivan et al. 2001, 2004; Galili 2004). Abrasion platforms, wave notches and coastal installations found elsewhere along the Israeli coast, confirm the sea-level patterns derived from the Carmel coast, and suggest that the curve (Fig. 2) may represent the entire Israeli coast.

d) Rates of Holocene sea-level rise

The local Holocene sea-level curve (Fig. 2) shows two dominant rates of rise: from the beginning of the Holocene about 10,000 yr. BP to about 7,600 yr. BP, sea level rose from 37 m to 8 m bsl at an average rate of 12.1 mm/yr. (slightly higher than that observed for 20,000 to 10,000 yr. BP); and from about 7,500 to about 4,000 yr. BP, the sea level continued to rise up to the present sea level at an average rate of 2.3 mm/yr. In the last 4,000 years, no major changes (exceeding 1 m) is observed, and the rate of sea-level change has been less than 0.25 mm/yr. The curve, however, is an estimate, there are considerable gaps in the data, and small fluctuations in sea level may not be represented in the curve.

The continental shelf of Israel

The coastal plain of Israel and its continental shelf is characterized by longitudinal kurkar ridges running parallel to the present coastline, and shallow troughs filled with terrestrial sediments between them. The continental shelf is generally flat and narrows to the north (from about 20 km in southern Israel to about 15 km in the study area (Fig. 3). The shelf drops to a depth of 80 to 110 m at its edge (Almagor and Hall 1980, 1984; Ben-Avraham and Hall 1977; Neev et al. 1976). The continental shelf offshore Apollonia site is flat and covered with sand and silt that were deposited from the LGM until the beginning of the Holocene (about 20,000 to 10,000 yr. BP) and unconformably overlaid the palaeo-dry land. The rising sea abraded the Pleistocene kurkar ridges and created an erosional surface (Neev et al. 1976). Marine Nile-derived sediments and sediments of terrestrial origin were embedded during the inundation and overlay the erosional surface and the submerged kurkar ridges and the troughs between them. In

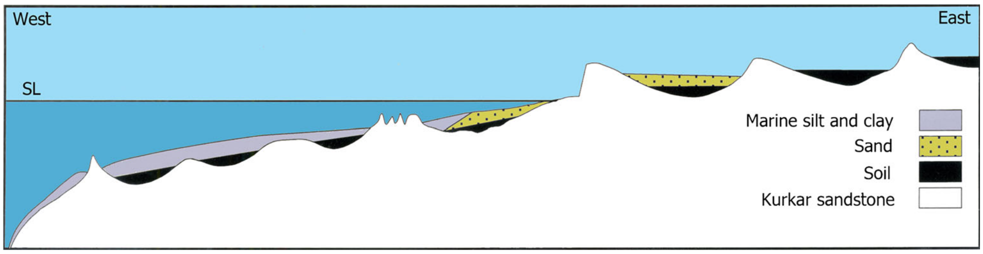


Fig. 3 Schematic cross-section across the coast and continental shelf of central Israel, showing the main morphological features, including the kurkar ridges, the troughs and terrestrial deposits between them, and the overlying sand and silt covering the coast and the seabed (after Almagor and Perath 2016: 3)

central Israel the thickness of these unconsolidated sediments may reach tens of metres, and in some places the peaks of the kurkar ridges protrude up to 10 m above the sea bottom (Fig. 3).

The Sharon coastal cliff

From a sedimentological perspective, the Sharon coastal cliff is poorly consolidated (Perath and Almagor 2000; Gill and Almagor 2002: 11; Katz and Mushkin 2013, and references therein) and consists of alternating layers of kurkar and palaeosols (Gvirtzman et al. 1984; Arkin and Michaeli 1985; Porat et al. 2004). Its stratigraphy (from bottom to top) comprises Ramat Gan kurkar, Nahsholim palaeosol (locally termed the '*Café-au-Lait*'), Dor kurkar, Netanya *Hamra* (palaeosol), Tel Aviv kurkar, and Hadera sands on top. Studies of prehistoric archaeology (Ronen 1977, 1980, 2011) and optically-stimulated luminescence (OSL) dating (Engelmann et al. 2001; Frenchen et al. 2001, 2002; Mauz et al. 2013) indicate that the kurkar and Nahsholim and Netanya palaeosols in the study area were formed between 70 kyr and 6,000 yr. BP. Thus, the coastal cliff in the Apollonia region is a product of the last postglacial sea level-rise and developed during the Holocene (Figs. 4, 5, and 6).

The Sharon cliff is part of a wide coastal kurkar ridge that stretches from Tel Aviv in the south to Hadera in the north (Fig. 1a).

Between the coastline and the cliff is a narrow (25 to 30 m wide) sandy beach, and at some places, beachrock deposits 0.5 to 1.5 m thick, composed of coarse sand, crushed and whole mollusk shells (mainly *Glycymeris insubrica*) are exposed at 0.5 m above present sea level (asl) to 1 m bsl (Fig. 7 marked with arrow). Potsherds recovered within the beachrock indicate that it is associated with the present sea level (the last 4,000 years). An OSL dating of a beachrock deposit some 1,000 m north of Apollonia yielded a date of about 2,000 yr. BP (Barbara Mauz pers. comm. 2009).

