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Holocene-era submerged notches along the southern Levantine coastline: Punctuated sea level rise?

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ABSTRACT

The study presented here reports on erosional notches, pits, and potholes observed at present sea level and submerged at a series of sites along the southern Levantine coastline. For such submerged features to be formed and preserved, there must be a period of relative sea level stagnation, followed by drowning. This process can occur in response to sea level change, tectonic or isostatic offsets. The specific coastline hosting these features is not considered tectonically or isostatically affected, and therefore, for much of the Mediterranean, is viewed as a eustatic sea level reference point. While similar features have been observed elsewhere in the eastern Mediterranean, confining their ages has been difficult due to the much older ages of the host rocks, in many cases encompassing multiple glacial cycles. Here, for the first time they are located in relatively young host rock (<65,000 years) confining their production age to the most recent glacial cycle. These features might suggest that a step-like, more punctuated process of sea-level rise occurred along this coastline, providing a window into what might be expected in the future as warming trends continue and the sea level responds.

1. Introduction

Marine notches have long been considered a useful sea-level proxy and important contributor to reconstructing the timing, rate, and magnitude of sea-level change. While broad trends in sea-level change are generally well-established (Fairbanks, 1989; Fleming et al., 1998; Peltier, 2002; Waelbroeck et al., 2002; Siddal et al., 2003; Lambeck et al., 2014) the more refined, localized sea level curves and sub-millennial resolution varies regionally in detail and scope (e.g. Morhange and Pirazzoli, 2005; Stocchi and Spada, 2007), and observations globally of variations in the rates and trends have motivated further investigation and ample debate (Cronin, 2012). Here, submerged erosional notches located along the southern Levantine coastline are reported for the first time and their origin, timing, and ramifications with respect to local and global sea level curves are considered. The current work presents quantified observations of the depth and morphology of notches and erosional pits along the Israeli coastline present at current sea level and submerged. Then, their observed setting was compared to tectonic and sea-level records in an effort to better understand the nature of the post LGM sea level rise along the Israeli coastline and its global implication.

Glacial and interglacial cycles are marked by the movement of water between ice caps and marine basins. These shifts produce sea level fluctuations in which sea level is lower during the height of an ice-age, and higher during the peak of an interglacial. Sea level change has the power of altering the coastal landscape dramatically. An approximate 120 m eustatic sea level rise during the past ~20,000 years has been established based on multiple isotopic studies from coral records, ice cores and extensive dating and modeling (Shackleton, 1987; Fleming et al., 1998; Siddall et al., 2003; Peltier and Fairbanks, 2006; Lambeck et al., 2014).

In the modern system, sea level changes are recorded instrumentally using means such as tidal gauge records and satellite imagery (see Church and White, 2006). Local relative sea level (RSL) reconstructions have been performed using a wide range of sea level indicators such as micropaleontology (e.g. salt marsh foraminifera and thecamoebians, Gehrels, 1999; Scott and Medioli, 1978; Scott et al., 2001), abrasion and tidal notches (e.g., Nixon et al., 2009; Evelpidou et al., 2012a, 2012b, 2012c; Marriner et al., 2014), beachrocks (Vousdoukas et al., 2007; Desruelles et al., 2009; Mauz et al., 2015), benches and shore platforms (Rovere

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et al., 2011; Vacchi et al., 2012; Mastronuzzi et al., 2014), archeological features (Sivan et al., 2001; Marriner and Morhange, 2007; Goodman et al., 2009), or marsh and peat deposits (Cronin et al., 2007; Engelhart and Horton, 2012; Engelhart et al., 2015). The smaller the range of vertical error and the more accurately the marker can be dated, the better the sea level marker. Some markers provide a bracketed 'supratidal' or 'sub tidal' indicator which confine the minimum and maximum values in meter resolution, while some proxies, such as saltmarsh microfossils, can give an accuracy of less than a decimeter (Scott and Medioli, 1978).

All sea-level markers face the challenge of differentiating between eustatic sea-level change and localized relative sea level that is a result of tectonic offsets and glacio-hydro-isostatic effects (Walcott, 1972; Chappell, 1974; Lambeck and Chappell, 2001). Therefore, efforts are made through comparisons of models to field observations and established sea level curves from relatively passive, seismically quiet regions as a means for comparison.

1.1. *Archaeological sea-level markers*

Coastal archaeological features with distinctive elevations and depths relative to sea level (e.g. mooring holds, piers, wells) and well-constrained ages are useful for sea level reconstruction. For example, an intact submerged, dated, mosaic floor discovered offshore at five meters water depth could provide a supratidal indicator because it most likely was not installed underwater. A well-developed harbor floor (fine muds, organic enrichment, artifacts (Reinhardt et al., 1994; Marriner and Morhange, 2007) would provide a constraint on the minimum water depth (such as >~1 relative to harbor floor). Features with more limited vertical constraints, such as harbor mole features, bollards, fishponds (piscina), or shipshed ramps, provide even more refined relative sea-level data and have been used successfully in many regions worldwide such as northwest Pacific coastlines (Fedje and Rosenhans, 2000), Pacific Islands (Dickinson, 2001), Atlantic Ocean and Gulf of Mexico (Bailey and Flemming, 2008). The Mediterranean is especially rich in well-dated coastal archaeological features and therefore has perhaps the most extensive sea level datasets and studies incorporating archeological observations (e.g. Flemming et al., 1969; Flemming and Webb, 1986; Galili and Sharvit, 1998; Sivan et al., 2004; Evelpidou et al., 2012b).

1.2. *Geomorphological sea-level markers*

Independent from archaeological features, natural sea level markers can be present such as marine notches, erosional pits and potholes. Marine notches are horizontal incisions (centimeters to meters size range) formed from biochemical and/or mechanical erosion (Alexander, 1932), which is later referred to as sea corrosion (Pirazzoli, 1986). Tidal notches are a specific form of marine notch that occur as a result of biological, chemical, and physical erosion at the tidal zone and have been used as sea-level markers because they are formed during sea-level stands that are long enough to permit their production (Pirazzoli, 1986; Kershaw and Guo, 2001; Benac et al., 2004; Wziatek et al., 2011, Evelpidou et al., 2012a; Trenhaile, 2014, 2015). The notch itself is semi-indicative of the tidal regime as its shape and dimensions have some association to the maximum and minimum tidal positions with the central dimensions typically correspond to mean sea level (Evelpidou et al., 2012a, Fig. 1), though recent observations also indicate that the notch can also exceed those limits (Antonioli et al., 2015; also see response by; Evelpidou and Pirazzoli, 2015). Rapid changes, either due to sea level change or vertical displacement, can lead to the preservation of these features, making them useful earthquake or sea level indicators (Neumann, 1966; Pirazzoli, 1986; Neumann and Hearty, 1996; Rust and Kershaw, 2000; Kershaw and Guo, 2001; Benac et al., 2004; Nixon et al., 2009; Vacchi et al., 2013).

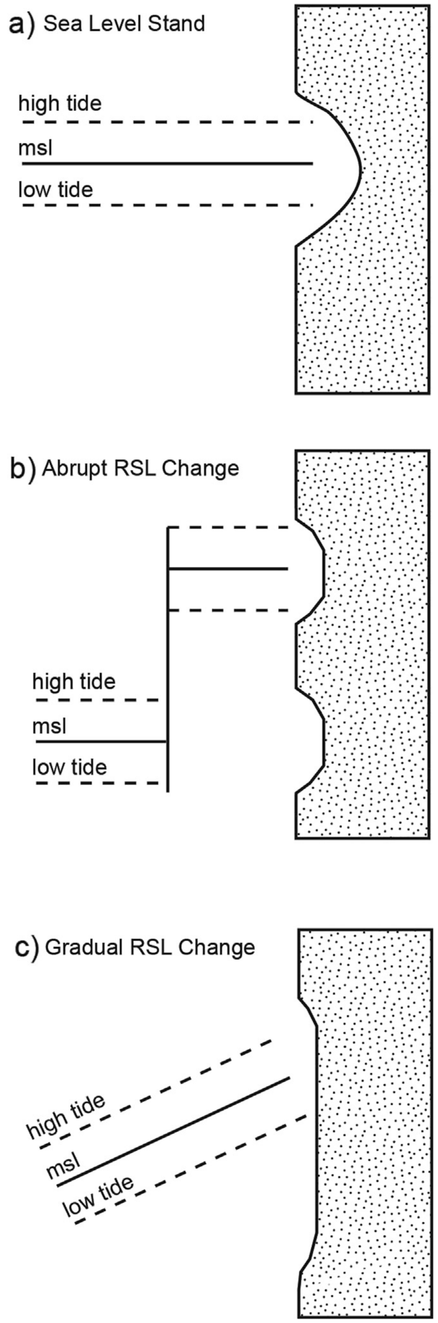

Fig. 1. Schematic diagram of an idealized notch development during stable sea level, rapid sea level change, and gradual change (adapted from Evelpidou et al., 2012a). Recent work by Antonioli et al., 2015 shows that the relationship between tidal range and notch size varies.

