

Geomorphological dynamics at the coast: A sedimentary stratigraphy for Atlit-Yam, the earliest coastal village at the Eastern Mediterranean and its submerged landscape

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ABSTRACT

During the early Holocene, rapid sea-level rise led to the inundation of coastal areas, with shallow landscapes being the most affected. The Carmel coast, located in the Eastern Mediterranean, preserves a rich record of such a submerged landscape, hosting numerous archaeological sites, including the well-preserved Atlit-Yam Neolithic village. In order to reconstruct the geomorphological evolution of the submerged coastal landscape, 23 underwater sediment cores of variable length (ranging from 60 to 240 cm) were drilled both inside and outside the known extent of the Atlit-Yam village. A detailed stratigraphy of the submerged landscape was generated based on the analysis of 18 representative cores. The sedimentary sequences identified in the analyzed cores were defined by respective facies associations, and combined with physical (grain size, magnetic susceptibility), chemical (elemental geochemistry), and organic (total organic content) properties of the sediments. Moreover, the sediment cores were constrained by a radiocarbon chronology. Our analysis reveals the spatially heterogeneous stratification of submerged coastal sediments, influenced by sediment supply, stratigraphic dynamics, rising sea level and human activity. The stratigraphic framework presented here allows identification of sedimentary facies associated with the period of active human occupation. We identify ten sedimentary facies characterized by elevated total organic content, magnetic susceptibility, P/Al, Ti/Al ratios together with distinct grain sizes highlighting the complex interplay between sea-level rise, sedimentary processes, and landscape evolution from Late Pleistocene to the Early Holocene. This study provides stratigraphic and chronological evidence for sustained Neolithic occupation between ~9600 and 8600 cal. Yrs BP, prior to the early stages of coastal inundation. These findings demonstrate the advantage of coring and sedimentological analysis for studying early human occupation of coastal areas in direct relations to landscape transformation due to rising sea levels.

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1. Introduction

The interplay between global warming and eustatic sea-level rise, particularly during the early Holocene, has led to the widespread inundation of low-lying coastal regions, significantly altering hydrological regimes and associated ecosystems (Nuttall and Portnoy, 1992; Masterson and Garabedian, 2007; Smith et al., 2011). These transgressive events not only disrupted sedimentary processes and reshaped coastal morphology but also submerged once-thriving landscapes that were habitat for early human settlements (Passeri et al., 2015; Ghosh, 2018; Eaton et al., 2024). The inundation of these zones often occurred rapidly, converting extensive floodplains, wetlands, and estuarine environments into shallow marine settings and fundamentally reorganizing coastal hydrodynamics (Bailey and Flemming, 2008; Lambeck et al., 2014). These episodic flooding phases imposed strong constraints on coastal morphodynamics, ecosystem stability, and human land use, leaving a distinct stratigraphic signature across submerged continental shelf environments (Deschamps et al., 2012; Törnqvist and Hijma, 2012). Such events not only displaced human populations but also sealed cultural deposits beneath marine sediments, complicating their discovery and enabling their preservation (Flemming, 2017; Bynoe et al., 2023). As a consequence, many of these coastal zones critical to

Neolithic societies now lie beneath the sea, preserved as submerged cultural relicts that offer valuable insights into early human-environment interactions (Erlandson, 2012). Therefore, a comprehensive geomorphological investigation of these submerged landscapes is crucial to understand how rising sea levels influenced Neolithic coastal societies and how these have adapted to the changing conditions through time.

The Carmel coast (SE Mediterranean Sea) (see Fig. 1b) hosts a high abundance of well-preserved Neolithic sites, out of which some are currently submerged by the sea, offering a unique opportunity to explore how the changing environments impacted these coastal societies in light of rising sea levels. Atlit-Yam (ca. 9500-8600 cal. B.P) is represented as one of the most exceptionally preserved submerged Neolithic site, offering critical insights into human adaptation to coastal and maritime environments (Galili et al., 2020). The outstanding preservation of architectural remains, utilitarian artifacts, and organic materials provides a rare window into lifeways in the coast prior to their inundation by post-glacial sea-level rise (Galili and Nir, 1993; Galili et al., 1993, 2004, 2017, 2020; Galili and Horwitz, 2025). In addition to the extensive archaeological research, numerous studies have examined the coastal morphology during the early Holocene at the Carmel Coast (Kadosh et al., 2004; Sivan et al., 2004a; 2004b, 2011, 2016; Galili et al.,

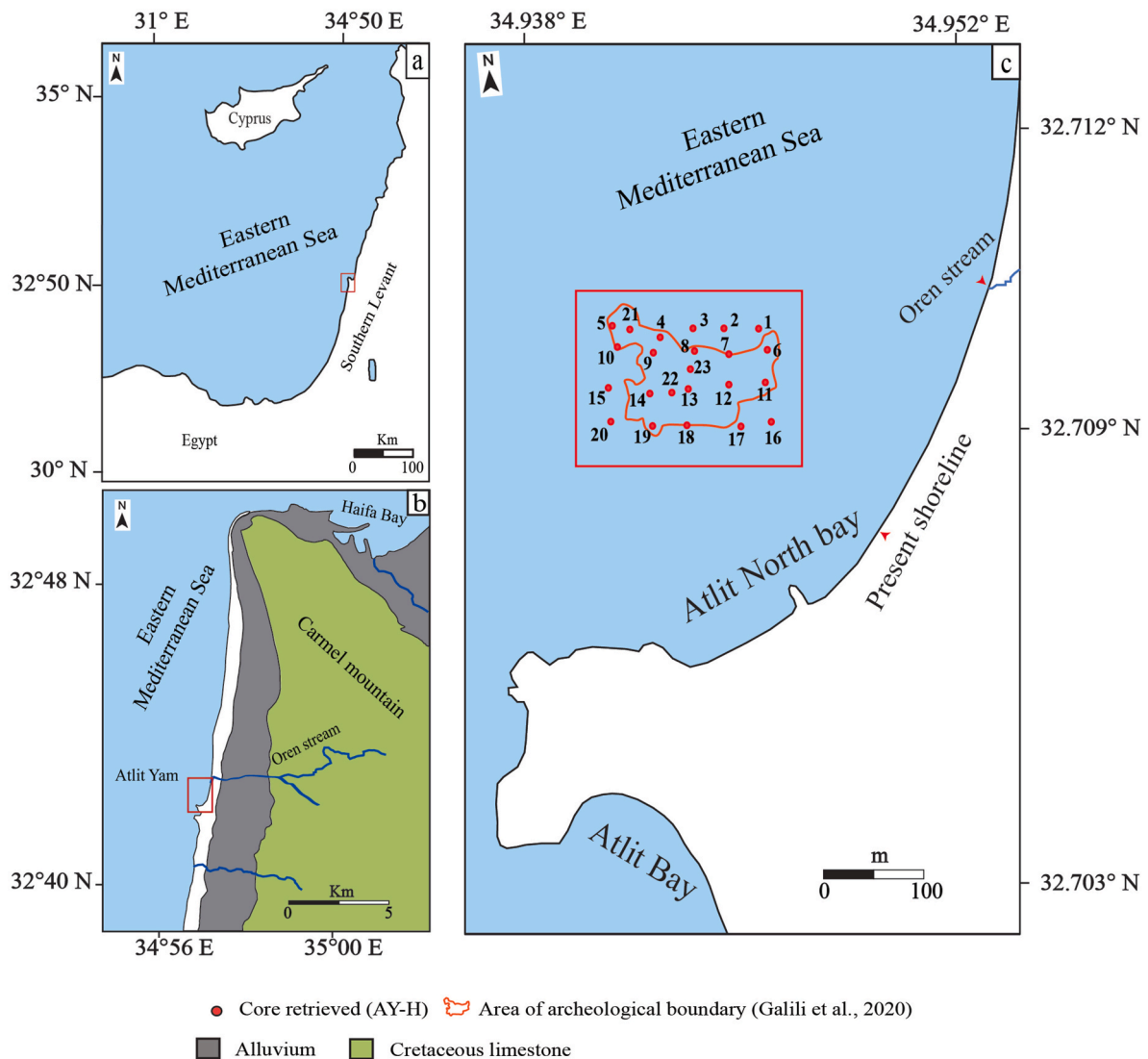


Fig. 1. Map of Study area. (a)- Overview of the mediterranean and levant area, (b)- Study area location in the carmel coast, (c)- Atlit-Yam area and locations of the retrieved sediment cores.

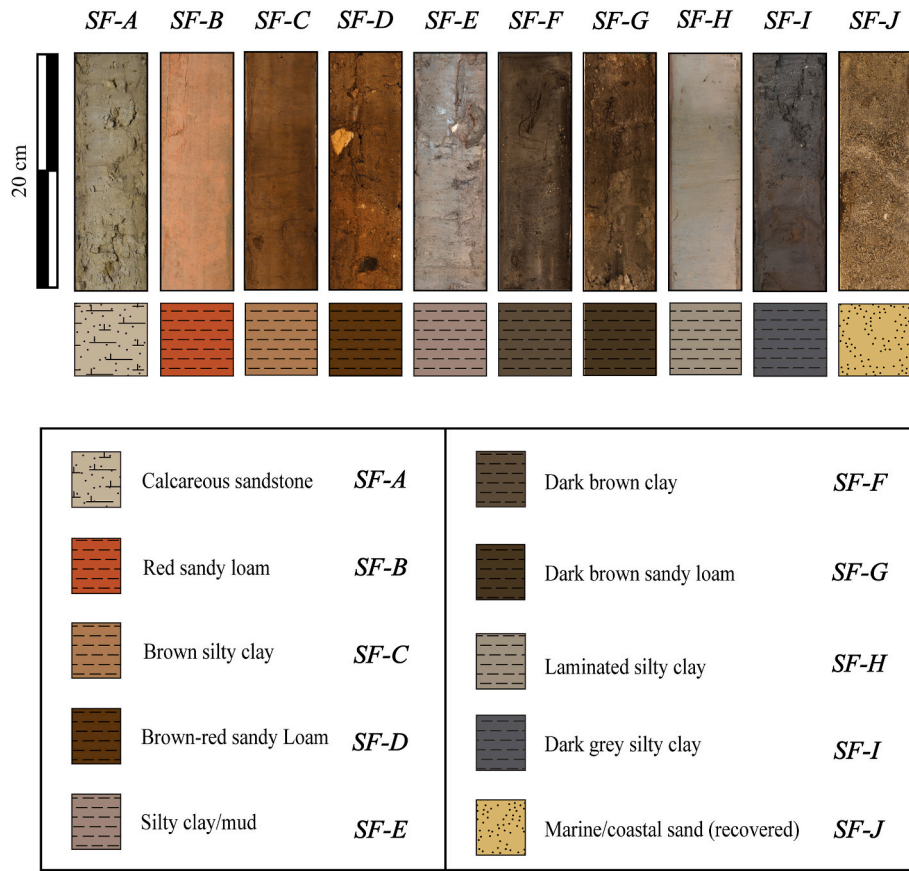


Fig. 2. Sedimentary facies and their representation.