The Apollonia (Arsuf) site and its anchorage

The Arsuf site was first occupied during the Persian Period. During the Hellenistic Period its name was changed to Apollonia (Roll 1999). It was a large urban centre during the Roman and Byzantine periods and was engaged in international commerce and the industries of glass and purple dye. During the Early Muslim Period the city was fortified. The

Fig. 4 Storm waves reach the base of the cliff during the winter (EG)

Fig. 5 Fresh landslide on the Apollonia coastal cliff (DZ)

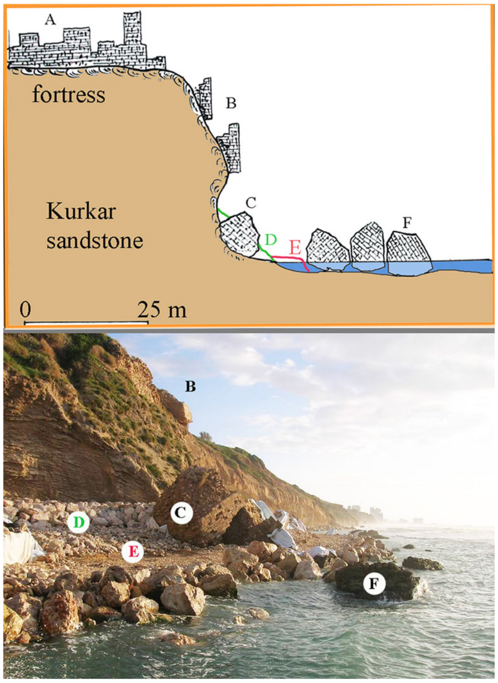


Fig. 6 The sea front of the Apollonia site: top - cross section, bottom - view from north to south: **a** Crusader castle, **b** endangered elements on the cliff, **c**, **f** fallen parts, **d** modern coastal defence, **e** Temporary road for constructing the coastal defence (EG)

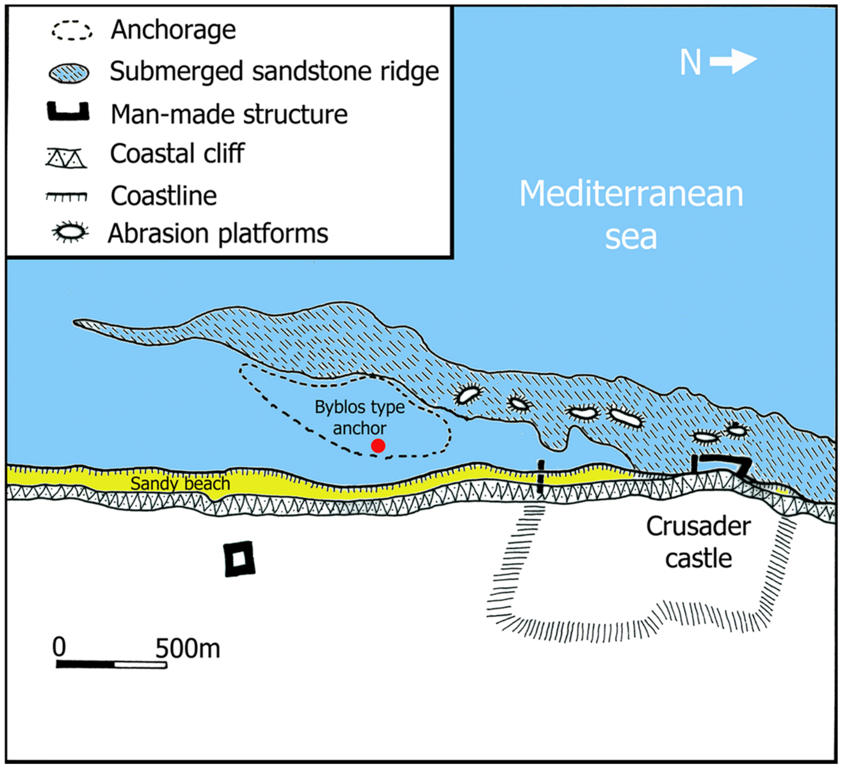
Crusaders fortified it by a castle with a wall and dry moat (Fig. 7). It was captured and destroyed by the Mamelukes during the thirteenth century and has remained in ruins ever since. The site was excavated during the twentieth century, and was designated a National Park. At the seafront of the fortress there is a partly flooded trapezoidal feature, creating a shallow, closed basin 50 m × 30 m (Fig. 8). It was suggested that it formed a harbour for small craft. Others believe that the walls, built in a shallow rocky, unprotected area, with no proper access to ships, are part of the Crusader fortifications (Galili et al. 1993a). South of the ruins are the submerged remains of a kurkar ridge connected to the shore at its northern edge.

Fig. 7 The crusader castle and the cliff north of Apollonia, the arrow marks the beachrock (IAA)

Fig. 8 The trapezoidal structure at the sea front of Apollonia (O. Tal, D. Mirkin)

Between this ridge and the shoreline there is a relatively protected area 3 m to 5 m deep that can provide some shelter for anchoring vessels (Fig. 9). The anchorage was surveyed by the Israel Association for Underwater Activity, the Israel Antiquities Authority and Tel Aviv University (Galili et al. 1993a; Grossmann 1997; Mirkin et al. 2016). About 50 anchors of several types were discovered in the anchorage. Among them was a Byblos-type triangular stone anchor with one perforation (Figs. 10 and 11), attributed to the Middle Bronze Age (see detailed discussion below) (E. Galili, Israel Antiquities Authority, unpublished diving report no. 32/90–17, dated 23.11.1990). The anchor was found at 3 m depth about 120 m offshore (Fig. 9). Additionally, fishing gear and artefacts associated with navigation were recovered. Finds in the southwestern part of the anchorage area included fragments of a broken bronze life-size statue of a male figure, a small bronze figurine of the goddess Minerva, bronze nails, and other artefacts made of bronze, stone and lead. Concentrations of small and medium-size ashlar stones and columns of various sizes made of granite, marble and kurkar, were also found. Many potsherds, including incised Byzantine amphorae, and pithoi and some fragments of 'basket handle' Persian amphorae and pottery vessels dating to the Persian, Hellenistic and Roman periods were collected. Broken glass ingots probably originating from the local glass industry were also found. The finds suggest that the natural anchorage was improved by dumping stones on the submerged kurkar ridge and closing gaps in it. Concentrations of ashlar stones, which were found in the anchorage area and on the ridge, may have been scattered when vessels were wrecked there. Judging by the archaeological finds, notably the stone anchors, it seems that the partly submerged kurkar ridge was used from the second century BC onward to provide anchorage for seagoing vessels during periods of calm sea (Galili et al. 1993a).