Certain circumstances, such as gradual sea level change or secondary erosion during later sea-level stands, can lead to their erasure or alteration, and specific sets of conditions can prevent their production (absence of biological assemblages or too hard/too soft substrates) (Evelpidou et al., 2011, 2012b; Pirazzoli and Evelpidou, 2013, see discussion in Antonioli et al., 2015). Therefore, when present, they are a clear indication of a period of continuous sea-level stand.

Once formed, preservation of notches depends on a range of variables, most importantly the fabric of the notch and

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disassociation of the feature from active erosion or sea corrosion, such as that which is present in the surf and beach zone or aerially. Once a notch is submerged below regular tidal and wave influence it can result in stagnation of its production and preservation of its morphology if the conditions are favorable. Above sea-level, features will contend with environmental effects and therefore their preservation is strongly associated with their fabric and protection from erosional processes. Generally, the more rapid the disassociation and the less exposure to eroding elements, the better the chances of preservation, aerially or sub-aerially.

Erosional pits and potholes are also features that form at sea-level along coastal platforms. They develop when abrasional materials (e.g. sand, shells, stones) concentrate in depressions on the surface and, over time, grind downward, ultimately producing a cylindrical or kettle-shaped feature (Alexander, 1932). They vary greatly in size, and a wide size range can be copresent at a single site due to variations in their time of initiation. A fairly conservative ratio between opening diameter and depth of the pothole of 1:4 is generally observed (Miller and Mason, 1994, Alexander, 1932). Like notches, they can become inactive if they are disassociated from sea level depths, and preserved if they are not exposed to further erosion. It is common to find the grinding materials encrusted and preserved in the base of inactive features.

1.3. Regional setting

The study sites (Dor, Caesarea, Olga, and Michmoret) are located in a 25 km long strip of the Mediterranean coast of Israel (Fig. 2). In general the coastal area is characterized by segmented north-south trending eolianite sandstone ridges (locally referred to as ‘kurkar’), consists of alternating late Pleistocene–Holocene (Engelmann et al., 2001; Frechen et al., 2001, 2004; Porat et al., 2004; Sivan and Porat, 2004) quartz dominated, carbonate cemented eolianites and clay bearing paleosols with common unconformable contacts (Ya'alon 1967; Gvirtzman et al., 1984). The lower-most Ramat Gan Eolianite (~65 ka) is overlain by the Nahasholim paleosol. Dor Eolianite (~50 ka) overlies Nahasholim and is overlain by the Natanya paleosol, which is capped by the uppermost Tel Aviv Eolianite (~5 ka). Within the study sites the Dor member is dominant and the beaches and the nearshore soft sediments vary from sandy to sandy-shelly. The sands, which originated in the Nile River, are characterized by quartz with some feldspar (Goldsmith and Golik, 1980; Zviely et al., 2007).

For the past 2.0 ka BP (and perhaps up to 10 ka BP), the southeastern Levantine coastline serves as a near direct reflection of the eustatic sea level component with little to no vertical offset or glacio-hydro-isostatic component (Lambeck et al., 2001; Sivan et al., 2001, 2004; Lambeck and Purcell, 2005; Pirazzoli, 2005; Anzidei et al., 2011). Anzidei et al. (2011) demonstrates that the rate of sea level rise is fivefold lower along this coast than the more northern Turkish coastlines, where active tectonics is present. Another source of support for the argument for relative stability in the past two millennium is the presence of sea-level associated archaeological features with constrained ages within the past 2000 years, as well as the presence of an 11 km long 2.0 ka BP year old aquaduct that lacks indications of earthquake damage or movement unrelated to construction on unconsolidated sediments (Sivan et al., 2001; Dey et al., 2014). An even longer stretch of tectonic stability (~125,000 ka BP) has been proposed due to the similarity in elevations of MIS 5 beach deposits across the coastal plain (Galili et al., 2007). Work addressing decadal variations has formed possible evidence for variations of lower sea level during the crusader period (0.9–0.7 ka BP) in the <1 m range (Toker et al., 2012).

1.4. Rates of sea level change

Within the overall timeframe of the most recent post Last Glacial Maximum sea-level rise, periods of more rapid rise have been identified and are referred to as meltwater pulses (Fairbanks et al., 1992). These ‘punctuated’, step-like features have been confirmed in multiple studies (Blanchon and Shaw, 1995; Liu and Milliman, 2004) but there remains some debate and discussion regarding the number of such phases and overall rate, age, timing and magnitude globally (see Bird et al., 2010). Blanchon and Shaw (1995) presented varying sea-level rise rates for post LGM of greater than 4.5 cm/yr during rapid periods, and less than 1.5 cm/year during the more gradual periods based on the nature of transitions between different coral assemblages. In their study, three ‘catastrophic rise events’ began at 14.2 ka (~13.5 m), 11.6 ka (~7.5 m), and 7.8 ka (~6.5 m), and agree with other records of faster sea level rise and/or climate change (Fairbanks, 1989). The circa 7.8 ka event has also been identified in coastal marshes along the eastern coast of North America (Bratton et al., 2003; Tornquist et al., 2004; Cronin et al., 2007), showing a fairly well established rapid increase at about 8.2–7.4 ka. These periods of rapid sea level rise have been linked to climatically driven increases in glacial melt and water input in to the oceans. Lambeck et al.'s (2014) comprehensive summary and inversion of far field (outside of glacial margins) sea level data places the most significant period of deglaciation between 16.5 and 8.2 ka BP with average rates of sea-level rise approximately 12 m ka^{-1}, with a small phase of punctuated sea level rise between 14.5 and 14 ka BP in which rates were above or equal to 40 mm y^{-1} (about fourfold rate relative to typical rate). Around 8.2 ka BP they observe a general sea level rise rate decrease that continues until 2.5 ka BP and thereafter remained at about the same level without major or long lasting changes until a century ago when sea level shows a rising trend. According to Lambeck et al., 2014, there is no evidence for the 8.2–7.4 ka BP rapid sea level increase in the Mediterranean that is seen elsewhere.

2. Methods

Four research sites were selected along a 25 km portion of the modern Israeli coastline (Fig. 2). Each site was surveyed by walking the coastline and diving in the shallow (all sites shallower than 7msl), to determine the presence or absence of notches and erosional pits at modern sea level and underwater. Where present, the erosional notches and pits were then measured with a fiberglass measuring tape, photographed, host fabric and condition described (lithology, anthropogenic/natural surface, rough/pocked surface, etc.), and the presence or absence of external biological encrustation recorded. Erosional notches were measured for maximum horizontal length, incision-depth and height of notch (see Antonioli et al., 2015). Erosional pits were measured for upper surface depth (rim), maximum pit depth, circumference, and presence of inner incision notches (or lack of). Measurements were made both with a digital UWATEC pressure bottom timer depth gauge (see Vacchi et al., 2012a, 2012b for discussion of underwater methods generally), fiberglass tape measure and then depths were adjusted to national tidal measurement changes taken less than 25 k from the study sites at the Hadera Power Station (isramar.ocean.org.il). Location was determined using a combination of rectification from aerial LIDAR images printed on waterproof paper for plotting positioning while in the water, and field rendering with a handheld GPS.