2005a,b; Cohen-Seffer et al., 2005; Sivan and Greenbaum 2017; Avnaim-Katav et al., 2012; Shtienberg et al., 2022). Yet, a significant knowledge gap still prevails in comprehending the localized geomorphic dynamics which took place specifically in relation to the Pre-Pottery Neolithic settlement of Atlit-Yam prior to its inundation. Here we present a high-resolution stratigraphic framework from the deep sediment

cores retrieved from this settlement and its surroundings (see Fig. 1c; Table 1 for locations). This framework was designed using a multi-proxy approach entailing elemental, organic, and physical properties of the sediment. Furthermore, the samples were anchored chronologically by radiocarbon dating. This integrated approach provides new insights into the dynamic interplay between human activity, sea-level fluctuations,

Table 1

Overview of core sampling and analytical measurements, with a total of 474 samples measured for various analysis such as XRF, MS, GS, TOC.

Core AY-H	Depth below PMSL (m)	Length of core (cm)	Decimal UTM coordinates (N, E)		XRF	MS	GS	TOC	No. of samples
1	7.5	238	32.710655	34.938332	58	58	58	58	58
4	9	104	32.71065	34.935933	16	16	16	16	16
5	9.5	121	32.710649	34.935133	25	25	14	25	25
6	7	96	32.710205	34.938334	17	17	17	17	17
7	8.5	81	32.710203	34.937534	19	18	18	18	19
8	9.5	120	32.710201	34.936734	20	30	16	16	30
9	9.5	65	32.710199	34.935934	19	19	19	19	19
10	9.5	72	32.710198	34.935134	12	12	12	12	12
12	8	95	32.709752	34.937535	12	12	12	7	12
13	9.5	155	32.70975	34.936735	46	49	15	49	49
14	10	135	32.709749	34.935935	6	6	6	6	6
16	6	160	32.709303	34.938336	54	20	20	20	54
17	6.5	180	32.709301	34.937536	39	39	59	59	59
18	8	55	32.709299	34.936737	5	5	5	5	5
19	10.5	177	32.709298	34.935937	31	30	17	30	33
20	10	81	32.709296	34.935137	13	13	13	13	13
21	9.5	101	32.710649	34.935453	29	11	17	11	31
22	10.5	80	32.709749	34.936362	15	16	9	16	16
total samples per analytical measurement					436	396	343	397	474

PMSL: Present mean sea level.

XRF: X-Ray Fluorescence.

MS: Magnetic Susceptibility.

GS: Grain size.

TOC: Total organic carbon.

sedimentary processes, and landscape transformation along the Carmel coast (see Fig. 2).

2. Study area

The Eastern Mediterranean region, particularly along the Levant margin (Fig. 1a), presents a geologically complex and dynamic coastal environment (Mauz et al., 2013; Galili et al., 2017a,b,c; Segev et al., 2018). This margin has been shaped since the late Quaternary by the interplay of tectonic activity, sediment supply, and sea-level fluctuations (Enzel and Bar-Yosef, 2017). It is considered as a passive margin and is influenced by seismicity related to subsurface halokinetic processes and nearby active faults (Netzeband, 2006; Carton et al., 2009; Segev et al., 2018). These factors, combined with climatic variations and relative sea-level changes make the region a key area for studying long-term environmental transformations and their impact on early human societies (Sivan et al., 2001, 2004b; Homberg and Bachmann 2010). The coastal plain in the region is primarily composed of Alluvial deposits and unconsolidated sediments, largely transported via longshore drift from Nile-derived sources since the Pliocene (Emery et al., 1960; Almagor, 1984; 1993; Stanley and Warne, 1998; Sivan et al., 2001, 2004a, 2004b; Elyashiv et al., 2016). Within this broader context, the Israeli coastal area, a prominent feature of the Levant margin, offers significant archaeological and geological insights. Relative sea-level changes here generally follow global eustatic trends, with only minor local deviations (Lambeck and Bard, 2000; Galili et al., 1988, 2007; Sivan et al., 2001a; 2004b).

The Carmel coast, a distinctive segment of the Israeli coastline (Fig. 1b), exhibits a varied geomorphological and sedimentary landscape comprising Pleistocene Calcareous cemented sandstone ridges (aeolianite, locally known as *Kurkar*; Sivan et al., 2011 and references therein), red-brown paleosols, dark silty clay deposits that fill up local depressions and sandy beaches (Kadosh et al., 2004; Shtienberg et al., 2022). Two parallel Calcareous sandstone ridges extend along the coastline from the northern sector to Atlit: the first ridge situated landward (to the east) and the other submerged offshore (to the west). Occasional short distance fluvial settings cut these aeolianite ridges. Subsurface stratigraphy in the Carmel coast has been extensively explored through sediment cores recovered from interdunal troughs and exposed outcrops, revealing a detailed sequence of depositional environments shaped by late Quaternary sea-level fluctuations and sedimentary processes (Kadosh et al., 2004; Sivan and Porat, 2004; Sivan et al., 2004; 2011; Cohen-Seffer et al., 2005; Shtienberg et al., 2022; Galili et al., 2017a; Galili et al., 2017b; Galili et al., 2017c). This coastal segment thus preserves a rich sedimentary archive that documents the interplay between marine transgression and sediment dynamics determining the landscape evolution (Shtienberg et al., 2022). Importantly, the Carmel coast preserves one of the most extensive archaeological records along the eastern Mediterranean, documenting Neolithic and later human occupations in a highly dynamic coastal setting (Galili and Weinstein Evron, 1985; Galili and Nir, 1993; Galili et al., 1997, 2019; Kislev et al., 2004; Rosen and Galili, 2007). However, despite the rich amount of archaeological records, the knowledge about the sedimentary processes impacting the Carmel coastal landscape and shaping its evolution through time as well as the background environmental conditions, are still lacking.

The Atlit-Yam site, located approximately 300–400 m offshore from the coast (Fig. 1c) and submerged at a depth of 8–12 m below present mean sea level (msl), was discovered in 1984 and is associated with the Pre-Pottery Neolithic C (PPNC) period (9000–8400 cal. BP following Grafinkel and Bar-Yosef 2008). Over the past four decades, extensive archaeological investigations have uncovered a wealth of material culture spanning for approximately 40,000 m², including domestic architecture, freshwater wells (Galili and Nir, 1993), multiple burials (Galili et al., 2005a,b; Hershkovitz and Galili, 1990), stone tools (Barkai and Galili, 2004; Yerkes et al., 2014), fishing gear (Galili et al., 2004,

2013), faunal (Horwitz and Tchernov, 1987) and botanical remains (Kislev et al., 2004; Hartmann-Shenkman et al., 2015). These findings indicate a coastal community with a mixed subsistence economy based on both marine exploitation and terrestrial agriculture and animal husbandry (Galili et al., 1993, 2017; Ogloblin Ramirez et al., 2023) and represents one of the oldest known permanent coastal settlement in the world (Galili et al., 2020; Galili and Horwitz, 2025). A recent deep drilling exploration at the Atlit-Yam site and its immediate surroundings has revealed the shallow substratum stratigraphy, suggesting a longer and more complex occupation history than previously understood (Friesem et al., 2022; Ogloblin Ramirez et al., 2023). The present study, therefore, further investigates this stratigraphic framework of the Atlit-Yam site by detailed identification of a set of sedimentary facies and their change through space and time in light of the governing Holocene rising sea level conditions.

3. Methods

3.1. Sediment coring

A two-day drilling survey was conducted at the Atlit-Yam site and its adjacent environment in November 2022. During the expedition, a total of 23 sediment cores, ranging in length from approximately 60 cm to 240 cm, were retrieved at various water depths (6 to ~11 m below present-day sea level) (see Fig. 1c for location) utilizing the 27 m long, 500-ton sea vessel *RV Shikmona*, which was equipped with a crane, hydraulic system, and surface-supplied air for helmet divers. Coring was conducted using galvanized steel pipes (8 cm diameter, 3 m length) mounted vertically in a custom-built steel base positioned on the sea-floor. Once deployed, the pipes penetrated the sediments using a hydraulically operated hammer controlled by a helmet diver. Core locations were recorded in UTM coordinates using a Garmin GPS, and drilling procedures were adapted from (Ramírez et al., 2020; Ramírez et al., 2021). Upon full insertion, the pipe barrels were sealed to decrease the air volume as much as possible and lifted vertically to the vessel, where the base was properly sealed to prevent sediment loss. Excess water was drained, and the cores were stabilized with absorbent foam, trimmed for transport, sealed, labelled, and transported to the University of Haifa laboratories for refrigeration at 4 °C and preservation, prior to be opened and sampled for further analytical experimental analyses.