Fig. 9 The natural anchorage south of Apollonia castle (EG)



The Byblos-type stone anchor as cultural marker of the early middle bronze age

It was stated that stone anchors are the potsherds of marine archaeology (Frost 1973). Some of them can be used as reliable cultural markers and help dating. The Byblos-type stone anchor is a specific type of anchor that was used in the eastern Mediterranean and Red Sea during the Middle Bronze Age. It is an isosceles triangle-shaped limestone slab of identical

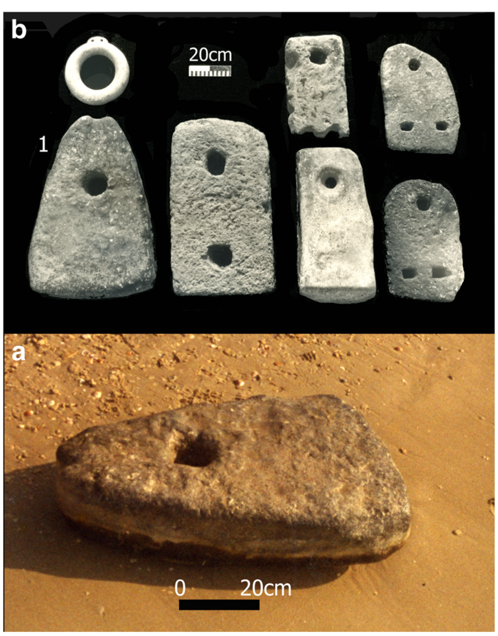


Fig. 10 a The Byblos-type anchor from Apollonia at time of retrieval, b 1 The Byblos-type anchor, and other stone anchors from Apollonia anchorage (after Galili et al. 1993b)

Fig. 11 A pair of Byblos-type stone anchors bearing inscriptions from Kfar Samir, Haifa south beach (Josef Galili)

thickness, often with oval top, having a perforation at its apex. Sometimes there is a shallow rope groove above the perforation. This type of stone anchors was recovered in sacred sites in Syria, Lebanon and on the Red Sea coast (Frost 1970).

Six clusters of Byblos-type stone anchors and several isolated ones were found off the Israeli coast between Haifa and Herzliya, most of them along the Carmel coast (Figs. 1a and 11) (Galili 1985a, b; Galili et al. 1994: 94–97, Fig. 1 Table 1). The distribution patterns of the Middle Bronze Age assemblages on the sea bottom, at water depths of 3 to 4 m bsl, indicate that they originated from ships that were driven ashore during storms and grounded (see paragraph 5.1 below). The Byblos-type anchors may thus provide an upper and lower possible sea-level marker at that period with accuracy range of ±0.5 m, suggesting that sea level reached the present level, or close to it (± 0.5 m) during the Middle Bronze Age (see above).

Dating the Byblos type stone anchors relies mainly on the finds from sacred sites on land, where anchors were votive offerings. An early example of a Byblos type anchor was recovered in Byblos, Lebanon, at the entrance to the sacred enclosure dated to 4,300 yr. BP (Frost 1970: 383, pl 1A, Fig. 1a). Another broken example was found within the sacred enclosure (Frost 1970, Fig. 1b). Two such anchors were found in a chapel attached to the obelisk temple in Byblos (Frost 1970, Fig. 3: b, c) dated to 3,900 yr. BP, and another was found in the temple of obelisks, but not in situ (Frost 1970, Fig. 2d). An almost identical anchor to the one found in the sacred enclosure in Byblos was recovered in the temple of Baal at Ugarit (Ras Shamra, Syria), and was dated to 3,900 yr. BP by the excavator (Frost 1970: 383, Fig. 1b). In Marsa Gawasis on the Red Sea coast, a complex of marine associated finds, including wooden parts of ships, ropes, pottery and stone anchors, was recovered. According to the excavators, the site served as an anchorage and a maritime base for Egyptian expeditions to the Land of Punt. The anchorage of Marsa Gawasis was dated to the 12th Dynasty (1991 to 1802 BCE, about 4,000 yr. to 3,800 yr. BP) (Bard and Fattovich 2007: 239–253). Twenty-six whole and broken stone anchors were recovered, many of them of the Byblos-type, and were dated to the Middle Kingdom (Zazzaro 2007: 153–163, Figs. 66, 67, 68). Judging by the anchors found in datable shrines in Ugarit, Byblos and Marsa Gawasis on the Red Sea coast, and the finds off the Israeli coast, these anchors may be dated to the early stage of the Middle Bronze Age, about 3,900 yr. BP.

Discussion

The coastal cliff erosion along the Sharon coast and its retreat rates are mainly dependent on sea level, wave regime, local rock consolidation, surface runoff and anthropogenic activities (sand quarrying, marine construction etc.). To reconstruct the destruction of Apollonia coastal cliff and assess its retreat rates during the Holocene, a curve of sea-level changes along the Israeli coast during the Holocene was used (Galili et al. 1988, 2005). This curve is based on archaeological (wells, submerged settlements, shipwrecks, anchorages, coastal installations) and geomorphological (wave notches, abrasion platforms) features.

Grounded shipwrecks as indicator for sea level and coastline location

Previous studies of site formation and post deposition processes associated with shipwrecks suggest that they can be used as approximate markers of sea level. Usually a shipwreck or an isolated anchor on shallow sea-bottom is evidence of a grounded ship and can provide the lowermost possible sea level at the time of grounding. However, shipwrecks may provide the lowermost and uppermost sea level at time of their grounding, with an estimated accuracy of 1 m (Galili 1985a: 144; Galili 1985b: Fig. 125; Galili et al. 1988, 2005). Observation on recent shipwrecks along the Israeli coast show that most wreckage events of small and medium sized vessels occurred close to the coastline, when the vessels lost propulsion and control during winter storms, drifted ashore and were grounded in shallow water (about 20 to 40 m offshore at a water depth of about 1 m). Clusters of anchors and heavy objects originating from shipwrecks dated to 3,900 to 1,500 yr. BP along the Israeli coast were found about 100 to 120 m offshore in 3 to 4 m water depth. Previous studies of dozens of grounded shipwrecks along the Israeli coast (reference see above) suggest that heavy stone anchors remained in situ after grounding, thus their location designate the final deposition of the ship's hull in shallow water close to the coast. After grounding on sandy beaches, post-deposition processes cause vertical subsidence of heavy artefacts (e.g. metals, anchors), while the light ones (wooden parts) drift away from the wreckage site. During and soon after grounding, the powerful waves and currents in the breaker zone start to erode the sandy seabed around heavy objects and they sink into the sand until they are buried. During the ages, extreme waves expose the objects again and again, and the settling in the sandy bottom continues until they finally reach bedrock or hard palaeosol. It should be noted that many archaeological objects found along the Israeli coast were originally overlain by a 1 to 2 m layer of sand before exposure (Galili et al. 1988, 2005).