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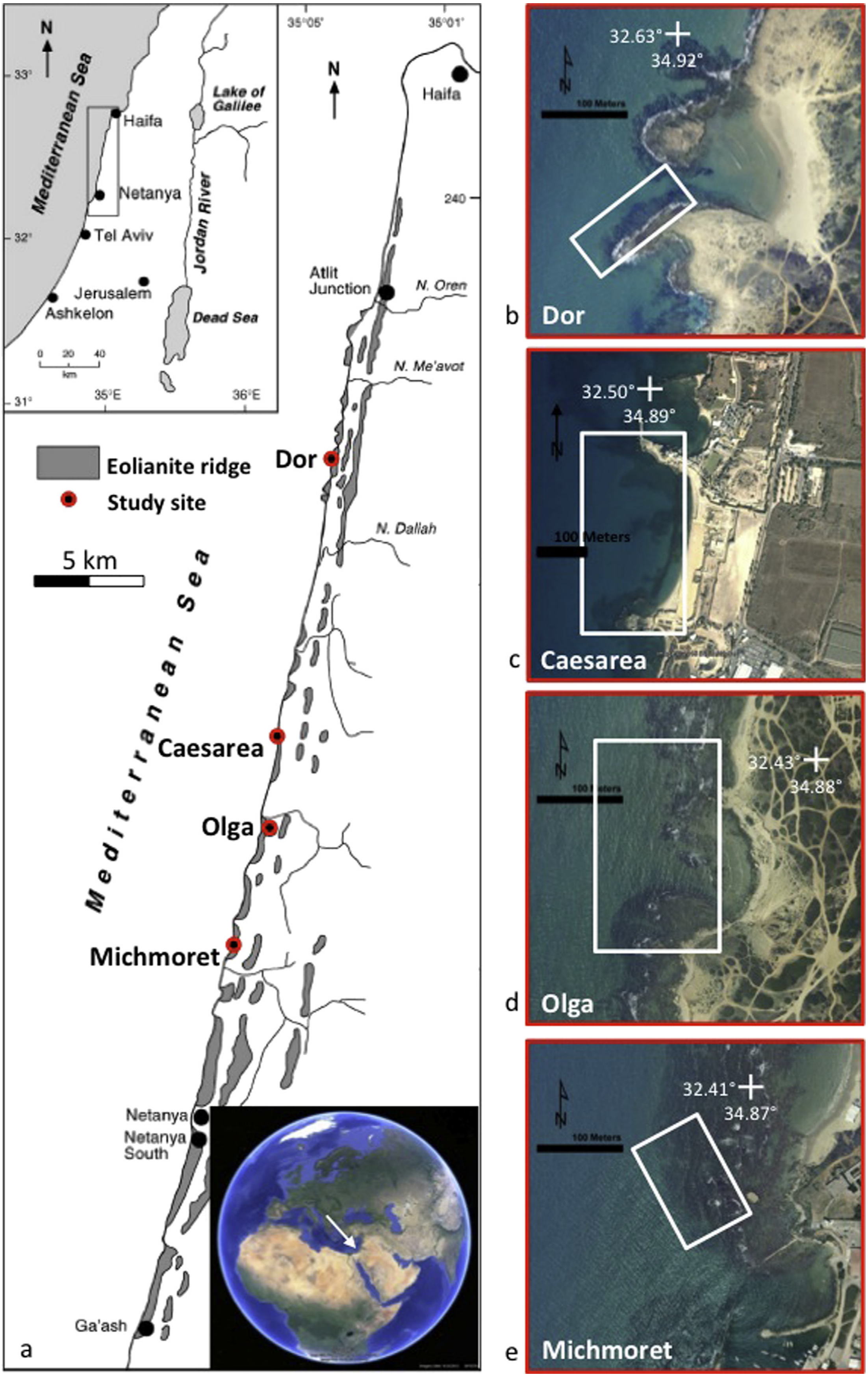

Fig. 2. Regional map and site locations.

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3. Results

3.1. Michmoret

Michmoret is located north of the mouth of Alexander River (Fig. 2) and is generally characterized by sandy beaches with eolianite capes of ~10 msl elevation. The study site was located north of a protruding eolianite cape composed of relatively porous, easily disaggregated type of kurkar formation.

At present sea level beachrock exists, but no significant erosional pits or notches were observed. Small boulders and rubble are present in the shallow water from periodic storm-driven cliff failures (Katz and Mushkin, 2013). Offshore, the eolianite slopes gradually and is covered in biological encrustation. Inactive submerged erosional pits are present with rims beginning at about −1.5 msl to −2.0 msl, which present a possible incision at −2.5 msl, and have a maximum depth of about 3.0 m from the rim. They are poorly preserved with very uneven edges and varying inconsistent shapes. Notches are visible at −2.5 msl, with sand sometimes obscuring a portion of the notch (Fig. 3).

3.2. Olga study site

The Olga site consists of a narrow beach (~25 m max) abutting cliffs of varying heights (~30 m height) made of eolianite. A paleoriver channel enters the beach through a canyon feature flanked at the shoreline by steep cliffs facing a rubble field that enters the water (Fig. 2).

At modern sea-level multiple notches were observed (Fig. 3). They were generally cylindrically shaped (i.e. maximum width measurement not at base of notch) with roughly similar width and height that also included an abrasional bottom surface. Two areas south and north of the paleochannel were measured and photographed. A notch present north of the paleochannel extended for 15 m horizontally. The height of the notch from the abrasional surface was 65 cm, and depth from the opening 60 cm. A second

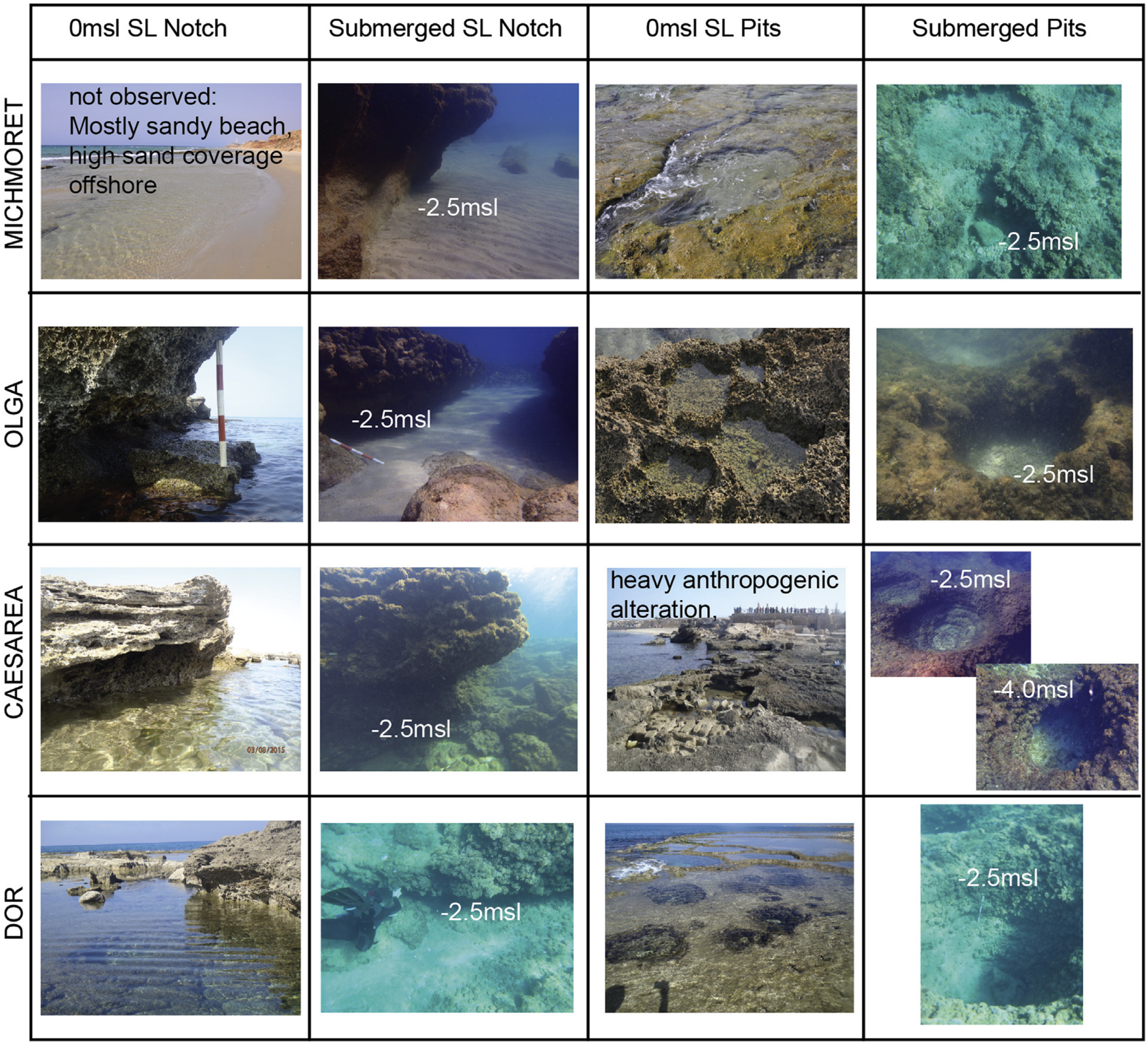

Fig. 3. Representative photos of features at each of the sites. Photographs of some of the current erosional pits and potholes are not available due to sea conditions and technical issues that prevented clear photo documentation. With the exception of Caesarea, the submerged erosional pits vary from upper rim depths typically from 1.0 to 2.0 m depth, regularly hosting an incision within the side of the pit at ~2.5 msl. The Caesarea pits from 4 m depth and below did not have distinctive incisions.

notch was recorded from the northern abrasional platform, located south of the paleochannel, along a northwestern facing portion. That notch was 6 m long and had height and depth dimensions of 85 cm. These positions were selected amongst many notches observed (>12) because they had the longest continuously preserved channels. Erosional pits (maximum observed around 1.5 m diameter) were present with rims just above and below present sea level. The shape of the pits was sometimes round, but also sub angular. Very small, recently developing pits were identified along beach rock surfaces within the tidal and surf zone (Fig. 3).

The submerged sea level features were analogous to observations at modern sea level. The features include notches, some intact, and in some cases collapsed, as well as erosional pits. The submerged notches were observed with maximum lateral extents of 3–4 m and they were identified on the basis of horizontality and notch shape. The shape of the notches is less cylindrical overall relative to the modern notches, with the maximum depth closer to the upper ceiling. Discontinuity occurred regularly, and observations of collapsed notch roofs were common, and coincided with some of these interruptions. An additional notch located on the western face of the southern erosional table was measured with a maximum width of 1.7 m located at −2.4 msl. The height of the notch was measured at minimum 1.5 m, but was limited by a sandy bottom (−2.5 m), which obscured the full measurement. The notch is eroded into the eolianite, which is submerged to 1 msl, the uppermost part of the notch was well preserved and began at about 1msl below current sea level. Erosional pits were present both at southern and northern portions of the site. They begin at the submerged surface of the abrasional platform (~1–1.5 msl) and were measured to 2.5 msl. The bases of the pits were encrusted with biological organisms, and sometimes-contained concreted pebbles, shell, sand or rubble at the base with an abrasional notch or incision at the base.