3.2. Laboratory measurements

Out of 23 retrieved sediment cores barrels (see Fig. 1c and Table 1 for core locations), 18 were opened lengthwise and split into two halves, following protocols and procedures described in Ogloblin Ramirez et al. (2023). The best representative of the core section halves were selected for photographing and their lithologies described immediately at high detail upon opening to avoid disintegration due to oxygen exposure, to consequently being stored in the cooling room. In parallel, the working halves were sampled for a series of analyses following specific sampling protocols detailed by Ohlendorf et al. (2011). Both halves of each core section were eventually wrapped in nylon sheets for preservation and to prevent oxidative degradation resulting from exposure and were stored for future or repetitive analyses in a cooling room. A total of 474 sediment samples, each weighing approximately 5–10 g, were sampled from the cores at intervals of 3, 5, and 10 cm, determined by lithological changes and stratigraphic context (see Table 1). Prior to analytical measurements, the sediment samples were freeze-dried by Lypholyzer for 48 h to remove moisture content for subsequent physical and chemical sediment analyses.

3.2.1. Magnetic susceptibility (MS)

MS provides valuable information on the variability in the paramagnetic and diamagnetic mineral content of the sediments, which in

turn may serve for interpreting several sedimentary processes, including the transport and deposition mechanisms, as well as weathering and erosional processes (Da Silva et al., 2009, 2010; Liu et al., 2010). Additionally, MS helps to separate the abundance of paramagnetic and diamagnetic minerals, such as carbonates, quartz and clays, from ferromagnetic minerals carrying Fe (Martín-Hernández and Ferré, 2007) and, among other functions, also provides hints to the oxic state of the sediment-water interface (Karbassi and Shankar, 1994). For MS measurements, we used a Bartington instrument attached to a Geotek Multi Sensor Core Logger (MSCL) (Nowaczyk, 2001), which was directly applied to a total of 396 powdered sediment samples (see Table 1) and an average of ten readings per sample was taken to increase precision. MS was not measured continuously on the sediment cores to avoid misreadings due to the magnetic properties of the liners. The measurements are reported in SI units expressed as $\times 10^{-5}$.

3.2.2. Grain size distribution (GS)

GS is a powerful tool for tracking sediment transportation dynamics and helps to disentangle, among other proxies, autochthonous from allochthonous processes (Yang et al., 2024). It also serves to calculate the clay/sand ratio, which is a reliable proxy for hydrological processes (Sun et al., 2002; Spencer, 1963; Visser, 1969). For GS, a Beckman Coulter LS 13,320 mw Laser Diffraction Particle Size analyzer was used for the granulometric analysis. In total, 343 samples (see Table 1) were analyzed. Prior to measurements, 2 g each sediment sample was treated with H_2O_2 (30%) for wet oxidation of organic materials and HCl (1N) for removal of carbonates. The relative proportions of clay ($<4\mu\text{m}$), silt ($4\text{--}63\mu\text{m}$), and sand ($63\text{--}2000\mu\text{m}$) fractions in the sediments were determined by summing the percentages of particles within these respective size ranges. We used Ocean Data View (ODV) software to plot the GS data.

3.2.3. Elemental Geochemistry (EG)

EG is a technique for reconstructing past environments and tracing sediment provenance, providing key insights into geomorphological processes and landscape evolution. It provides a wide range of interpretations for the origin and sediment deposition in both terrestrial as well as aquatic systems (e.g., allochthonous vs autochthonous; Zolitschka et al., 2003; Boyle et al., 2005; Weltje and Tjallingii, 2008; Löwemark et al., 2011; among others). In the current study, the elemental variability was determined by introducing 0.5 g of homogeneous powdered sediment sample ($n = 436$) (see Table 1) to a Xenometrix X-Ray Fluorescence (XRF) instrument. The XRF instrument was used to qualitatively detect major elements ranging from Mg to Br, with the elements measured in counts per second (cps), and their abundances described as a ratio between a mobile and a more stable element.

3.2.4. Total Organic Carbon (TOC)

In both aquatic and terrestrial archives (such as soils), TOC provides valuable information on different parameters, including sources of organic matter, preservation conditions, and paleo-productivity (Goñi

et al., 2003). When preserved in the sedimentary record, TOC may contain mixed environmental signals (Wu et al., 2007; Leng et al., 2013). Moreover, TOC indicates the productivity and oxic state at the sediment-water interface and can also be used to track changes in organic depositional conditions through the sedimentary sequence (Hollander et al., 1992; Wilkes et al., 1999; Chen et al., 2001). For the measurements, 100 mg of powdered sediments ($n = 397$) (see Table 1) were treated with 1N HCl to remove carbonates, prior to analysis using a Skalar Primacs TOC Analyzer.

3.2.5. Radiocarbon dating

Radiocarbon dates were obtained from twelve charcoal samples collected at different depths across multiple sediment cores to establish the chronological framework of the sedimentary sequence Table 2. Charcoal fragments were recovered from the cores and isolated from selected horizons by wet sieving through a 1-mm mesh. Analyses were conducted at the Center for Applied Isotope Studies (CAIS), University of Georgia, using a standard acid-alkali-acid (AAA) pretreatment (1 N HCl at 80°C for 1 h, NaOH, final HCl), with rinsing between steps and drying at 105°C (Brock et al., 2010). Pretreated samples were combusted at 900°C in sealed evacuated tubes with CuO, and the resulting CO_2 was cryogenically purified and graphitized following Vogel et al., 1984. Radiocarbon measurements ($^{14}\text{C}/^{13}\text{C}$) were obtained using the CAIS 0.5 MeV AMS and normalized to oxalic acid I (NBS SRM 4990); stable carbon isotope ratios were measured separately and reported as $\delta^{13}\text{C}$ relative to the Pee Dee Belemnite standard (analytical uncertainty $<0.1\text{‰}$). The obtained dates were calibrated using the OxCal v4.4 software (Ramsey, 1995; Brock et al., 2010) and the IntCal20 atmospheric calibration curve (Reineck and Singh, 2012). Calibrated ages are reported as calendar years before present (cal BP) and are presented as 95.4% probability ranges (2σ). See Table 2.

4. Results

4.1. Sedimentary facies

The analytical results are presented using a sedimentary facies framework based on the visual description, physical and geochemical properties of the sediments. Variations in results such as grain size, MS, TOC, and EG were used to define ten sedimentary facies (*SF-A* to *SF-J*) (see Fig. 2). Each facies is characterized by a distinct combination of texture, consolidation, MS values, TOC content, and dominant elements, and occurs either within individual cores or across multiple cores. This classification provides a consistent basis for organizing and presenting the analytical measurements. The characteristics of each sedimentary facies are described below with reference to the corresponding analytical data and figures.

SF-A is characterized by calcareous, consolidated quartz sand, interspersed with occasional sand-sized marine bioclasts. MS remains consistently low, between 5 and 10×10^{-5} SI, while grain-size analysis indicates predominantly coarse-grained sand, with occasional unimodal

Table 2

Radiocarbon dates obtained from twelve samples and their distinctive depth, with their 2σ standard deviation.

Sample ID	Core ID	Depth (cm)	Dated material	lab code	Calibration curve	Calibrated age (2σ , cal BP)	Median cal age (BP)
AY-H1-24	AY-H1	24	Charcoal	UGAMS-87144	IntCal20	8762–8546	8625
AY-H4-52	AY-H4	52	Charcoal	UGAMS-87144	IntCal20	8981–8602	8741
AY-H7-20	AY-H7	20	Charcoal	UGAMS-87144	IntCal20	8983–8640	8784
AY-H9-20	AY-H9	20	Charcoal	UGAMS-87144	IntCal20	9122–8785	9009
AY-H12-55	AY-H12	55	Charcoal	UGAMS-87144	IntCal20	9677–9530	9551
AY-H13-49	AY-H13	49	Charcoal	UGAMS-87144	IntCal20	8983–8640	8784
AY-H13-110	AY-H13	110	Charcoal	UGAMS-87144	IntCal20	9125–8988	9024
AY-H13-130	AY-H13	130	Charcoal	UGAMS-87144	IntCal20	9283–9026	9176
AY-H16-112	AY-H16	112	Charcoal	UGAMS-87144	IntCal20	8781–8596	8703
AY-H17-15	AY-H17	15	Charcoal	UGAMS-87144	IntCal20	9542–9477	9510
AY-H17-59	AY-H17	59	Charcoal	UGAMS-87144	IntCal20	8983–8605	8760
AY-H17-100	AY-H17	100	Charcoal	UGAMS-87144	IntCal20	9283–9021	9152

to bimodal distributions. The near absence of organic matter ($\sim 0.1\%$ TOC) suggests limited preservation, EG confirms a Ca dominated composition with minor contributions from Al, Si, and Fe (cores AY-H1, H10, H13, and H14; Figs. 3a and 3ba and b).

SF-B is composed of a paleosol that is laterally discontinuous, showing a high content of Al and Fe oxides, which is accompanied by a distinct increased in the MS values ranging 60 to 130×10^{-5} SI (see Fig. 3a). Moreover, this unit is characterized by very low TOC values (ranging from 0.1 to 0.3%), with seldom high peaks, coinciding with finer grain sizes and reduced sorting. Elemental analysis shows significant elevated levels (in cps) of Fe and Al, with Si as the predominant element (most probably related to the presence of quartz grains) and a low range in Ca counts.

SF-C is characterized by brown fine silt clay and represents the most laterally extensive facies within the studied cores, occurring in AY-H1, H4, H5, H6, H7, H8, H9, H12, H13, H16, H18, H19, H20, H21, and H22 (see Figs. 3a, 3b, and 3c as well as in [supplementary material S1, S2, and S3](#)). The sediment is fine-grained and generally massive, with minor textural variability. MS values show a wide range from 40 to 400×10^{-5} SI, spanning moderate to very high values. TOC contents are moderate to high, ranging between 0.8 and 2.7 wt%. Elemental composition is dominated by Si, P, and Fe.