Recent formation of the Apollonia coastal cliff

Studies relying on archaeological and geomorphological markers suggest that the coastal zone of Israel has been relatively tectonically stable during the last 3,000 years (Galili and Sharvit 1989; Sivan et al. 2001, 2004). Thus, the coastal cliff in the study area is a product of erosion, rather than vertical earth crust movements. During the twentieth century, natural coastal processes, global sea-level rise of about 15 cm (Church and White 2011) and anthropogenic impact, mainly the construction of the Marina Herzliya (built between 1990 and 1992) located about 2.8 to 3.5 km south of the Apollonia site (Klein and Zviely 2001), caused severe erosion of the Apollonia coastal cliff and its sandy seashore. This, in turn, has accelerated the retreat of the cliff and the destruction of ancient and modern structures on it. During winter storms wave runup reaches the foot of the cliffs, creating notches and occasional landslides (Figs. 4 and 5). These rock-slides (slumps) and surface runoff are the main erosional agents responsible for the cliff's collapse and its retreat eastward. The coastal cliff and the remains of structures of the ancient site of Apollonia on it fall onto the beach (Fig. 6). The unconsolidated sediments (fines and sand) of these slumps are washed away by waves and coastal currents, leaving behind solid kurkar plates and pebbles (1–3 cm thick and up to 20 cm long), as well as ancient building blocks originating from the Apollonia site.

Assumptions used for calculating the retreat values and rates of the coastal cliff of Apollonia

To reconstruct the coastline location in Apollonia during the last 8,000 years, assumptions and observations based on previous studies were used:

a) The general sea conditions (i.e. wave and tide regime) along the Israeli coast during the Holocene, were similar to those presently active (Zviely et al. 2006, 2007). This may indicate that the sea bottom profiles and the cliff erosion mechanisms were similar to those of today.
b) A sandy coast naturally tends to be in an equilibrium profile. According to the Bruun Rule (Bruun 1962), when sea-level rises, the shoreface will adjust itself to re-establish an equilibrium thus maintaining its profile. This means that the entire profile of the shoreface will shift landward by an amount dependent on the rise in sea level, resulting in erosion of the upper shoreface.
c) Based on aerial photographs, Zviely et al. (2000) and Klein and Zviely (2001) show that before the construction of the Herzliya Marina (1990–1992), the northern coast of Herzliya (i.e. the study area) was about 30 to 40 m wide.
d) Studies of Holocene sea-level changes along the Israeli coast (Galili et al. 1988, 2005; Sivan et al. 2001) suggested that at about 7,500 yr. BP the sea level reached the elevation of about 8 m bsl (Fig. 2). At that time the rising sea reached the western edge (now submerged) of the current coastal kurkar ridge and its erosion began, resulting in the formation of a retreating coastal escarpment.

Location of the western edge of the coastal ridge about 8,000 BP

The coastline location during the Holocene can be roughly assessed from the local sea-level curve and the current bathymetry of the rocky seabed. Therefore, the key issue for assessing the rate and time of the coastal cliff retreat in the study area is the location and water depth of the submerged western edge of the coastal kurkar ridge.

To find out the location of the submerged western edge of the coastal ridge, we compared it to offshore ridges in the region. The submerged kurkar ridges offshore central Israel, are partly covered by fine sediment, and full mapping of the sub-bottom layers is not available. However, hydrographic and geophysical surveys conducted on the continental shelf show that some patterns of the submerged offshore ridges are similar to those of the coastal kurkar ridges. Thus, they can be used to determine the general patterns of the coastal ridge prior to the coastal cliff. The coastal ridges, are usually continuous, while the submerged ridges are more fragmented and appear in isolated patches (Almagor 1979; Almagor and Hall 1984; Fugro 1998). The submerged offshore kurkar ridges that underwent coastal erosion in the course of the rapid post glacial sea-level rise are today at water depths of 32–42 m offshore in the study area. The remains of these ridges, which were subject to palaeo coastal erosion between 10,000 and 9,500 yr. BP, are often more than 2 km wide. Thus, it seems reasonable to assume that the width of the current coastal ridge was similar. Previous studies suggested that the western edge of the current coastal cliff is located some 200 m offshore (Neev et al. 1987: Fig. 2; Katz et al. 2016: 2, Fig. 11). Given the patterns of the offshore submerged ridges in the study area (particularly their width) and based on vertical aerial photography with high resolution bathymetry (Fig. 12), it is suggested that the western edge of the currently eroded and submerged coastal ridge is about 690 m offshore at water depth of about 8 m. The submerged remains of the coastal kurkar ridge can be clearly be seen under water, west of the present coastline. The local sea-level curve (Fig. 2) suggests that at about 7,500 BP the sea level was about 8 m bsl. Thus, it is deduced that the post-LGM rising sea reached the western edge of the current coastal kurkar ridge and its erosion started at about 7,500 BP. The local Ramat Gan and Dor kurkar units, comprising the main components of the Apollonia kurkar ridge, are poorly consolidated and contain a high percentage of fine sand (see above). Thus, it is most probable that a rapid retreat of the ridge occurred when the sea reached its western edge.