3.3. *Caesarea study site*

Caesarea's current coastal morphology is characterized by a series of eolianite ridges running near parallel above, at and below the modern coastline with local elevation highs of +12 msl that are co-present with cape-like features suggestive of previous aeolinite cliffs, and in many places there were clear signs of quarrying activities. The study site is immediately within the constructed area of the ancient Roman city of Caesarea, established in around 12 BC by Herod (2.0 ka BP) (Fig. 2).

Observations were made for a 500 m stretch from the ancient harbor cape to the next projection in the eolianite to the south, which was the location of Herod's palace complex (Figs. 2 and 3). In the northern cape, a series of modern sea level and submerged notches were recorded. At modern sea level, a notch carved into a Byzantine-era constructed ashlar wall (approximately 1.4 ka BP) was measured for 14 m length, which was interrupted by modern construction on one side and a collapse on the other. The width and height of the notch were measured at 80 cm × 80 cm. Notches were present at about −2.6 msl along the southern side of the northern promontory (Fig. 2). On the western side of the northern promontory a sequence resembling submerged coastal cliff morphology (i.e. overhanging cantilever geometry), was recorded. Here, the modern abrasional platform, which included active erosional pits serve as the upper surface of the overhanging part of the submerged cliff. Below the overhanging part at about −1.5 msl the cliff was cut inwards, sloping up to a maximum incision-width (depth into the cliff) of about 2.9 m and then dropping nearly vertically to a submerged encrusted platform at −4 msl. The height of the submerged cliff below the overhanging part is also 2.9 m. In some areas where overhanging cantilever geometry was not observed, elongated rock-blocks were present on the seafloor parallel to the cliff. These are interpreted as collapsed overhanging blocks, a process that is described along the modern subaerial coastal cliff (Katz and

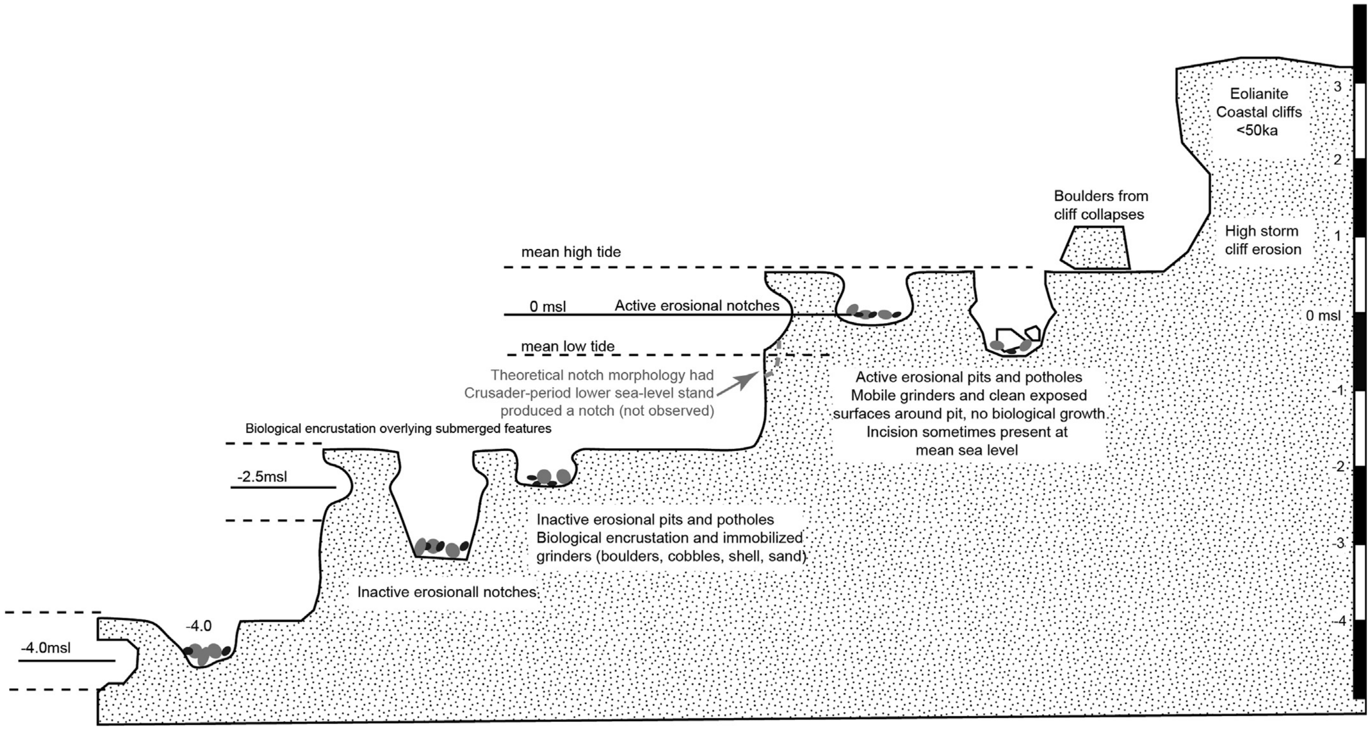

Fig. 4. Schematic cross-section of appearance of the current and submerged coastline. While in the figure only erosional notches above mean sea level are illustrated, they can also be present in platforms slightly below mean sea level.

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Mushkin, 2013). Erosional pits are present along the lower submerged abrasional platform at −4 msl and in other areas rising to higher depths of about 2.0 msl. The pits were of varying widths and maximum depths (maximum diameter size approximately 2 m), with a variety of morphologies. Cemented pebbles, large stones, and shell were observed within all the pits. Oblong and peanut-shaped erosional pits were also seen that appear to be the result of two independently initiated pits that at some point connected.

Between the two eolianite capes, the submerged abrasional platform meets a sandy area at about -6msl, and no erosional pits were observed beyond about 5 msl. The sandy patch gives way again to exposed, encrusted eolianite. The southern cape was used as the foundation for part of the original construction campaign (~2.0 ka). Herod's palace structure includes a pool cut directly into the eolianite. Within the pool there are notches at sea-level (30 × 30 cm incision depth and height, see Fig. 5). In a channel entering the pools, which is more exposed directly to the sea and waves, the notches are 60 cm depth and 60 cm height. Below sea level notches of similar size and character to the northern cape are present, with associated erosional pits and failed cantilever blocks.

3.4. *Dor study site*

The Dor coastline consists of eolianite ridges that run generally coast-parallel. The highest elevation to the south is about 10 msl which then slopes to 6 msl in the north. The high elevations are associated with cape-like features and protrude into the sea creating small bay features between them. The Dor sample area is offshore from the southern cape (Fig. 2).

Dor's occupational history is long, with remnants of architectural features beginning in the Middle Bronze Age (4.0 ka BP) and continuing to the present. The eolianite at present sea-level is heavily altered anthropogenically for a variety of purposes such as quarrying, fishponds ('piscina'), and assorted industrial aims. Erosional notches were observed in these features.

Erosional pits along the present sea-level abrasional platform were common and sometimes very large relative to the other sites in the study. Offshore, submerged notches were covered with biological encrustation, were typically in the range of 30–40 cm in height and 40–50 cm maximum incision depth at approximately −2.5 msl, Erosional pits were present and very well developed, sometimes reaching over 3 m in diameter (Fig. 3). Within these large submerged erosional pits, a narrow lateral incision is often observed at about −2.5 msl. The seaward extent of the submerged abrasion platform was covered by sand, so any lower features were not observable.

4. Discussion

Along the Mediterranean coast of Israel, erosional notches, potholes, and pits as well as overhanging coastal cliffs are situated at the current sea level and are genetically related to it (Katz and Mushkin, 2013). In the current work, similar morphologies were found submerged, mostly at a water depth of 2.5 m at four sites along 25 km of the coastline, suggesting the existence of a submerged paleo-coastline (Fig. 4). At Caesarea erosional pit features were identified both at −2.5 and at −4.0 msl. The submerged coastline could only have developed while positioned at sea level for an extended period of time. Then, it was disconnected from sea level at rates exceeding its typical morphologies production rates until sea level rose above the features, ultimately leading to their current position submerged below sea level.