SF-D consists of reddish coarse silt with a loamy texture and was identified only in core AY-H9 (see Fig. 3c). The sediment is relatively compact, with a coarser grain size compared to other fine-grained facies. MS values range from 40 to 140×10^{-5} SI, while TOC contents are low

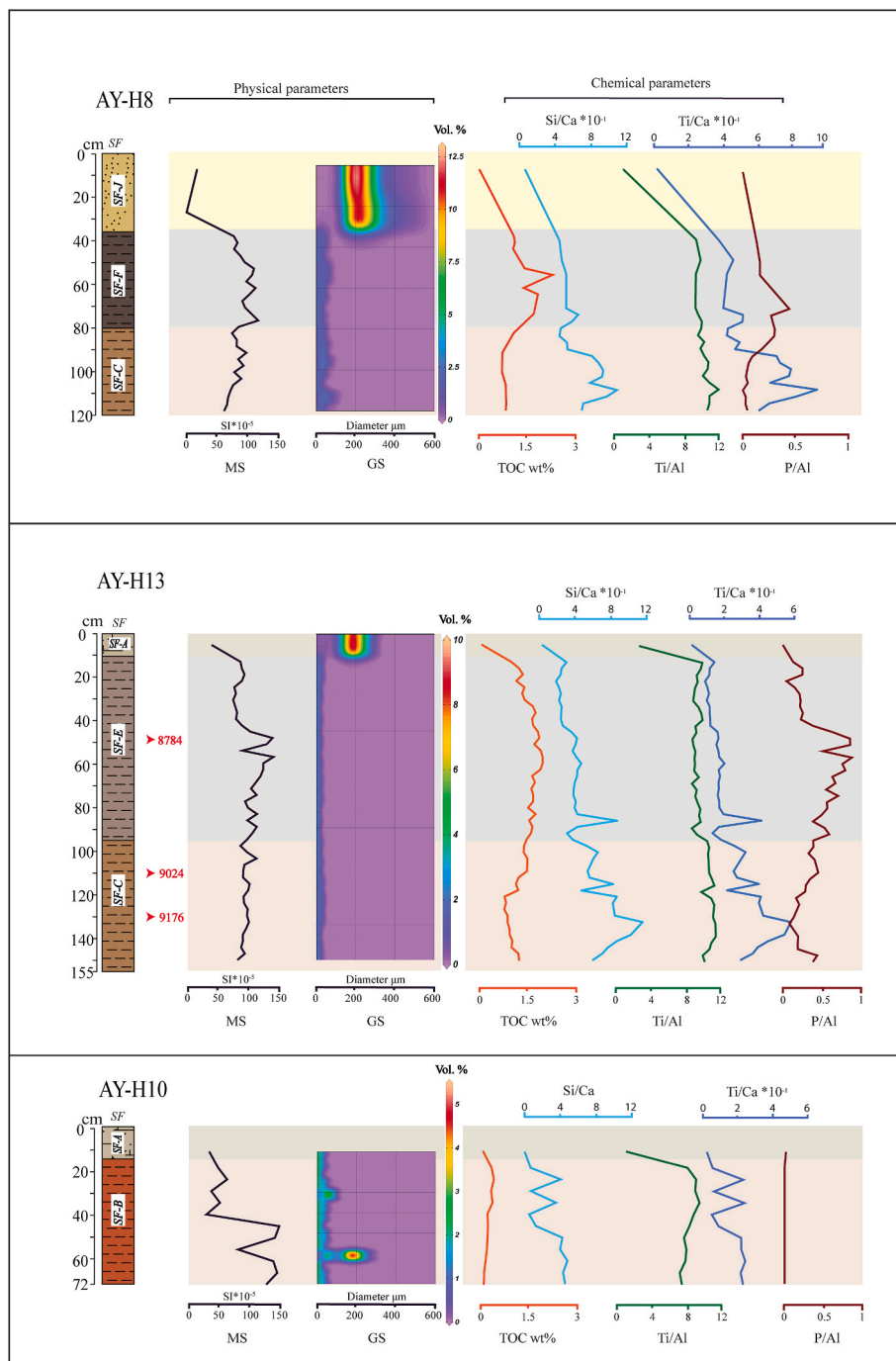


Fig. 3a. Analytical results of core AY-H8, H13, H10.

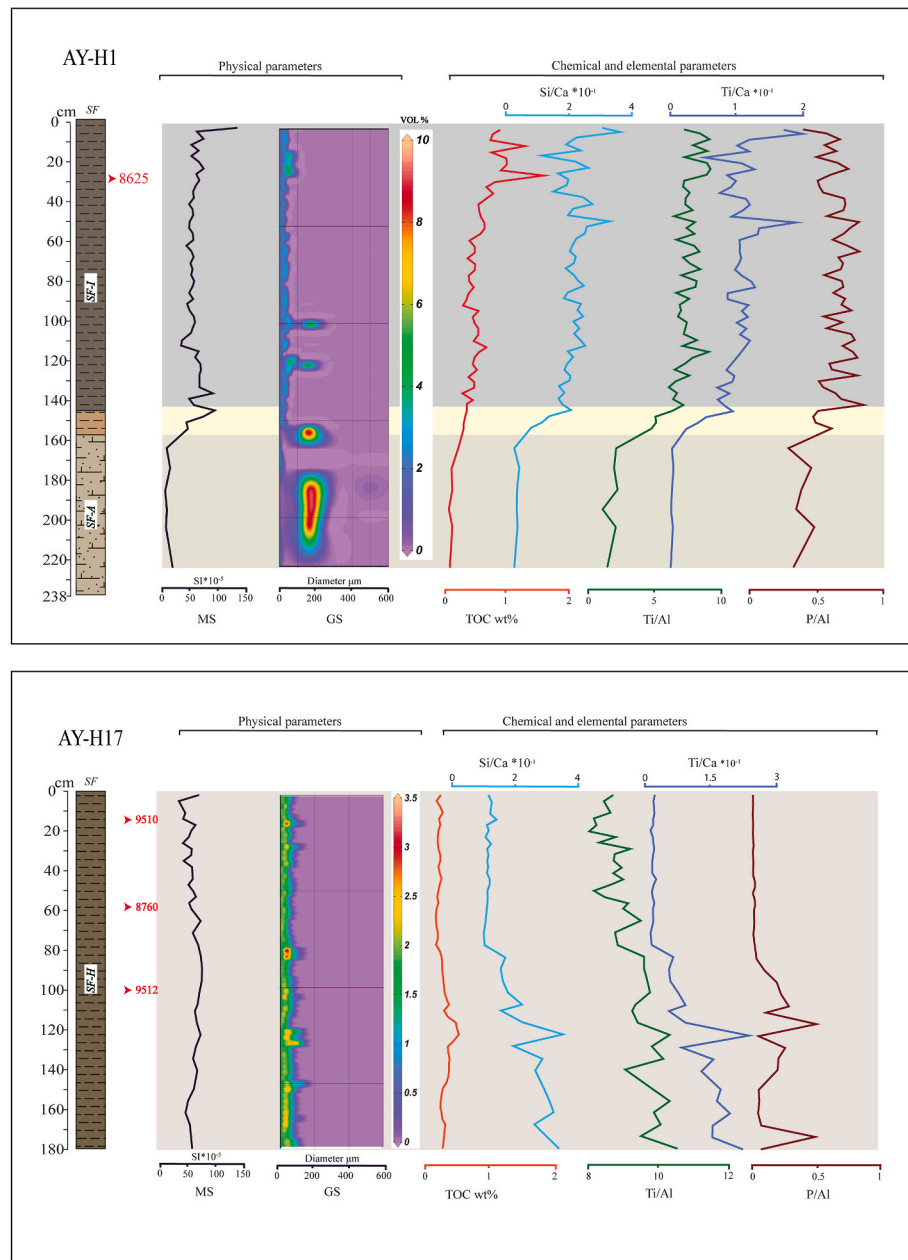


Fig. 3b. Analytical results of core AY-H1 and H17.

(0.1–0.3 wt%). The elemental composition is mainly characterized by Si and P.

SF-E is composed of very fine grayish clay and occurs exclusively in core AY-H13 (see Fig. 3a). The sediment is fine-textured and uniform. MS values are moderate, ranging between 50 and 130 $\times 10^{-5}$ SI, whereas TOC contents are relatively high (1.2 to 1.8 wt%). Major elements identified in this unit include Si, P, Cl, and Fe.

SF-F consists of fine dark brown silty clay and was identified in core AY-H8. The sediment is fine-grained and massive, with a dark coloration. MS values range between 80 and 120 $\times 10^{-5}$ SI. TOC contents vary from moderate to high (ranging between 0.5 and 2.2 wt%). The dominant elements in this unit are Si, P, S, and Ti.

SF-G is characterized by coarse dark brown silty clay with a loamy texture and occurs in core AY-H21 (see Fig. 3c). The sediment displays a relatively coarse fine-grained texture compared to other clay-rich facies. MS values are very low, ranging from 5 to 10 $\times 10^{-5}$ SI. TOC values are moderate to high (0.6 to 2.2 wt%). Elemental composition is dominated

by Si, S, Ca, and Cl.

SF-H consists of fine-to moderate-grained silty clay, displaying distinct green laminations and was identified in core AY-H17 (see Fig. 3a). MS values range from 40 to 70 $\times 10^{-5}$ SI, while TOC contents are low (0.3 to 0.5 wt%). Major elements include Si, Ca, and Fe.

SF-I is composed of fine dark-gray silty clay and occurs in core AY-H1 (see Fig. 3b). The sediment is fine-grained and homogeneous in appearance. MS values range 50 to 130 $\times 10^{-5}$ SI, and TOC contents are moderate to high (0.4–1.45 wt%). The dominant elements are Si, Al, and P.

SF-J is mainly characterized by unconsolidated sand. MS is extremely low, typically ranging from 1 to 5 $\times 10^{-5}$ SI units. TOC content is very minimal, typically ranging between 0.01 and 0.1%. Elemental analysis indicates predominance of Si, with secondary Ca counts, and very minimal counts of Al, Fe, and Mg. The facies granulometric values is dominant by sand (Fig. 3a).