The location of the coastline and its cliff in the study area at about 3,900 yr. BP

The location of the coastline at about 3,900 yr. BP may be deduced from the find of Middle Bronze Age stone anchor in

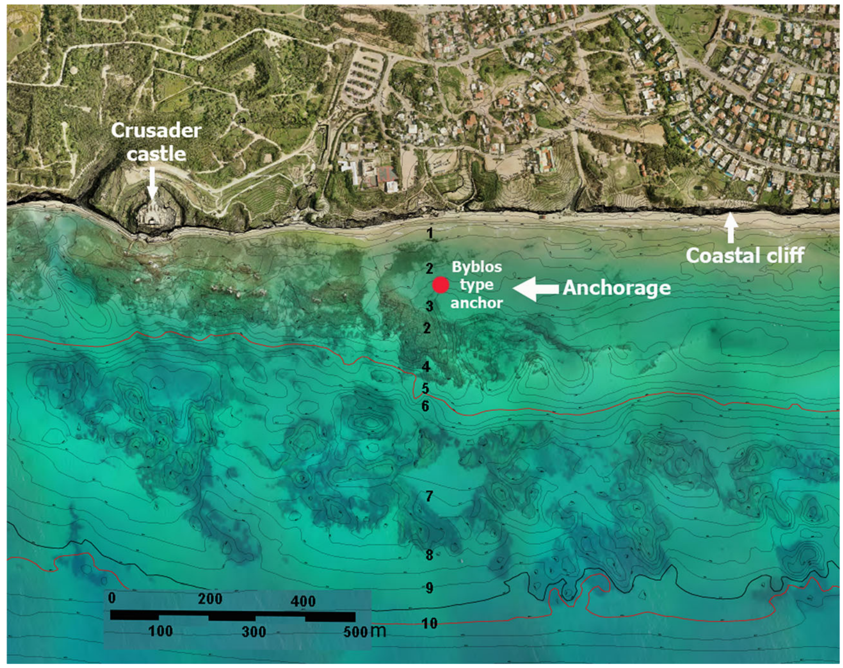


Fig. 12 Aerial photo of the Apollonia area, the anchorage, the location of the Byblos-type anchor and the submerged remains of the eroded kurkar ridge and its western edge

anchorage site. Observations on such anchors recovered elsewhere along the Israeli coast suggest that they were deposited on the seabed when ships were grounded and wrecked nearshore. Thus, it is assumed that at about 3,900 yr. BP, when the wrecking occurred, the water depth where the anchor was recovered was about 1 m bsl. This enables us to reconstruct the location of the associated coastline and the coastal cliff during the Middle Bronze Age. Judging by the patterns of the recent coastal zone in the study area and given the above reconstruction of the wrecking that deposited the anchor on the seabed, it may be assumed: a) the coastline at the time of the wrecking was about 30 m east of the anchor; b) the foot of the coastal cliff was about 65 m east of the anchor; and c) the top of the cliff was about 85 m east of the anchor (Fig. 13).

The coastal cliff retreat rates in the study area

The average rate of cliff retreat in the last 7,500 years can be calculated by dividing the length of the eroded portion of the ridge by the time that passed since the rising sea started to erode the ridge. The current study observations indicate that the submerged western edges of the ridge are situated about 690 m offshore the present coastline, some 730 m west of the current coastal cliff (Fig. 13). These distances indicate that the average retreat rate of the cliff during the last 7,500 years was about 9.7 cm/yr. This rate is similar to the present coastal cliff retreat rate (of maximum 10 cm/year) evaluated by Katz et al. (2016). The considerations associated with the find of the Byblos-type anchor offshore Apollonia, may, however, help

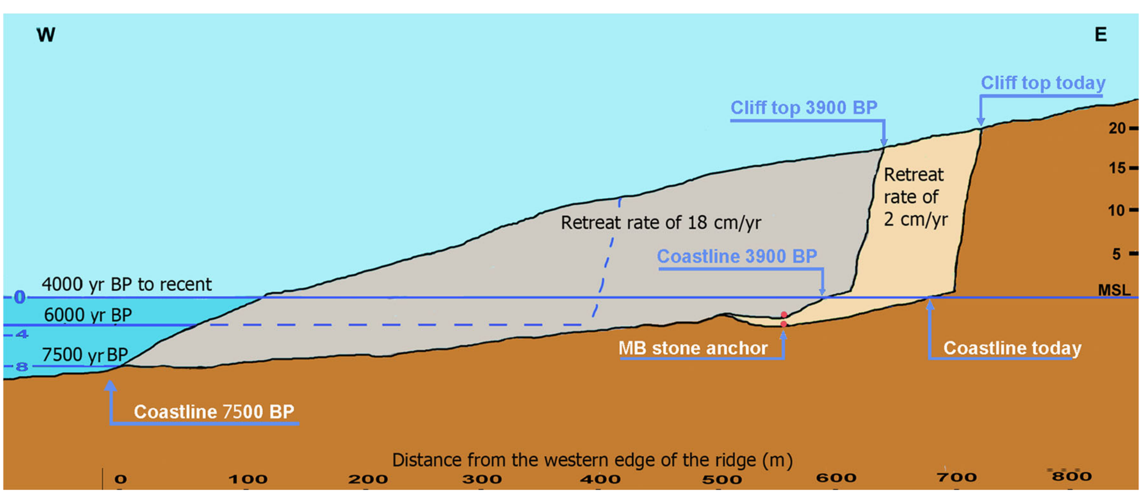


Fig. 13 Cross-section in the study area, showing the location of the western fringes of the submerged ridge, the location of the Byblos-type anchor and the retreat of the coastal cliff (EG)