The pits identified at −4.0 msl in Caesarea may or not be an isolated occurrence. First, at all other sites (Olga, Michmoret and Dor), the sand coverage was obscuring what might be present below −3.0 msl, and therefore with this study alone it is not possible to compare properly between the sites for these lower depths because the features may or may not be present at those sites. There are two explanations that we might present for those that were recorded. One explanation is that the 4.0 msl notch features are contemporaneous with the −2.5 msl features, but are merely the surviving remnants of the lower portion of the pits, the remainder of which underwent severe erosion. This might explain the poor condition of the pits and unusual morphologies. Or,

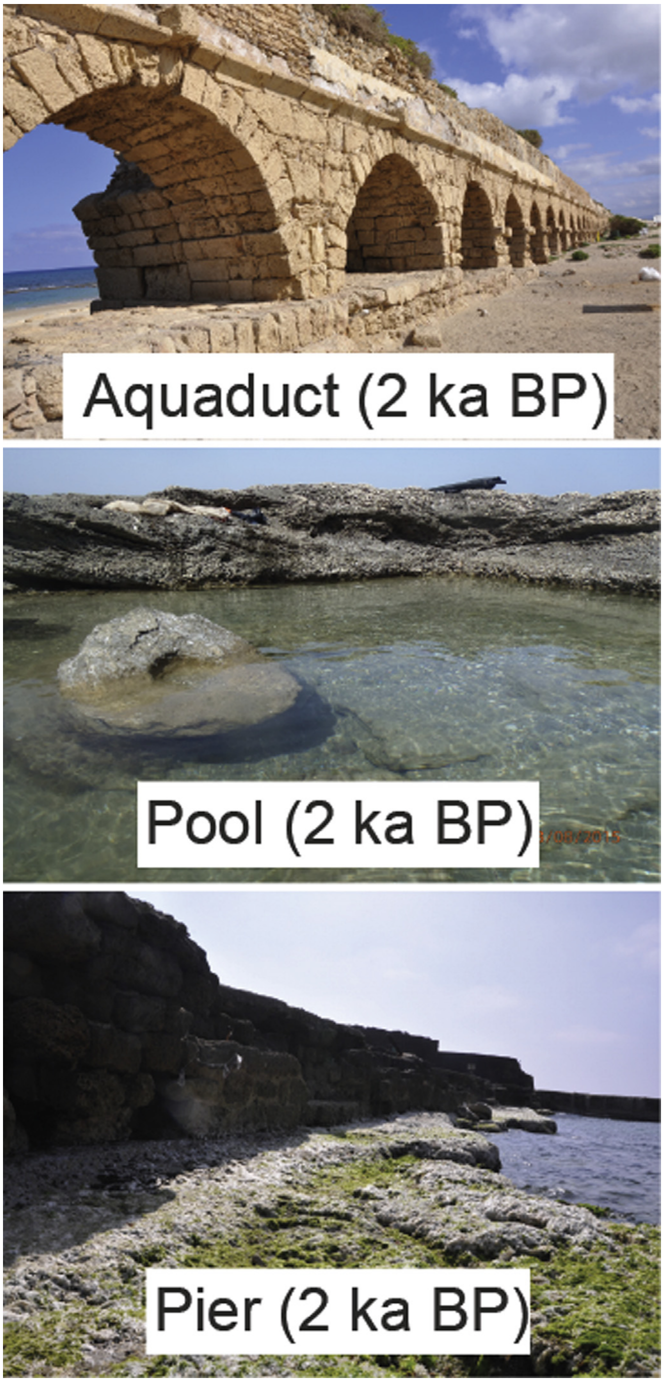

Fig. 5. Roman features (2000 year old) along coastline that support stable tectonics and sea level for past 2.0 ka. Top photo: Aquaduct built primarily on bedrock that does not present signs of fractures, offsets, or other earthquake damage or movement. Middle photo: Pool within Herod's Palace situated at correct position relative to sea level. Bottom photo: Concrete Roman pier (at low tide) intact and located at sea level.

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alternatively, the −4.0 msl pits are a different period of sea level stagnation altogether. Future efforts to determine the age of the pits directly will help resolve this.

A few geological scenarios can explain this general setting of sea level related features, now submerged at a few meters depth: tectonic-related subsidence and/or eustatic sea level change. Tectonic activity along this coastline, and the Galilee coast to the north has been suggested by some (Bakler et al., 1985; Sivan and Galili, 1999; Sivan et al., 1999) and challenged by others (Sneh, 2000; Goodman-Tchernov and Austin, 2015). At Caesarea, many features from about 2.0 ka BP that have distinctive associations to sea level and were built on, or into the aeolianite bedrock can be found today in the same position, supporting the suggestion that in that time period no major tectonic offsets occurred, even though earthquakes are documented (Amiran et al., 1994; Fig. 5: Stable SL, tectonics), Finally, in the studied eolianite sequence no evidence for tectonic deformation (e.g. joints, faults or crushed rocks) are observed and thus we rule out the tectonic scenario as a possible mechanism explaining our field observations. Isostatic uplift of the coast, if present whatsoever, is viewed upon as a relatively minor component for this specific coastline, with a maximum contribution of about a meter per 10,000 years (Lambeck and Purcell, 2005). Thus the eustatic sea level rise scenario remains as the best explanation of our field observations.

In the following, we will discuss the submerged coastline nature, its estimated age according to known curves of post LGM sea level rise and the implications of the new findings on the current understanding of past and future sea level rise, particularly given current concerns associated with global warming, climate change, and accelerated deglaciation.

4.1. *Submerged notches, pits, and overhanging cliffs*

Observed notches, pits, and overhanging cliffs related to the submerged coastline present varying physical appearances. Intra and intersite variations in the appearance of the features are most likely the result of differences in the positioning of the eolianite face relative to incoming wave and wind energy, as well as a range of strength within the eolianite itself. Unlike notches documented elsewhere in the Mediterranean (Antonioli et al., 2006), many of the notches recognized here are within host rock of limited vertical height, and regularly scattered along the surf zone rather than a smooth, steep rockface. For example, Michmoret and Olga site features were especially poorly preserved, both at sea-level and underwater, and the fabric of the eolianite there was highly porous and easily disaggregated. In contrast, the eolianite at Dor is slightly stronger, and the features are better formed and preserved. Where the eolianite is weaker, it is also more prone to collapse, further limiting its preservation potential and increasing the overall amount of fallen cantilever blocks from the over hanging notch (Young and Ashford, 2008). Intrasite, the variations in erosional depth of the features is associated to how direct or indirect the host rock is to the incoming wave direction. At Caesarea, for example, seaward facing modern sea level notches were measured to dimensions of up to 85 cm, while leeward, protected areas were smaller, in the range of 15–65 cm.

Erosional notch-like features could theoretically develop *in situ*, underwater, particularly those defined as ‘abrasional’ notches (Pirazzoli, 1986). Abrasional notches can form subtidally where sand meets the rock formation and through a process of mechanical erosion results in a notch feature. While the possibility that these features have some association or relationship to abrasional notches, there is ample cause to argue that they are not abrasional notches (or, at least, did not originate as abrasional notches). In Rovere et al., 2011's study of submerged notches and features in the northwestern Mediterranean, they describe multiple sub tidal abrasional notches, but also raise the issue that these abrasion notches are succeeding underlying structural or other developmental conditions. Otherwise stated, an abrasion notch may obscure the prior presence of an original notch feature. Within our study area, there are a series of reasons to question these features as abrasion features. First, abrasional notches occur where loose sediment (sand) meets the host rock, and therefore are not necessarily constrained to a particular depth. Here, the depth of the notches is consistent across multiple studies. This consistency may also point towards some sort of regional influence, and not site-specific, as would be the case for the depth of an abrasional notch. The features also are, in most cases, overgrown with encrusting biological layers and not showing any signs of being actively abraded, as would be expected if they are abrasion notches. Also, in the study area, the sand level at these depths is not stable and is observed to change significantly seasonally as well as annually depending on the events of that year. For example, for many years during excavations at Caesarea, a stabilized benchmarker within the archaeological site at a depth of 9 m on the entry towers to the ancient harbor served as a relative sand height indicator for the underwater archaeologists (Raban, 2009). Variations of up to 1.5 m summer to summer were recorded even during ‘uneventful’ years. In December 2010, following a very large storm, aerial photographs of the ancient harbor revealed massive sand movement that exposed the inner basin of the ancient harbor to depths of about 6 m. Similar exposures were recognized by divers at other coastal sites including Michmoret, Olga, and Dor. Therefore, while in some of this study the submerged notches were partially obscured at their bases by sand, this does not represent a constant condition. Also, in lower depths at the study sites the meeting point of the sand and eolinite in submerged areas does not always occur in tandem with the presence of a notch, as might be expected if this were a constant condition and regular process, though variations in the slope of the eolinite must also be taken into consideration.

There are other examples of submerged abrasional notches, however, the environments where such notches have been observed are different from this study site with regard to the broader geomorphology and climate of the region and texture of the notch. For example, steep canyons off river mouths that are susceptible to sediment movement (creep, slumps, turbidites) have also been reported to have erosional features (Dill, 1964). Also, in that case, the erosional features were interpreted as having a subaqueous genesis because of their dissimilarity to features at and above sea level today, which is in stark contrast to the observations of this study. Also, in this study site there are no significant rivers or steep canyons. Other descriptions are linked to glacial melting and related lake drainages (Kehew and Lord, 1986), which are also easily excluded from the processes present in the study site. In addition, the directionality of the features, like in the modern condition, occur both seaward and leeward facing, a condition that is also related to the biological contributor to the notches' evolution, which appears to be both primarily sea corrosion and abrasion driven. Lastly, though in many cases it is difficult to recognize due to the overgrowth, the rippled, bumpy surface typical of this process (see Fig. 3, Olga 0 msl pit photograph) is sometimes still observable where exposed.