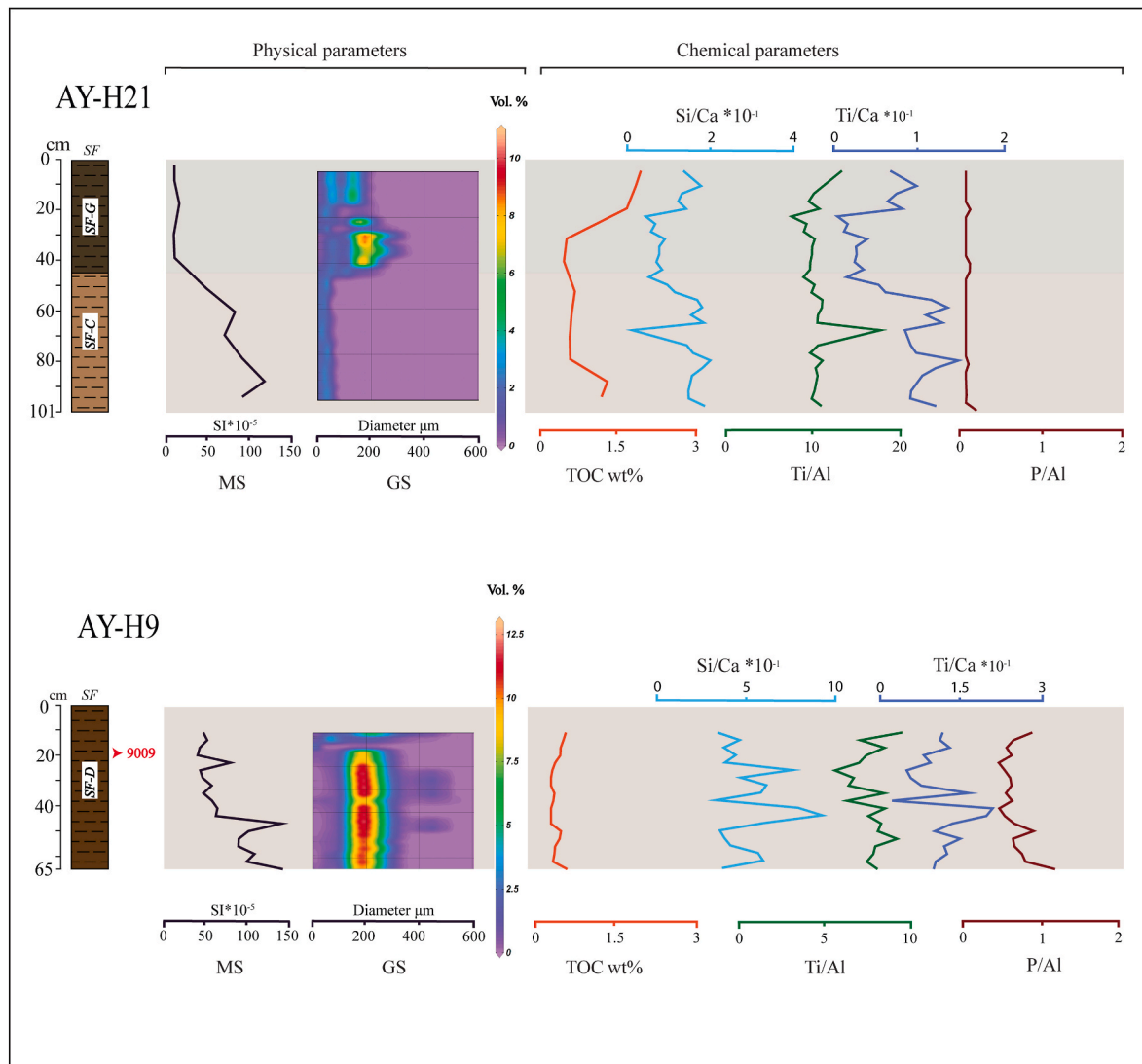


Fig. 3c. Analytical results of core AY-H21 and H9.

4.2. Stratigraphy

The sedimentary succession recovered from the Atlit-Yam area comprises a vertically stacked sequence of distinct sedimentary facies identified across 18 sediment cores (Figs. 3a, 3b, 3c, 4a, 4b, 4c, and 4d). Core lengths range from ~60 to 240 cm and exhibit variable recovery, particularly within fine-grained intervals. Throughout the study area, the uppermost stratigraphic unit consists of unconsolidated sand (SF-J) forming a laterally continuous cover, with its base defining a clear stratigraphic boundary overlying finer-grained deposits dominated by silty-clay facies (SF-C to SF-I) that consolidate units with variable thicknesses. The lateral continuity is mainly characterized by changes in color, grain size, magnetic susceptibility, total organic carbon, and elemental composition. Internal contacts within the fine-grained interval are commonly sharp to gradational. A reddish-brown loamy unit (SF-B) occurs discontinuously within the stratigraphic succession and is restricted to the western part of the study area, where it directly overlies the basal unit. The lowermost unit, where recovered, is composed of consolidated calcareous sandstone (SF-A) identified at the base of selected cores. The defined sedimentary facies enable a reconstruction of a reliable stratigraphy, which, when constrained by radiocarbon chronology (Table 2), provide the framework for understanding their spatial distribution and investigating their temporal variability.

4.3. Chronological framework

The radiocarbon dates were recovered from eight sediment cores (AY-H1, AY-H4, AY-H7, AY-H9, AY-H12, AY-H13, AY-H16, and AY-H17) at different depths ranging 15 and 130 cm below the cores top (see Table 2). The dated samples were obtained within the fine-grained sedimentary facies units (SF-C to SF-I), providing a chronological framework for the stratigraphy described herein. In summary, the calibrated radiocarbon ages for the SF-C to SF-I sedimentary package range between ~9600 and 8600 cal BP.

5. Discussion

5.1. Chronostratigraphy and landscape evolution of Atlit-Yam

The stratigraphy identified here for the Atlit-Yam site captures a time capsule in the evolution of the Carmel coastal landscape, which was driven by post-glacial sea-level rise and diverse sedimentary processes, which in turn influenced the coastal morphography. Overall, our results are consistent with existing regional stratigraphic frameworks (e.g., Galili and Inbar, 1987; Sivan and Porat, 2004; Kadosh et al., 2004; Galili et al., 2020), yet it provides a higher resolution chronological control of the Atlit-Yam archaeological site. The radiocarbon chronology indicates

that deposition of the fine-grained SF-C to SF-I succession occurred between approximately 9600 and 8600 cal. BP, during a period of rapid Early Holocene relative sea-level rise (see Figs. 4a, 4b, 4c, and 4da to d & Fig. 5). The age-depth relationships generally support the proposed stratigraphic framework, although the age from 15 cm depth in core AY-H17 is interpreted as a probable outlier. Together, the chronology constrains the timing of sediment accumulation and environmental changes preceding marine inundation.

The oldest sedimentary unit in our study area – **SF-A** – represents a cemented calcareous sandstone, locally known as *Kurkar*, with its western ridges at the Carmel coast dated to the Pleistocene (>80,000; see Sivan and Porat, 2004; Mauz et al., 2013; Shtienberg et al., 2020, 2022). In this study, **SF-A** appears only in two cores (AY-H1 and AY-H14). However, **SF-A** appears as well in the uppermost parts of two cores (AY-H13 and AY-H10), which we interpret to represent secondary deposition of loose calcareous sandstone rocks that were detached and occasionally are found on the seabed (Bar et al., 2022). Previous studies at the Carmel coast reported that in some areas, a red loamy paleosol unit (**SF-B**, locally known as *Hamra*) overlies the basal calcareous

sandstone bedrock (**SF-A**) and was dated between 80,000 and 30,000 BP (see Kadosh et al., 2004; Mauz et al., 2013; Sivan and Porat 2004; Ronen, 2018). In our case, this unit was identified only at the western part of the site (in cores AY-H10 and AY-H20). However, a significant shift is recorded in **SF-C** to **SF-I**, associated with the deposition of silty-clay sediments (see Figs. 4a, 4b, 4c, and 4da to d).

When comparing our investigation based on the cores obtained in Atlit-Yam, with previous studies (Adler, 1985), we recognize an increase in the thickness of **SF-C** to **SF-I** sedimentary package. We interpret this to be the result of an irregular and confined morphological setting that constrain the depositional system, which in parallel was locally inhabited by humans. This interval ends with deposition of **SF-J**, a sand-dominated facies representing high-energy coastal or nearshore deposition in a rising sea level that inundated the lower landscape. Since the **SF-J** facies consists of unconsolidated sand, it remains mobile and therefore cannot provide a reliable contextual upper age boundary for the end of the **SF-C** to **SF-I** succession. Yet, considering our chronology and correlation with previous studies (Galili et al., 2020), we speculate that the **SF-J** unit started to cover the Atlit-Yam site around the end of