to assess the average retreat rate values between 7,500 and 3,900 yr. BP, and in the last 3,900 years. The Byblos-type anchor was found in the anchorage site located about 120 m offshore the present coastline, some 570 m east of the submerged western edge of the kurkar ridge. The anchor find suggests that around 3,900 yr. BP a ship was wrecked or lost an anchor at the location where the anchor was found. The depth at this location during the Middle Bronze Age must have been shallower (1.5 to 2 m), as more sand was available at the site at that time. It is unlikely that a ship lost an anchor while anchoring at such a shallow depth, so close to the coast. Thus, the anchor most probably originated from a ship that was grounded and wrecked at that site. The coastline and cliff locations during the Middle Bronze Age can thus be estimated by the location of this anchor. The anchor was found some 570 m east of the submerged edge of the kurkar ridge. Thus, the coastline at the time of the wrecking was some 30 m east of the anchor (about 560 m east of the western edge of the ridge), and the cliff top was some 55 m east of the Middle Bronze Age coastline (about 650 m east of the submerged western edge of the ridge). The cliff top at that time must have been about 80 m west of the present cliff top (Fig. 13). The estimated location of the coastline and the associated cliff during the Middle Bronze Age enables to calculate the cliff retreat rates in two time-spans: from 7,500 to 3,900 yr. BP, before the wrecking of the Middle Bronze Age ship, the cliff retreated some 650 m westward at an average rate of about 18 cm/yr., while in the last 3,900 years the cliff retreated 80 m at a considerably lower rate of about 2 cm/yr.

Relation to other recent studies determining the Sharon coastal cliff retreat rate

Recent studies on the coastal cliff in central Israel, evaluated its retreat rate based on landslide measurements (Katz et al. 2016) and the destruction of archaeological features (Barkai et al. 2017). They suggested an average rate of 10 cm/yr. and 2 to 3 cm/yr. respectively in the last 2,500 years. These rates are slower than the current study evaluated rates for the time span from 7,500 to 3,900 yr. BP. It seems reasonable to assume that when sea level reached the coastal ridge, rapid erosion occurred, as attested by our study. Later, after sea level stabilized at 4,000 yr. BP, the retreat rates were considerably reduced.

Conclusions

Given that the sea reached its present elevation at about 4,000 yr. BP and the tectonic stability of the Israeli coast (Galili and Sharvit 1998), the current findings suggest that the coastal cliff in Apollonia retreated some 730 m during the last 7,500 years, at an average rate of about 9.7 cm/yr. The most significant initial and main phase of the coastal cliff retreat took place between 7,500 and 3,900 yr. BP (about 650 m in 3,600 years at a rate of about 18 cm/yr). Since the Middle Bronze Age (about the last 3,900 years) the cliff retreated only 80 m at a rate of about 2 cm/yr. Human activity and sea-level rise in the last 100 years have significantly accelerated coastal erosion, cliff retreat and the formation of new cliffs. The differences between the rates of coastal cliff retreat proposed by Zviely and Klein (2004) and those of Katz and Mushkin (2013) and Barkai et al. (2017) may stem from the fact that these studies covered only the last 3,650 years and are associated with relatively stable sea level conditions. The high values of cliff retreat observed by Zviely and Klein (20 to 30 mm/yr) are probably associated with the observed sea-level rise of about 17 cm during the last 100 years (1.7 mm/yr) (Church and White 2011) an, in places, the influence of marine installations built during recent decades.

The current study uses archaeological and geological features to identify long duration processes, during sea level-rise, before the sea reached its present level. It evaluates the patterns, time scale and erosion rates of the Apollonia coastal cliffs and retreat in the last 7,500 years. Future sea-level rise of 1 m during the twenty-first century, as predicted by scholars (De Conto and Pollard 2016), (at a rate of 10 mm/yr) is slightly lower than that observed for the beginning of the Holocene (12.1 mm/yr., see above) and considerably higher than that which occurred at the end of the Neolithic Period (2.3 mm/yr., see above). Such a sea-level rise, if it occurs, will probably cause cliff retreat of about 15 cm/yr. or more (similar to that observed between 7,500 and 3,900 yr. BP).

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References`

Almagor G (1979) Relict sandstone of Pleistocene age on the continental shelf of northern Sinai and Israel. Isr J Earth Sci 28:70–76

Almagor G, Hall JK (1980) Morphology of the continental margin off northern Israel and southern Lebanon. Isr J Earth Sci 29(4):245–252

Almagor G, Hall JK (1984) Morphology and bathymetry of the Mediterranean continental margin of Israel. Geol Surv Isr Bull 77, Jerusalem, 31 pp

Almagor G, Perath I (2016) The Mediterranean coast of Israel. Geol Surv Isr, Rep GSI/28/2016, Jerusalem, 469 pp (in Hebrew)

Arkin Y, Michaeli L (1985) Short- and long-term erosional processes affecting the stability of Mediterranean coastal cliffs of Israel. Eng Geol 21:153–174

Bard KA, Fattovich R, (2007) Chapter 9, Synthesis. In: Bard KA, Fattovich R, (eds) Harbor of the pharaohs to the land of Punt: archaeological investigations at Mersa/Wadi Gawasis, Egypt, 2001–2005, pp 239-253

Bard E, Hamelin B, Fairbanks RG, Zindler A (1990) Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. Nature 345:405–409

Bard E, Hamelin B, Arnold M, Montaggioni L, Cabioch G, Faure G, Rougerie F (1996) Deglacial Sea-level record from Tahiti corals and the timing of global melt water discharge. Nature 382:241–244

Barkai O, Katz O, Mushkin A, Goodman-Tchernov BN (2017) Erosion of archaeological sites along the Israeli Mediterranean coastline and its application for assessing long-term retreat rates of the sea cliff. Geoarchaeology 2017:1–14

Ben-Avraham Z, Hall JK (1977) Geophysical survey of Mount Carmel and its extension into the eastern Mediterranean. J Geophys Res 82(5):793–802

Bruun P (1962) Sea-level rise as a cause of shore erosion. J Waterw Harbours Div 88(1–3):117–130

Church J, White N (2011) Sea-level rise from the late 19th to the early 21st century. Surv Geophys 32:585–602

De Conto RM, Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. Nature 531:591–597

Engelmann A, Neber A, Frenchen M, Boenigk W, Ronen A (2001) Luminescence chronology of Upper Pleistocene and Holocene aeolianites from Netanya South Sharon coastal plain, Israel. Quat Sci Rev 20:799–804