4.2. *Sea level change and notch development*

As a general time frame, the OSL ages of the rock hosting the now submerged sea level related morphologies, limit them to the past 65,000 years (Porat et al., 2004), thereby excluding earlier higher sea levels, such as various phases of isotope stage 5, that might otherwise explain the presence of the submerged features. In

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this study the now submerged coastline with its sea level related morphologies can be limited to the most recent post-glacial maximum period and therefore can be compared to known sea level records to estimate their age (Fig. 6).

Additional temporal consideration is the minimum time required to produce a notch or erosional pit. This timeframe can be generally estimated using notches eroded into host rock with dateable context. In Caesarea and Dor sites, for example, notches in eolianite features associated to Roman and Byzantine periods (2.0–1.4 ka BP) were present, but notches were not present within host rock modified in the last 100 years or artificial placed sandstone and concrete breakwaters (such as at Michmoret and Caesarea). In addition, relative sea level evidence described by Toker et al. (2012) supports the presence of a lower sea-level stand (~0.5 ± 0.3 m) for a period of 100–300 years (~1.0–0.7 ka BP). If this were enough time to produce a notch, we would expect to see it reflected in the shape of the notches, but no such feature was observed (see Fig. 6 for theorized short-term notch). Therefore we broadly speculate that notch development requires greater than 300 years of sea level stability, and more likely something in the realm of 1000 years, given that the protected portions of the 2.0 ka BP pools of Caesarea have notches of 30 × 30 cm dimensions (Fig. 5). While this assumption is in agreement with observations and models by Evelpidou et al. (2012a) and the experimental observations of Trenhaile 2014, it is clear that a wide range of variables (host rock fabric, tidal regime, wind and storm cycles, etc.) influence this rate. Therefore, we suggest here that the development of sea level related morphology in the extent observed in the studied area require an approximate minimum 1000 years of sea level stability.

When the water depth (−2.5 msl) of the observed submerged coastline is compared to the local relative sea level marker data and model sea-level curves curve (Sivan et al., 2001, 2004, Fig. 6), and adding the presumption that it must represent a minimum <1000 year sea level stand, it could lie somewhere in the range between 7000 years BP to 4500 years BP without conflicting with any known local sea-level markers (mainly archeological) from these periods (Fig. 6) and agreeing with established sea-level curves. In fact, the period and water-depth of interest happens to coincide with a data-poor period in which there is a dearth of information regarding the coastal archaeological record (Fig. 6, Raban and Galili, 1985; Sivan et al., 2001). In other areas of the world there is a well-studied global sea level rise 'meltwater pulse' at 8.2–7.4 ka BP (Blanchon and Shaw, 1995; Bratton et al., 2003; Törnqvist et al., 2004; Cronin et al., 2007), and it might be proposed that the observed submerged coastline could signify a period of no sea level change immediately following that rise event. Lambeck et al. (2014) puts forth that in the past 6.7 ka there has been about a 4 m rise in sea level, the majority of which (75%) occurred between 6.7 and 4.2 ka BP, a period of 2.5 ka, while the remaining meter rose over the course of nearly 4.0 ka. This rate is still considerably slower than estimated rates prior to 7.0 ka BP (12 m per 1000 years versus about 0.8 m per 1000 years). Taking this into account, the relatively faster rate of rise, we speculate that if this occurred in pulses, it might account for the observed submerged sea level features (Figs. 6 and 7).

It is difficult to identify the specific years during which there was a sea level rise quiescence, but it is possible to determine the range of time within which it is a possibility. First, the period of sea level rise quiescence to produce a notch should be postulated at a minimum of 1.0 ka. The depth −2.5 msl further limits the time range that can be considered (Figs. 6 and 7) to around 7.0 to 5.0 ka msl by comparing to previously proposed sea level curves, leading to a more constrained period of time than the data hiatus alone (~4.6–7.4 ka). The 4.0 msl feature depth range also falls within the data hiatus, but within a more constrained range of ages according to the model sea level curves (Figs. 6 and 7).

5. Conclusions

Holocene-era submerged coastline features identified in this study suggest that sea-level rise during the Holocene has occurred in varying rates, pausing for periods with relatively little change (or limited rises and falls) intermingled with more rapid increases. Throughout the study, it has been apparent that the defining and categorization of these features is not always straightforward and therefore the conclusions have an inherent degree of speculation (Mauz et al., 2015). However, the potential for these observations to

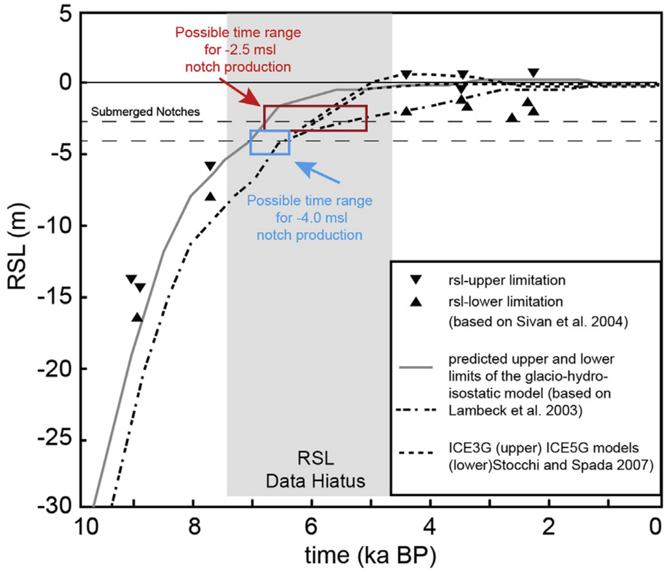

Fig. 6. Established local sea level curves from field observations and modeling (Sivan et al., 2001, 2004; Lambeck et al., 2004; Stocchi and Spada, 2007) with observed submerged notch depth plotted for comparison.

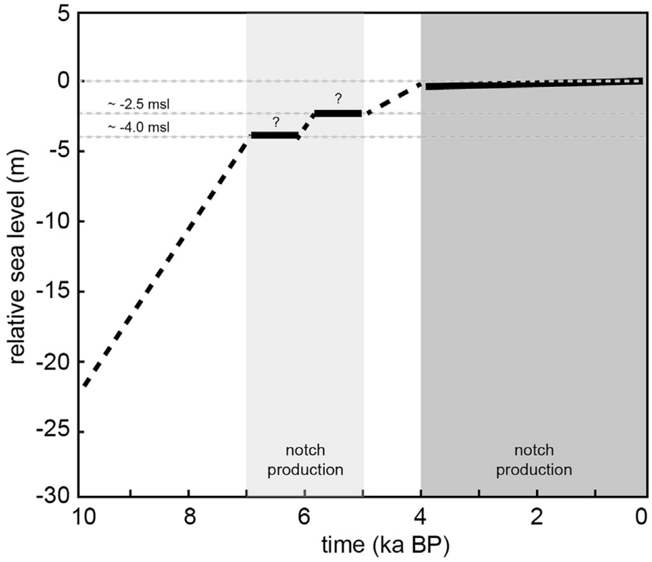

Fig. 7. Proposed sea level curve modified to accommodate presence of notches. Based on the observed features in the study, two phases of notch production are proposed within the timeframe of ~7 to 5 ka BP based on considerations of published sea level curves and field sea level marker observations (see Fig. 6).

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hold significant relevance on the Levantine coastline merits further consideration and continued investigation into the features' distribution and ages.

It is significant today because glacial melting is characterized by these sudden, rapid additions of massive quantities of water into the marine system that can result in varying sea levels worldwide (Stocchi and Spada, 2007; Blanchon et al., 2009; Lambeck et al., 2014). Estimates based on Greenland glacial contribution and sustained dynamic thinning leading to the possible release of quantities with the potential of producing a 3 m sea level rise in a time frames of decades (Khan et al., 2014). The maximum heights recognized for stages of the MIS 5 sea level highstand (+6 msl) provide a prediction for the potential volume that is available, and it is concerning for management and risk planning on the valuable and vulnerable coastal zone.

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References

Alexander, S., 1932. Pothole erosion. The Journal of Geology. Journal of Geology 40, 305–337.

Amiran, R., Arieh, E., Turcotte, T., 1994. Earthquakes in Israel and adjacent areas: observations. Israel Exploration Journal 44, 260–305.

Antonioli, F., Ferranti, L., Kershaw, S., 2006. A glacial isostatic adjustment origin for double MIS 5.5 and Holocene marine notches in the coastline of Italy. Quaternary International 145–146, 19–29.