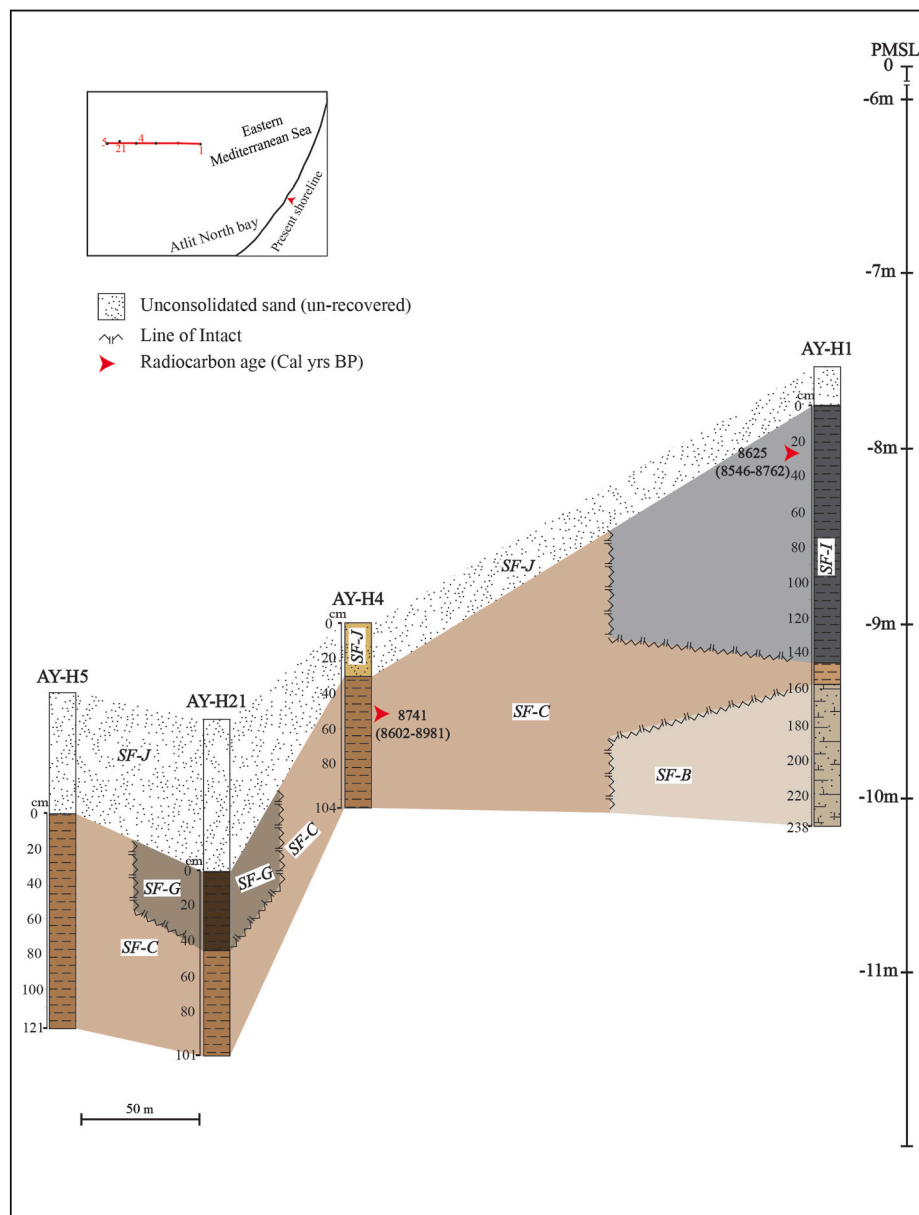


Fig. 4a. Stratigraphic correlation from east to west transect 1 (core AY-H1, H4, H21, H5).

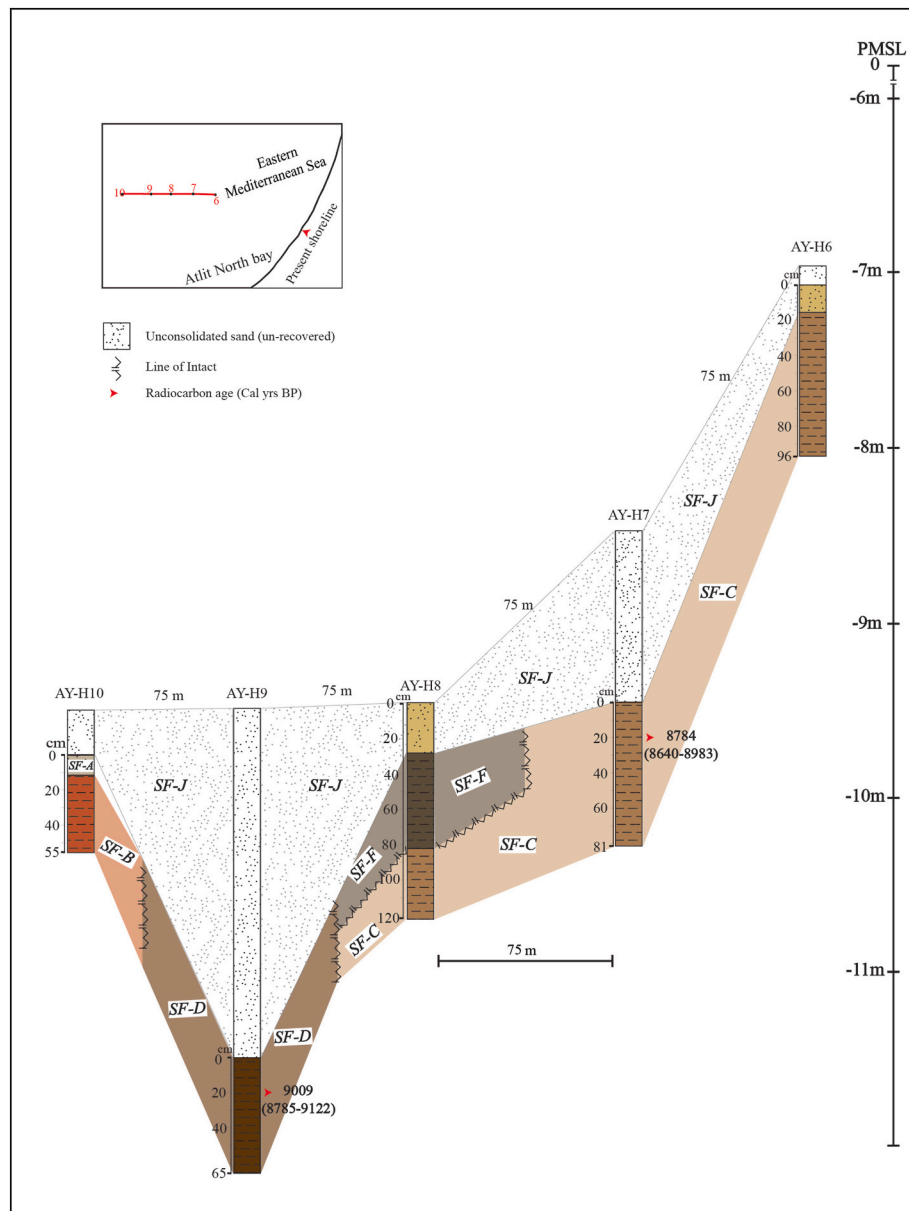


Fig. 4b. Stratigraphic correlation from east to west transect 2 (core AY-H6, H7, H8, H9, H10).

the 9th millennium, or beginning of the 8th millennium BP (see Fig. 5).

5.2. Landscape reconstruction

The high-resolution scientific work carried out in this study provides an exceptional opportunity for studying the evolution of a coastal setting in light of sea-level rise, both in space and time. This is highly pivotal for understanding the response of the coastal Neolithic settlements to continuous Holocene rising sea level and associated changing coastal morphology. The facies assemblages identified at the Atlit-Yam site, which likely represent the broader Carmel coastal system, can be categorized into distinct sedimentary facies (*SF-A to SF-J*; see Figs. 4a, 4b, 4c, and 4d a to d). Please see Table 3 for a summary of the sedimentary facies while a detailed discussion of each facies is provided in Supplementary Text S1.

5.3. Geomorphological evolutionary model for Atlit-Yam

The current high-definition study of the sedimentary facies and

associated interpretation enables the reconstruction of an evolutive model for the Atlit-Yam site and its immediate landscape. Four major stages characterize the region (Fig. 6):

Stage 1 (Late Pleistocene – > 20,000 BP): Prior to the occupation by Neolithic people, the area was characterized by the *Kurkar* ridges (*SF-A*), which were developed parallel to a currently submerged coastline. In the troughs between the *Kurkar* ridges tops, red loamy paleosols (*SF-B*) of changing thicknesses were developed (Mauz et al., 2013; Sivan and Porat 2004; Farrand and Ronen, 1974).

Stage 2 (Terminal Pleistocene to Early Holocene – ~20,000 to 8200 cal. BP): During this interval, the Carmel coastline underwent significant geomorphological changes. Sea levels at ca. 10,000 BP are estimated between 25 and 35 m below PMSL, with the shoreline located ca. 2.5 km westwards to the current position (Sivan et al., 2004a,b; Galili et al., 2019) (Fig. 5). Archaeological finds from the site were dated between 9400 and 8200 cal. BP (Galili et al., 2020), with sea level at that interval estimated to stand between 16 m and 20 m below PMSL and the coastline distanced about 1.5 km

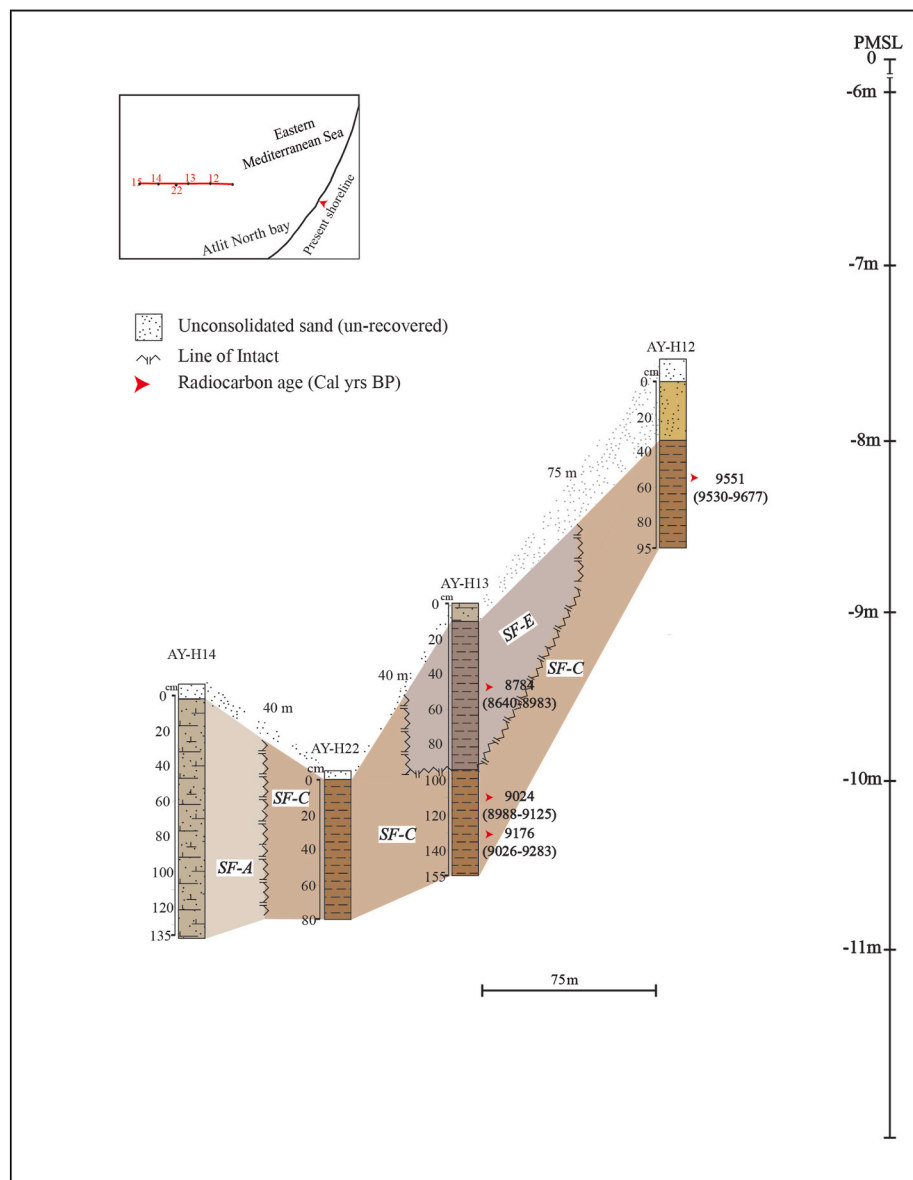


Fig. 4c. Stratigraphic correlation from east to west transect 3 (core AY-H12, H13, H22, H14).