Fairbanks RG (1989) A 17,000-year Glacio-Eustatic Sea-level record: influence of glacial melting rates on the younger Dryas event and deep-ocean circulation. Nature 342:637–642

Flemming NA, Raban A, Goetschel C (1978) Tectonic and eustatic changes on the Mediterranean coast of Israel in the last 9,000 years. In: Gamble JC, Yorke RA (eds), progress in underwater science, Vol. 3 (new series) of the report of the underwater association, proceedings of the 11th symposium at the British museum (natural history), 33–93

Frenchen M, Dermann B, Boenigk W, Ronen A (2001) Luminescence chronology of aeolianites from the section at Givat Olga coastal plain of Israel. Quat Sci Rev 20:805–809

Frenchen M, Neber A, Dermann B, Tsatskin A, Boenigk W, Ronen A (2002) Chronostratigraphy of aeolianites from the Sharon coastal plain of Israel. Quat Int 89:31–44

Frost H (1970) Bronze-age stone anchors from the eastern Mediterranean. Dating and identification. Mariners Mirror 56:381–385

Frost H (1973) Anchors, the potsherds of marine archaeology: on the recording of pierced stones from the Mediterranean. In: Blackman D, (ed), Marine Archaeology, London, 397–409

Fugro Engineers BV (1998) Geotechnical survey, offshore sand resources, Israel. Report N-3607/01F: 4 pans appendices 1, 4, 5.

Galili E (1985a) A group of stone anchors from Newe-yam. Int J Naut Archaeol 14.2:143–153

Galili E (1985b) Clay exposures and archaeological finds on the sea bottom, between Haifa and Atlit. Unpublished MA Thesis, Dept. of Maritime Civilizations, University of Haifa, Israel (in Hebrew)

Galili E (2004) PhD Dissertation, Faculty of Humanities, Department of Archaeology and Near- Eastern cultures, Tel Aviv University, Submerged settlements of the ninth-seventh mill. BP off the Carmel coast (in Hebrew)

Galili E, Arenson S (2014) Ancient coastal and underwater sites on the Mediterranean coast of Israel: risk assessment, protection, salvage excavations and conservation of endangered maritime cultural resources: Part I - Riparia 0:151–177 http://hdl.handle.net/10498/17040

Galili E, Arenson S (2015) Ancient coastal and underwater sites on the Mediterranean coast of Israel: risk assessment, protection, salvage excavations and conservation of endangered maritime cultural resources: Part II - Riparia 1:55–96 http://hdl.handle.net/10498/17335

Galili E, Nir Y (1993) The submerged pre-pottery Neolithic water well of Atlit-yam, northern Israel, and its palaeoenvironmental implications. The Holocene 3:265–270

Galili E, Rosen B (2010) Preserving the maritime cultural heritage of the Mediterranean, a cradle of cultures, religions and civilizations - the holy land perspective. J Coast Conserv 14:303–315

Galili E, Sharvit J (1989) Ancient coastal installations and the tectonic stability of the Israeli coast in historical times. In: Stewart IS, Vita-Finzi C (eds) Coastal Tectonics, Geological Society, vol 146. Special Publications, London, pp 147–163

Galili E, Weinstein-Evron M, Ronen A (1988) Holocene Sea-level changes based on submerged archaeological sites off the northern Carmel coast in Israel. Quat Res 29:36–42

Galili E, Dahari U, Sharvit J (1993a) Underwater surveys and rescue excavations along the Israeli coast. Int J Naut Archaeol 22:61–77

Galili E, Weinstein-Evron M, Hershkovitz I, Gopher A, Kislev M, Lernau O, Kolska Horowitz L, Lernau H (1993b) Atlit-yam: a prehistoric site on the sea floor off the Israeli coast. J Field Archaeol 20:133–156

Galili E, Sharvit J, Artzy M (1994) Reconsidering Byblian and Egyptian stone anchors using numeral methods: new finds from the Israeli coast. Int J Naut Archaeol 23.2:93–107

Galili E, Raban A, Sharvit J (2002) Forty years of marine archaeology in Israel. In: Tzalas H (ed) Tropis VII, Proceedings of 7th international symposium on ship construction in antiquity. Pylos 1999, 927–961

Galili E, Zviely D, Weinstein-Evron M (2005) Holocene Sea-level changes and landscape evolution on the northern Carmel coast (Israel). Mediterranée 1.2–2005:1–8

Galili E, Kolska-Horwitz L, Eshed V, Rosen B, Hershkovitz I, (2015a) Submerged prehistoric settlements off the Mediterranean coast of Israel, Skyllis, 13 Jahrgang 2013 Heft 2 pp 181–204

Galili E, Sevketoglu M, Salamon A, Zviely D, Mienis HK, Rosen B, Moshkovitz S (2015b) Late Quaternary morphology, beach deposits, sea-level changes and uplift along the coast of Cyprus and its possible implications on the early colonists. In: Harff J, Bailey G, Lüth F (eds) Geology and Archaeology: submerged landscapes of the continental shelf, vol 411. Geological Society, London, Special Publications, pp 179–218

Galili E, Kolska-Horwitz L, Rosen B, Eshed V (2017), Submerged Pottery Neolithic settlements off the Mediterranean Coast of Israel., In Bailey G, Harff J, Sakellariou D (eds) Under the Sea: Archaeology and Palaeolandscapes of the Continental Shelf, Cham, Switzerland, pp 105–130

Gill D, Almagor G (2002) The geological infrastructure of the coastal escarpment, factors affecting its retreat and methods of its preservation. Geol Surv Isr Rep GSI/21/2002, Jerusalem (in Hebrew)

Grossmann E (1997) Maritima Apollonia (Arsuf) and its harbours. Mariner's Mirror 83:80–83

Gvirtzman G, Shachnai E, Bakler N, Ilani S (1984) Stratigraphy of the Kurkar group (quaternary) of the coastal plain of Israel. Geol Surv Isr Curr Res 1983-4:70–82

Katz O, Mushkin A (2013) Characteristics of sea-cliff erosion induced by a strong winter storm in the eastern Mediterranean. Quat Res 80:20–31