Antonioli, F., Lo Presti, V., Rovere, A., Ferranti, L., Anzidei, M., Furlani, S., Mastronuzzi, G., Orru, P.E., Scicchitano, G., Sannino, G., Spampinato, C.R., Pagliarulo, R., Deiana, G., de Sabata, E., et al., 2015. Tidal notches in Mediterranean Sea: a comprehensive analysis. Quaternary Science Reviews 119, 66–84.

Anzidei, M., Antonioli, F., Benini, A., Lambeck, K., Sivan, D., Serpelloni, E., Stocchi, P., 2011. Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. Quaternary International 232, 13–20.

Bailey, G., Flemming, N., 2008. Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. Quaternary Science Reviews 27, 2153–2165.

Bakler, N., Neev, D., Magaritz, M., 1985. Late holocene tectonic movements at Tel Haraz, southern coast of Israel. Earth and Planetary Science Letters 75 (2–3), 223–230. http://dx.doi.org/10.1016/0012-821X(85)90104-9.

Benac, Č., Juračić, M., Bakran-Petricioli, T., 2004. Submerged tidal notches in the Rijeka Bay NE Adriatic Sea: indicators of relative sea-level change and of recent tectonic movements. Marine Geology 212, 21–33.

Bird, M.I., Austin, W.E.N., Wurster, C.M., Fifield, L.K., Mojtahid, M., Sargeant, C., 2010. Punctuated eustatic sea-level rise in the early mid-Holocene. Geology 38, 803–806.

Blanchon, P., Shaw, J., 1995. Reef drowning during the last deglaciation-Evidence for catastrophic sea level rise and ice-sheet collapse. Geology 23, 4–8.

Blanchon, P., Eisenhauer, A., Fietzke, J., Liebetrau, V., 2009. Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. Nature 458, 881–884.

Bratton, J.F., Colman, S.M., Thieler, E.R., Seal, R.R., 2003. Birth of the modern Chesapeake Bay estuary between 7.4 and 8.2 ka and implications for global sea-level rise. Geo-Marine Letters 22, 188–197.

Chappell, J., 1974. Department of Geography, School of General Studies, Australian National University Canberra, A.C.T. Quaternary Research 4, 405–428.

Church, J.A., White, N.J., 2006. A 20th century acceleration in global sea-level rise. Geophysical Research Letters 33, 1–4.

Cronin, T.M., 2012. Rapid sea-level rise. Quaternary Science Reviews 56, 11–30.

Cronin, T.M., Vogt, P.R., Willard, D.A., Thunell, R., Halka, J., Berke, M., Pohlman, J., 2007. Rapid sea level rise and ice sheet response to 8,200-year climate event. Geophysical Research Letters 34, 1–6.

Desruelles, S., Fouache, É., Ciner, A., Dalongeville, R., Pavlopoulos, K., Kosun, E., Coquinot, Y., Potdevin, J.L., 2009. Beachrocks and sea level changes since Middle Holocene: comparison between the insular group of Mykonos–Delos–Rhenia (Cyclades, Greece) and the southern coast of Turkey. Global and Planetary Change 66 (1–2), 19–33. http://dx.doi.org/10.1016/j.gloplacha.2008.07.009.

Dey, H., Goodman-Tchernov, B., Sharvit, J., 2014. Archaeological evidence for the tsunami of January 18, 749 Islamic: a chapter in the history of Early Caesarea, Qaysariyah (Caesarea Maritima). Journal of Roman Archaeology 27, 357–373.

Dickinson, W.R., 2001. Paleoshoreline record of relative Holocene sea levels on Pacific islands. Earth-Science Reviews 55, 191–234.

Dill, R.F., 1964. Sedimentation and erosion in Scripps submarine canyon head. In: Miller, R.L. (Ed.), Papers in Marine Geology, Shepard Commemorative Volume. MacMillan, New York, pp. 23–41.

Engelmann, A., Neber, A., Frechen, M., Boenigk, W., Ronen, A., 2001. Luminescence chronology of Upper Pleistocene and Holocene aeolianites from Netanya South — Sharon Coastal Plain, Israel. TL/ESR Special 20, 799–804.

Engelhart, S.E., Horton, B.P., 2012. Holocene sea level database for the Atlantic coast of the United States. Quaternary Science Reviews 54, 12–25.

Engelhart, S.E., Vacchi, M., Horton, B.P., Nelson, A.R., Kopp, R.E., 2015. A sea-level database for the Pacific coast of central North America. Quaternary Science Reviews 113, 78–92.

Evelpidou, N., Kampolis, I., Pirazzoli, P.A., Vassilopoulos, A., 2012a. Global sea-level rise and the disappearance of tidal notches. Global and Planetary Change 92–93, 248–256.

Evelpidou, N., Pirazzoli, P., 2015. Comment on «Tidal notches in the Mediterranean Sea: a comprehensive analysis» by Fabrizio Antonioli, Valeria Lo Presti, Alessio Rovere, Luigi Ferranti, Marco Anzidei, Stefano Furlani, Giuseppe Mastronuzzi, Paolo E. Orru, Giovanni Scicchitano, Gianmaria Sannino, Cecilia R. Spampinato, Rossella Pagliarulo, Giacomo Deiana, Eleonora de Sabata, Paolo Sansò, Matteo Vacchi and Antonio Vecchio. Quaternary Science Reviews 119 (2015) 66–84. Quaternary Science Reviews 1–2. http://dx.doi.org/10.1016/j.quascirev.2015.08.023.

Evelpidou, N., Pirazzoli, P.A., Saliège, J.F., Vassilopoulos, A., 2011. Submerged notches and doline sediments as evidence for Holocene subsidence. Continental Shelf Research 31, 1273–1281.

Evelpidou, N., Pirazzoli, P., Vassilopoulos, A., Spada, G., Ruggieri, G., Tomasin, A., 2012b. Late Holocene Sea Level Reconstructions Based on Observations of Roman Fish Tanks, Tyrrhenian Coast of Italy. Geoarchaeology 27, 259–277.

Evelpidou, N., Vassilopoulos, A., Pirazzoli, P.A., 2012c. Submerged notches on the coast of Skyros Island (Greece) as evidence for Holocene subsidence. Geomorphology 141–142, 81–87.

Fairbanks, R.G., 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.

Fairbanks, Richard G., Charles, Christopher D., Wright, J.D., 1992. Origin of global meltwater pulses. In: Radiocarbon After Four Decades. Springer, New York, pp. 473–500.

Fedje, D.W., Rosenhans, H.W., 2000. Drowned forests and archaeology on the continental shelf of British Columbia, Canada. Geology 28 (2), 99–102.

Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. Earth and Planetary Science Letters 163, 327–342.

Flemming, N., 1969. Archaeological evidence for eustatic change of sea level and earth movements in the western Mediterranean during the last 2,000 years. Geological Society of America Special Papers 109, 1–98.

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 62, 1–29.

Frechen, M., Dermann, B., Boenigk, W., Ronen, A., 2001. Luminescence chronology of aeolianites from the section at Givat Olga – coastal Plain of Israel. Quaternary Science Reviews 20, 805–809.

Frechen, M., Neber, A., Tsatskin, A., Boenigk, W., Ronen, A., 2004. Chronology of Pleistocene sedimentary cycles in the Carmel Coastal Plain of Israel. Quaternary International 121, 41–52.

Galili, E., Sharvit, J., 1998. Ancient Coastal Installations and the Tectonic Stability of the Israeli Coast in Historical Times Coastal Tectonics. Geological Society, pp. 147–163. Special Publications, 146.

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.

Gehrels, W.R., 1999. Middle and Late Holocene Sea-Level Changes in Eastern Maine Reconstructed from Foraminiferal Saltmarsh Stratigraphy and AMS 14C Dates on Basal Peat. Quaternary Research 52, 350–359.

Goldsmith, V., Golik, A., 1980. Sediment transport model of the Southeastern Mediterranean Coast. Marine Geology 37, 147–175.

Goodman, B.N., Reinhardt, E.G., Dey, H.W., Boyce, J.I., Schwarcz, H.P., Sahoğlu, V., Erkanal, H., Artzy, M., 2009. Multi-proxy geoarchaeological study redefines understanding of the paleocoastlines and ancient harbours of Liman Tepe (Iskele, Turkey). Terra Nova 21, 97–104.

Goodman-Tchernov, B.N., Austin Jr., J., 2015. Deterioration of Israel's Caesarea Maritima's ancient harbor linked to repeated tsunami events identified in Geophysical Mapping of offshore Stratigraphy. Journal of Archaeological Science: Reports 3, 444–454.

Gvirtzman, G., Shachnai, E., Bakler, N., Ilani, S., 1984. Stratigraphy of the Kurkar Group (Quaternary) of the Coastal Plain of Israel. Geological Survey of Israel, pp. 70–82. Current Research 1983–4.

Katz, O., Mushkin, A., 2013. Characteristics of sea-cliff erosion induced by a strong winter storm in the eastern Mediterranean. Quaternary Research (United States) 80, 20–32.

Kershaw, S., Guo, L., 2001. Marine notches in coastal cliffs: indicators of relative sea-level change, Perachora Peninsula, central Greece. Marine Geology 179, 213–228.