westwards from present day shore (Sivan et al., 2004a,b; Galili et al., 2019; Fig. 5). It appears that stage 2 culminates with a drastic change in the climatic conditions in the whole region, with increase in cooling coupled by augmentation in the precipitation regime (Bar-Matthews et al., 1999; Migowski et al., 2006), which majorly contributed to the changing environmental conditions along the Carmel coast. Whether the apparent termination of anthropogenic activity at the site reflects settlement abandonment in response to these environmental changes, or alternatively a partial loss or masking of the uppermost archaeological sedimentary facies due to erosion and/or continued marine transgression, cannot be conclusively resolved with the available data. Both processes may have contributed to the observed stratigraphic pattern and are therefore considered plausible explanations.

Stage 3 (8200 cal. BP until present): After the abandonment of the site, at ~8200 cal. BP, the continuous sea-level rise, attaining ca. 10–12 m below PMSL by ~8000 cal. BP, was accompanied by an eastward shift of the coastline, inundating the *Kurkar* ridge and depositing sand (SF-J) over the site. Due to the mobile characteristics of SF-J, we cannot determine if the initial deposition of the facies was

aeolian-driven (then it predated the marine inundation), or whether the sea-level rise was rapid enough to submerge the site and the sand was provided by the marine currents (Fig. 5). According to Galili et al. (2020), the main phase of occupation of the site occurred 9402 to 8200 cal. BP. However, the stratigraphic relationship documented in this study provides new sedimentological evidence that the site abandonment likely occurred at 8200 cal. BP, preceded the full marine inundation at ~8000 cal. BP. Therefore, our findings suggest a potential temporal decoupling between human abandonment and physical submergence of the site, indicating that abandonment may have been influenced by progressive environmental deterioration prior to inundation, rather than by a direct marine flooding.

5.4. Interrelation and dynamics between sea-level rise and Neolithic settlements

During the early Holocene, eustatic sea-level rise, driven by post-glacial ice melt, profoundly influenced the geomorphological and hydrogeological evolution of coastal plains (Lambeck et al., 2014;

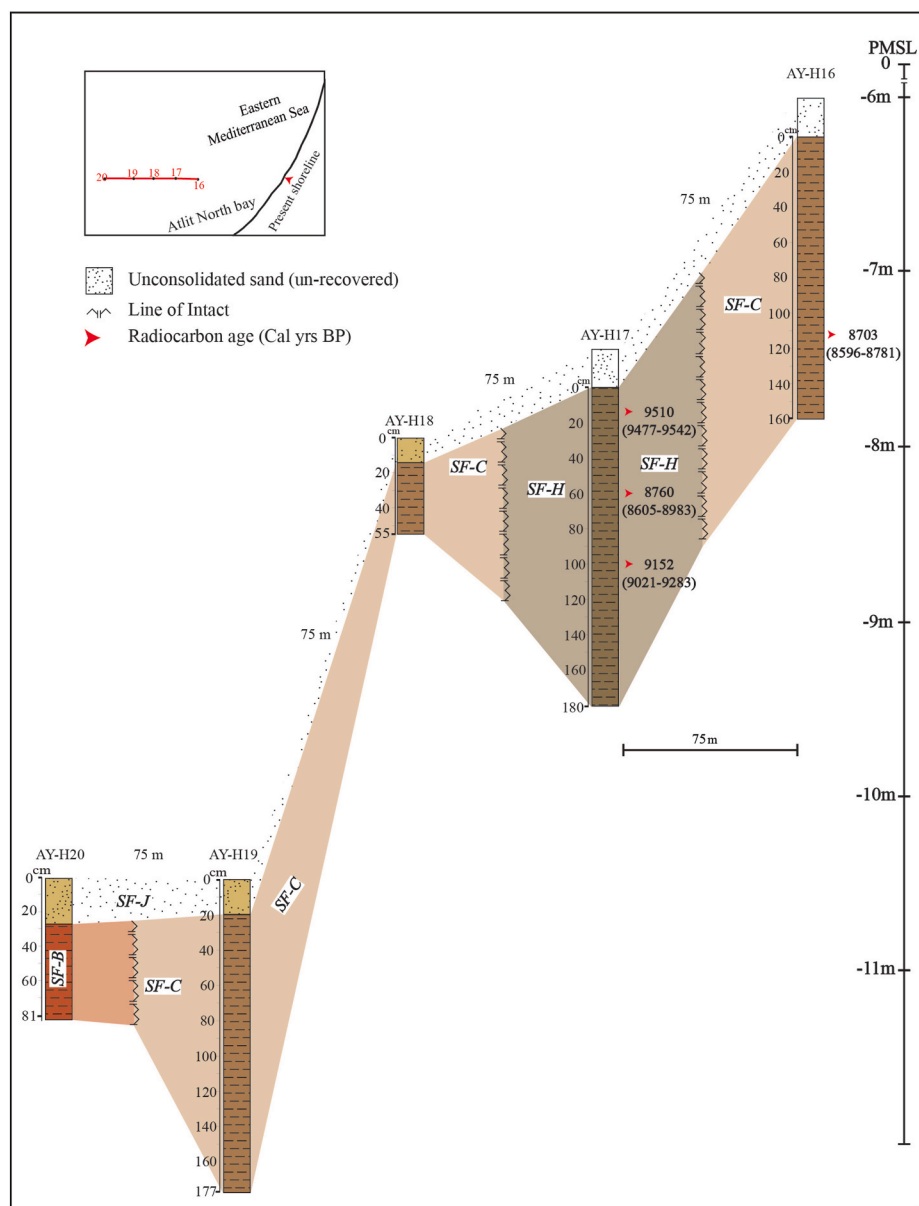


Fig. 4d. Stratigraphic correlation from east to west transect 4 (core AY-H16, H17, H18, H19, H20).

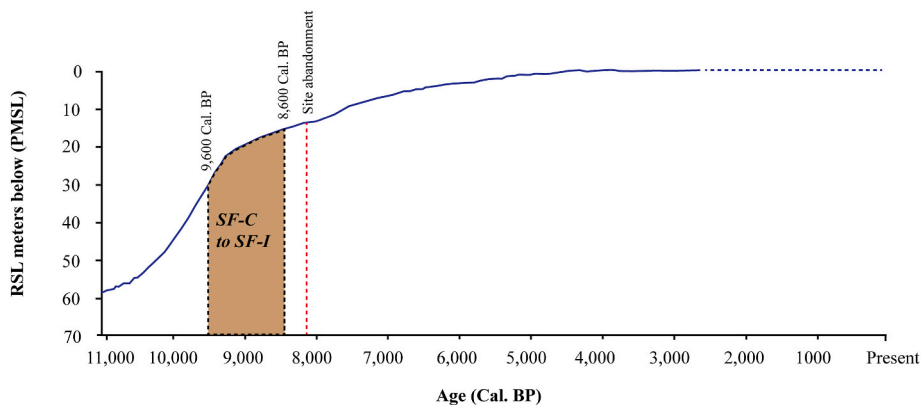


Fig. 5. Relative sea-level (RSL) rise along the Carmel coast and the timing of sediment accumulation at Atlit-Yam. The RSL curve is modified after Sivan et al. (2004a, b) Lambeck et al., 2014, Vacchi et al., 2016, and Galili et al., 2020. The shaded interval (~9600-8600 cal BP) denotes the period during which the fine-grained sedimentary succession (SF-C–SF-I) accumulated, based on the radiocarbon chronology established in this study.

Table 3

Summary of the sedimentary facies (SF-A to SF-J) identified in the Atlit-Yam sediment cores, including their principal sediment type, distinguishing lithological characteristics, and spatial occurrence within the study area. Detailed sedimentological descriptions and analytical characteristics of each facies are provided in [Supplementary Text S1](#).