Katz O, Hecht H, Petranker G, Almog E (2007) Retreat rate of the Israeli coastal cliff and its estimated location at 2100. Geol Surv Isr Rep GSI/21/07, Jerusalem, 34 pp (In Hebrew, abstract in English)

Katz O, Mushkin A, Crouvi O, Shemesh R (2016) The background and modern retreat rates of Israel's coastal cliffs and a new method for effective monitoring of changes in rates. Geol Surv Isr Rep GSI/26/2016, Jerusalem

Klein M, Zviely D (2001) The environmental impact of marina development on adjacent beaches: a case study of the Herzliya marina Israel. Appl Geogr 21:145–156

Lambeck K, Bard E (2000) Sea-level change along the French Mediterranean coast for the past 30,000 years. Earth Planet Sc Lett 175:203–222

Lambeck K, Purcell A (2005) Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. Quat Sci Rev 24:1969–1988

Lambeck K, Yokoyama Y, Purcell T (2002) Into and out of the last glacial maximum: sea-level change during oxygen isotope stages 3 and 2. Quat Sci Rev 21:343–360

Lambeck K, Antonioli F, Purcell A, Silenzi S (2004) Sea-level change along the Italian coast for the past 10,000 yr. Quat Sci Rev 23:1567–1598

Marriner N, Morhange C, Boudagher-Fadel M, Bourcier M, Carbonel P (2005) Geoarchaeology of Tyre's ancient northern harbour, Phoenicia. J Archaeologi Sci 32:1302–1132

Mauz B, Hijma MP, Amorosi A, Porat N, Galili E, Bloemendal J (2013) Aeolian beach ridges and their significance for climate and sea level: concept and insight from the Levant coast (East Mediterranean). Earth-Sci Rev 121:31–54

Mirkin D, Cvikel D, Tal O (2016) Arsur castle maritime installation (1241-1265 CE). Palest Explor Q 148.4:294–312

Morhange C, Laborel J, Hesnard A (2001) Changes of relative sea-level during the past 5,000 years in the ancient harbor of Marseilles, southern France. Palaeogeogr Palaeocl 166:319–329

Morhange C, Pirazzoli PA, Marriner N, Montaggioni LF, Nammour T (2006) Late Holocene relative sea-level changes in Lebanon, eastern Mediterranean. Mar Geol 230:99–114

Neev D, Almagor G, Arad A, Ginsburg A, Hall JK (1976) The geology of the southeastern Mediterranean Sea. Geol Surv Isr Bull 68, Jerusalem, 51 pp

Neev D, Bakler N, Emery KO (1987) Mediterranean coast of Israel and Sinai. Taylor & Francis, New York, 130 pp

Perath I (1982) Rate of retreat of the Sharon escarpment - a new method of measurements. In: Erlich A, Katz B, (eds), Geol Surv Isr, Curr Res 1982, Jerusalem, 62–65

Perath I, Almagor G (2000) The Sharon escarpment (Mediterranean coast, Israel): stability, dynamics, risks and environmental management. J Coast Res 16:207–224

Pirazzoli PA (1991) World atlas of Holocene sea-level changes. Elsevier Oceanography Series 58, Elsevier, Amsterdam, 299 pp

Porat N, Wintle AG, Rite M (2004) Mode and timing of kurkar and hamra formation, central coastal plain, Israel. Isr J Earth Sci 53:13–25

Rohling EJ, Fenton M, Jorissen FJ, Bertrand P, Ganssen G, Caulet JP (1998) Magnitude of sea-level lowstands of the past 500,000 years. Nature 394:162–165

Roll I (1999) Introduction: history of the site, its research and excavations. In: Roll I, Tal O, (eds) (1999) Apollonia-Arsuf, final report of the excavations, Volume 1: The Persian and the Hellenistic Periods, Emery and Clair Yass Publications in Archaeology: 1–62

Ronen A (1977) Mousterian sites in the red loam in the coastal plain of Mount Carmel. In: Arensburg B, Bar-Yosef O, (eds), Eretz Israel - archaeological, historical, and geographical studies, Israel Exploration Society Publication 13 (Moshe Stekelis Volume):183–190

Ronen A (1980) The origin of the reddish pelecypod beds along the Mediterranean coast of Israel. Paléorient 6:163–170

Ronen A (2011) An AMS of the "Café-au-Lait" paleosol (Nahsholim horizon) in the Sharon coastal plain, Israel, (poster). Radiocarbon Archaeology, 6th international Symposium, 10–15.4.2011, Paphos, Cyprus

Sivan D, Widowinski 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. Palaeogeogr Palaeocl 167:101–117

Sivan D, Lambeck K, Toueg R, Raban A, Porath Y, Shirnam B (2004) Ancient coastal wells of Caesarea Maritima, Israel, an indicator for relative sea level changes during the last 2000 years. Earth Planet Sc Lett 222(1):315–330

Zazzaro C (2007) Stone anchors and pierced stones. In: Bard KA, Fattovich R (eds) Harbor of the pharaohs to the land of punt: archaeological investigations at Mersa/Wadi Gawasis, Egypt. Università degli Studi di Napoli "l'Orientale", Naples, pp 2001–2005

Zviely D, Klein M (2004) Coastal cliff retreat rates at Beit-Yannay, Israel, in the 20th century. Earth Surf Process Landf 29:175–184

Zviely D, Klein M, Rosen DS (2000) The impact of the Herzliya marina, Israel, on the width of its neighbouring beaches. 27th international conference on coastal engineering (ICCE), book of abstracts, Vol. 2, poster no. 62, Sydney (16-21.7.2000)

Zviely D, Sivan D, Ecker A, Bakler N, Rohrlich V, Galili E, Boaretto E, Klein M, Kit E (2006) The Holocene evolution of Haifa Bay area, Israel, and its influence on the ancient human settlements. The Holocene 16(6):849–861

Zviely D, Kit E, Klein M (2007) Longshore sand transport estimates along the Mediterranean coast of Israel in the Holocene. Mar Geol 238:61–73