Kehew, A.E., Lord, M.L., 1986. Origin and large-scale erosional features of glacial-lake spillways in the northern Great Plains. Geological Society of America

Bulletin 97, 162–177. http://dx.doi.org/10.1130/0016-7606(1986)97<162. February.

Khan, S., Kjaer, K.H., Bevis, M., Bamber, J.L., Wahr, J., Kjeldsen, K.K., Bjork, A., Korsgaard, N.J., Stearns, L., van den Broeke, M.R., Liu, L., Larsen, N.K., Muresan, I.S., 2014. Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. Nature Climate Change 4, 292–299.

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

Lambeck, K., Chappell, J., 2001. Sea level change through the last glacial cycle. Science (New York, N.Y.) 292, 679–686.

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., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proceedings of the National Academy of Sciences 111, 15296–15303.

Liu, J.P., Milliman, J., 2004. Reconsidering melt-water pulses 1A and 1B: global impacts of rapid sea-level rise. Journal of Ocean University of China 3, 183–190.

Marriner, N., Morhange, C., 2007. Geoscience of ancient Mediterranean harbours. Earth-Science Reviews 80, 137–194.

Marriner, N., Morhange, C., Faivre, S., Flaux, C., Vacchi, M., Miko, S., Dumas, V., Boetto, G., Radic Rossi, I., 2014. Post-Roman sea-level changes on Pag Island (Adriatic Sea): dating Croatia's "enigmatic" coastal notch? Geomorphology 221, 83–94.

Mastronuzzi, G., Calcagnile, L., Pignatelli, C., Quarta, G., Stamatopoulos, L., Venisti, N., 2014. Late Holocene tsunamogenic coseismic uplift in Kerkira Island, Greece. Quaternary International 332, 48–60.

Mauz, B., Vacchi, M., Green, A., Hoffmann, G., Cooper, A., 2015. Beachrock: a tool for reconstructing relative sea level in the far-field. Marine Geology 362, 1–16.

Miller, W.R., Mason, T.R., 1994. Erosional features of coastal beachrock and aeolianite outcrops in Natal and Zululand, South Africa. Coastal Education and Research Foundation, Inc. 10 (2), 374–394.

Morhange, C., Pirazzoli, P.A., 2005. Mid-Holocene emergence of southern Tunisian coasts. Marine Geology 220 (1–4), 205–213. http://dx.doi.org/10.1016/j.margeo.2005.06.031.

Neumann, C.A., 1966. Observations on coastal erosion in Bermuda and measurements of the boring rate of the sponge, *Cliona lampa*. Limnology and Oceanography 11, 92–108.

Neumann, C.A., Hearty, P.J., 1996. Rapid sea-level changes at the close of the last interglacial (substage 5e) recorded in Bahamian island geology. Geology 24, 775–778.

Nixon, F.C., Reinhardt, E.G., Rothaus, R., 2009. Foraminifera and tidal notches: dating neotectonic events at Korphos, Greece. Marine Geology 257, 41–53.

Peltier, W.R., 2002. On eustatic sea level history: Last Glacial Maximum to Holocene. Quaternary Science Reviews 21, 377–396.

Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews 25, 3322–3337.

Pirazzoli, P.A., 2005. A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. Quaternary Science Reviews 24, 1989–2001.

Pirazzoli, P.A., 1986. Marine Notches. Sea-level Research. Springer, Netherlands, pp. 361–400.

Pirazzoli, P.A., Evelpidou, N., 2013. Tidal notches: a sea-level indicator of uncertain archival trustworthiness. Palaeogeography, Palaeoclimatology, Palaeoecology 369, 377–384.

Porat, N., Wintle, A.G., Ritte, M., 2004. Mode and timing of kurkar and hamra formation, central coastal plain, Israel. Israel Journal of Earth Sciences 53, 13–25.

Raban, A., 2009. The Harbour of Sebastos (Caesarea Maritima) in its Roman Mediterranean Context. In: British Archaeological Reports International Series 1930. Oxford.

Raban, A., Galili, E., 1985. Recent maritime archaeological research in Israel: a preliminary report. International Journal of Nautical Archaeology 14, 321–356.

Reinhardt, E.G., Patterson, R.T., Schroeder-Adams, C.J., 1994. Geoarchaeology of the ancient harbor site of Caesarea Maritima, Israel; evidence from sedimentology and paleoecology of benthic foraminifera. Journal of Foraminiferal Research 24, 37–48.

Rovere, A., Vacchi, M., Firpo, M., Carobene, L., 2011. Underwater geomorphology of the rocky coastal tracts between Finale Ligure and Vado Ligure (western Liguria, NW Mediterranean Sea). Quaternary International 232, 187–200.

Rust, D., Kershaw, S., 2000. Holocene tectonic uplift patterns in northeastern Sicily: evidence from marine notches in coastal outcrops. Marine Geology 167, 105–126.

Scott, D.S., Medioli, F.S., 1978. Vertical zonations of marsh foraminifera as accurate indicators of former sea-levels. Nature 272, 528–531.

Scott, D.B., Medioli, F.S., Schafer, C.T., 2001. Monitoring in Coastal Environments Using Foraminifera and Thecamoebian Indicators. Cambridge University Press.

Shackleton, N.J., 1987. Oxygen isotopes, ice volume and sea level. Quaternary Science Reviews 6, 183–190.

Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I., Smeed, D.A., 2003. Sea-level fluctuations during the last glacial cycle. Science 423, 19–24.

Sivan, D., Galili, E., 1999. Holocene tectonic activity in the Galilee coast and shallow shelf, Israel. A geological and archaeological study. Israel Journal of Earth Sciences 48, 47–51.

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

Sivan, D., Porat, N., 2004. Evidence from luminescence for Late Pleistocene formation of calcareous aeolianite (kurkar) and paleosol (hamra) in the Carmel Coast, Israel. Palaeogeography, Palaeoclimatology, Palaeoecology 211, 95–106.

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

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.

Sneh, A., 2000. Faulting in the coastal plain of Israel during the Late Quaternary, reexamined. Israel Journal of Earth Sciences 49, 21–29.

Stocchi, P., Spada, G., 2007. Glacio and hydro-isostasy in the Mediterranean Sea: Clark's zones and role of remote ice sheets. Annals of geophysics 50 (no. December).

Toker, E., Sivan, D., Stern, E., Shirman, B., Tsimplis, M., Spada, G., 2012. Evidence for centennial scale sea level variability during the Medieval Climate Optimum (Crusader Period) in Israel, eastern Mediterranean. Earth and Planetary Science Letters 315–316, 51–61.

Törnqvist, T.E., Bick, S.J., González, J.L., van der Borg, K., de Jong, A.F.M., 2004. Tracking the sea-level signature of the 8.2 ka cooling event: new constraints from the Mississippi Delta. Geophysical Research Letters 31 (23), 1–4. http://dx.doi.org/10.1029/2004GL021429.

Trenhaile, A.S., 2015. Coastal notches: their morphology, formation, and function. Earth-Science Reviews 150, 285–304.

Trenhaile, A.S., 2014. Modelling tidal notch formation by wetting and drying and salt weathering. Geomorphology 224, 139–151.

Vacchi, M., Rovere, A., Chatzipetros, A., Zouros, N., Firpo, M., 2013. An updated database of Holocene relative sea level changes in NE Aegean Sea. Quaternary International. http://dx.doi.org/10.1016/j.quaint.2013.08.036.

Vacchi, M., Rovere, A., Schiaffino, C.F., 2012a. Monitoring the effectiveness of re-establishing beaches artificially: methodological and practical insights into the use of video transects and SCUBA-operated coring devices. International Journal of the Society for Underwater Technology 30, 201–206.

Vacchi, M., Rovere, A., Zouros, N., Desruelles, S., Caron, V., Firpo, M., 2012b. Spatial distribution of sea-level markers on Lesvos Island (NE Aegean Sea): evidence of differential relative sea-level changes and the neotectonic implications. Geomorphology 159–160, 50–62.

Vousdoukas, M.I., Velegrakis, A.F., Plomaritis, T.A., 2007. Beachrock occurrence, characteristics, formation mechanisms and impacts. Earth-Science Reviews 85, 23–46.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quaternary Science Reviews 21, 295–305.

Walcott, R.I., 1972. Past Sea Levels, Eustasy and Deformation of the Earth. Quaternary Research 14, 1–14.

Wziatek, D., Vousdoukas, M.V., Terefenko, P., 2011. Wave-cut notches along the Algarve coast, S. Portugal: characteristics and formation mechanisms. Journal of Coastal Research 855–859. October 2015.

Yaalon, D.H., 1967. Factors affecting the lithification of eolianite and interpretation of its environmental significance in the coastal plain of Israel. Journal of Sedimentary Petrology 37, 1189–1199.

Young, A.P., Ashford, S.A., 2008. Instability investigation of cantilevered seacliffs. Earth Surface Processes and Landforms 33, 1661–1677.

Zviely, D., Kit, E., Klein, M., 2007. Longshore sand transport estimates along the Mediterranean coast of Israel in the Holocene. Marine Geology 238, 61–73.

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