Sedimentary facies	Sediment type	Distinguishing characteristics	Spatial occurrence
SF-A	Calcareous sandstone (Kurkar)	Lithified quartz-rich coastal sandstone	Basal unit in multiple cores
SF-B	Red sandy loam	Fe-rich sandy-silty loam developed on Kurkar	Confined to the western part of the area above SF-A
SF-C	Brown silty clay	Fine-grained terrestrial deposit containing archaeological remains and organic matter	Widespread within the Early Holocene fine-grained succession
SF-D	Brown-red sandy loam	Sand-rich deposit with archaeological micro-remains	Present only in core AY-H9, from the deepest part of the topography
SF-E	Silty Clay/mud	Clay-rich, organic-rich deposit	Restricted to the upper part of core AY-H13
SF-F	Dark brown clay	Organic-rich fine-grained deposit	Occurs only to core AY-H8
SF-G	Dark brown sandy loam	Loamy deposit with archaeological micro-remains	Only described in core AY-H21
SF-H	Laminated silty clay	Fine-grained laminated deposit with limited organic preservation	Only identified in the core AY-H17
SF-I	Dark gray silty clay	Fine-grained organic-bearing sediment outside the archaeological site	Only identified in core AY-H1
SF-J	Marine/Coastal sand	Well-rounded quartz sand representing the upper sand cover	Uppermost unit across the study area

[Vacchi et al., 2016](#)). This period was marked by the progressive inundation of low-lying coastal areas, a concurrent rise in groundwater levels, reorganization of fluvial systems, and increased salinization of coastal aquifers, all of which significantly altered regional habitability ([Stanley and Warne, 1994](#); [Lambeck et al., 2014](#); [Vacchi et al., 2016](#)). The stratigraphic succession at Atlit-Yam should therefore be viewed within the broader context of the Late Pleistocene - Early Holocene marine transgression, during which shoreline position, accommodation space, and coastal hydrodynamics changed substantially through time ([Sivan et al., 2011](#); [Greenbaum et al., 2010](#)). Although the Levant margin has been influenced by tectonic processes over geological timescales, the present study does not allow the independent assessment of possible tectonic or isostatic contributions to the submergence of Atlit-Yam, and our interpretations are therefore primarily framed within the context of relative sea-level rise. Our study provides stratigraphic and geochemical evidence indicating a marked increase in anthropogenic sediment accumulation between approximately 9600 and 8600 cal. BP, predating human settlement at the coast and suggesting intensified human occupation and land-use activity during this interval, possibly continuing until 8200 cal. BP ([Galili et al., 2020](#)). The Atlit-Yam settlement appears to have been strategically positioned on silty-clay deposits (SF-C to SF-I) overlying the local calcareous sandstone ridge,

which may have provided a relatively stable and resource-rich land conducive to Neolithic lifeways ([Galili et al., 2020](#)). However, continued sea-level rise and associated environmental stressors, such as increased influx of sand from the marine environment and further salinization of water wells, likely exceeded and challenged the adaptive capacity of the community. These stressors likely interacted with shorter-term climate variability, including the widely documented 8200 cal. BP event, which may have influenced regional hydroclimate, freshwater availability, and coastal wetland stability during the later stages of occupation and/or abandonment.

The 8200 cal. BP event has been associated with abrupt cooling in the North Atlantic, and hydrological reorganization across Europe ([Rohling and Pälike, 2005](#); [Weninger et al., 2006](#)) affecting both coastal lowlands and inland regions in the eastern Mediterranean. Comparable disruptions in settlement continuity and environmental conditions around this interval have been reported from coastal plains in western Europe, estuarine systems of the North Sea basin, and wetland-dominated landscapes in the Levant, suggesting that short-lived climatic perturbations may have amplified the impacts of ongoing sea-level rise ([Rohling et al., 2019](#)).

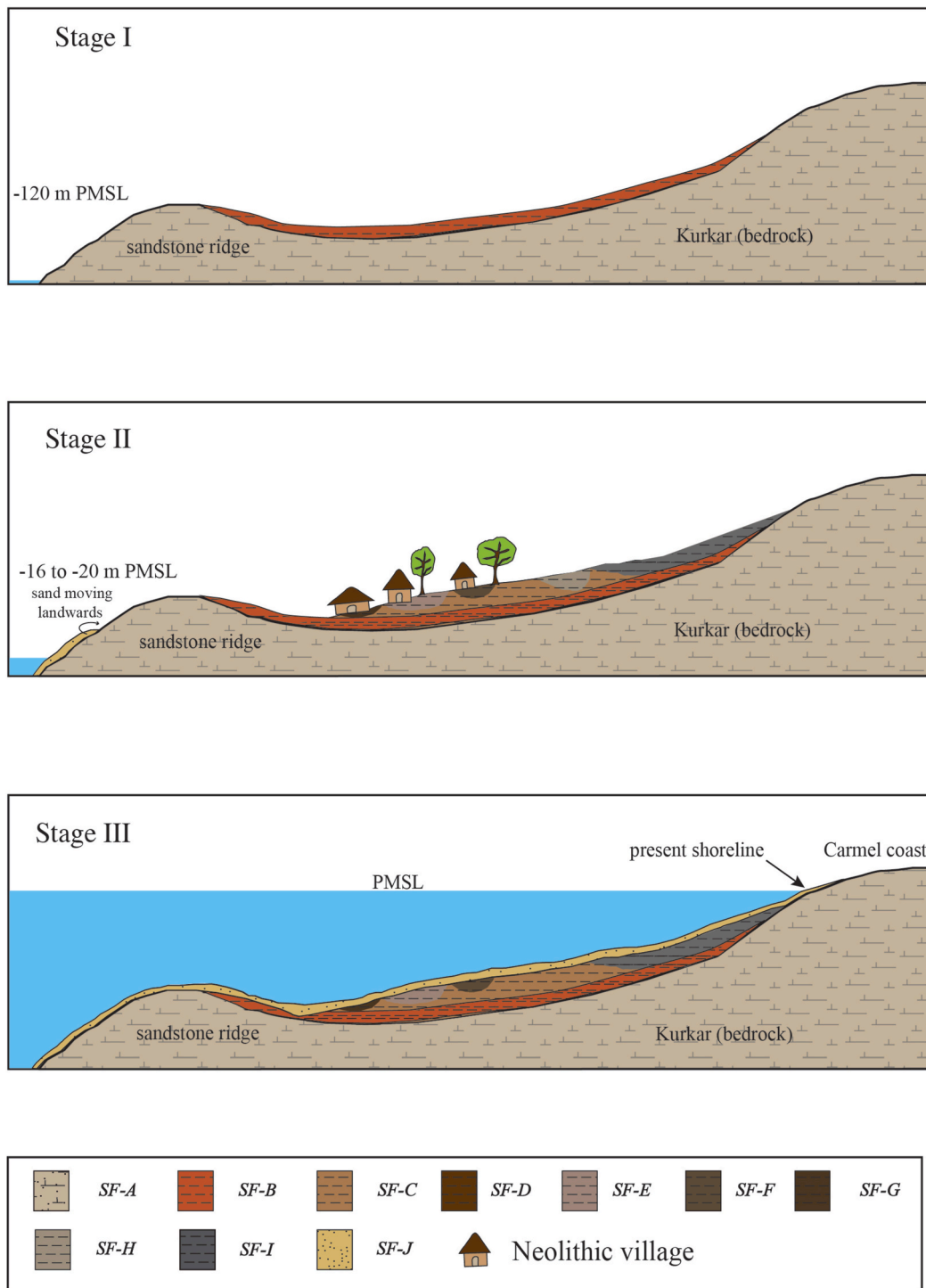
Accordingly, the observed anthropogenic signals are interpreted as superimposed on a dynamically changing coastal system, rather than being the sole driver of stratigraphic variability. This is reflected in the attempts to cope with the salinization of water wells at Atlit-Yam, eventual abandonment of the site towards the end of the 9th millennium BP, and later construction of a coastal defensive sea-wall in the Pottery Neolithic site of Tel Hreiz ([Galili et al., 2019](#)).

In this broader perspective, Atlit-Yam represents a well-constrained example of how an early coastal community responded to the combined effects of long-term marine transgression and short-term climatic perturbations. The spatial and temporal patterns of occupation and abandonment underscore the vulnerability of early sedentary societies to dynamic sedimentary environments such as coastal settings, and highlight the complex interplay between sea level, sedimentary processes, and human resilience in the face of climatic and hydrological transformation.

6. Conclusions

This study presents a high-resolution, multi-proxy reconstruction of early Holocene coastal dynamics along the Carmel coastal plain, focusing on the submerged Neolithic site of Atlit-Yam within the context of post-glacial sea-level rise and associated coastal transformation prior to complete marine inundation. Integrated sedimentological, geochemical, stratigraphic, and chronological analyses of multiple cores reveal the presence of anthropogenic facies with elevated TOC, MS, and P/Al, dated to ~9600–8600 cal. BP, reflecting intensified Neolithic activity, fire use, and localized land management. These anthropogenic signals are superimposed on background terrestrial and low-energy coastal sedimentation processes, indicating sustained human presence within a dynamically evolving landscape rather than episodic or short-lived occupation.

Fine-grained, organic-rich sediments from this interval indicate deposition in a coastal environment influenced by sea-level rise, which initially supported settlement but were ultimately destabilized by progressive transgression, salinization of the coastal aquifer, coupled by sand invasion, leading to site abandonment. The stratigraphic relationship between anthropogenic silty-clay deposits and the overlying high-



The figure is schematic and not to scale

Fig. 6. Landscape evolution model for Atlit-Yam with three stages of sea level rise in different time period.

energy sand unit demonstrates that abandonment occurred prior to the final marine submergence, implying environmental deterioration rather than abrupt flooding as the primary driver of settlement cessation. This study provides direct stratigraphic and chronological evidence for Neolithic occupation between ~9600 and 8600 cal. BP within sediments that predate complete marine inundation.

These findings refine our understandings of early Holocene coastal change, highlight the resilience and vulnerability of Neolithic communities occupying dynamic coastal zones, and provide a framework for

interpreting submerged archaeological sites elsewhere. The identification of anthropogenic facies within the silty-clay unit (*SF-C* to *SF-I*) demonstrates that human activity and landscape modification occurred contemporaneously with early Holocene sea-level rise. Our findings provide a rare anatomic insight into human-environment interactions immediately prior and during a natural catastrophic event (in this case, marine inundation and coastal submergence). Therefore, we provide critical empirical evidence for how early sedentary societies responded to the combined effects of long-term sea-level rise and shorter-term

climatic and hydrological stressors, with broader implications for coastal heritage preservation under ongoing and future sea-level rise.

CRedit authorship contribution statement

Vishal Kataria: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gilad Shtienberg:** Writing – review & editing, Visualization, Investigation, Data curation. **Isaac Ogloblin Ramirez:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Roni Zuckerman-Cooper:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Formal analysis. **Nimer Taha:** Resources, Methodology, Investigation, Formal analysis. **Elle Grono:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis. **Marko Runjajić:** Writing – review & editing, Software, Data curation. **Ehud Galili:** Writing – review & editing, Visualization, Validation. **Nicolas Waldmann:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **David E. Friesem:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quaint.2026.110434>.

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