Marine geoarchaeological survey in the Vathy bay of Astypalea island, south Aegean Sea. 

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Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and do not compromise in any way the rights of third parties, including those relating to the security of personal data.

Alexandra Noti

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* This dissertation is presented in partial fulfillment of the requirements for Ph.D. degree in the Graduate School of Natural Sciences of the University of Patras.
Στην αγαπημένη μου οικογένεια.

Dedicated to my loving family.
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Marine Geoarchaeological survey in the Vathy bay of Astypalea island, South Aegean Sea.

Alexandra Noti

Abstract

Coastal restricted basins serve as invaluable repositories of information concerning global sea level changes and regional climate shifts, offering crucial insights into paleogeographic, paleoenvironmental and paleoclimatic conditions. This study employs a multi-faceted approach, integrating geophysical, visual, sedimentological, and geochemical data, to meticulously reconstruct the paleogeography, paleoenvironment, and paleoclimate of Vathy bay, in the South Aegean Sea. Examining a submerged archaeological site near cape Elliniko, the study utilizes dense radiocarbon analyses, providing accurate dating of ancient constructions and human activities.

The research delineates three major environmental stages during the Holocene, identified as seismic facies (SF1-3) and lithological units (LU I-III). These stages highlight the basin's gradual transition from isolated to shallow marine conditions over the last 9.1 thousand years. Notably, the study pinpoints the onset of marine influence around 7.3 thousand years ago, coinciding with a global mean sea level of approximately -8 meters. Analysis further reveals arid periods between 7.3–6 and 4.1 thousand years ago, leading to Sr-rich carbonate precipitation in the basin and a general trend of aridification. Conversely, wetter conditions prevailed during the intervals of 9.1–7.3 and 6–5.4 thousand years ago.

Additionally, geochemical proxies, particularly ASTC1 records, provide high-resolution climate reconstructions for the last 8.7 thousand years, aligning with aridity cycles identified in various Northern Hemisphere records. These findings demonstrate a correlation between mid-Holocene aridity events and the southern migration of the Intertropical Convergence Zone (ITCZ), followed by a retreat of monsoonal rains by the end of the African Humid Period (AHP). Short-term fluctuations in Ti/Al and Zr/Si ratios indicate transient cycles of enhanced terrigenous supply, correlating with Holocene "Rapid Climate Change" events (RCCs). Importantly, the study's spectral analysis identifies cyclical patterns of dry/cold climatic conditions with periodicities at 2500, 1200, and 525 years, corresponding with Hallstatt and Bond cycles, reflecting drier conditions and heightened dust input.

The marine geoarchaeological research unveils submerged ancient structures, including linear constructions, conical rubble structures, and submerged walls, indicating potential harbor installations and navigational landmarks. These findings underline the intricate relationship between sea level changes, climate variability, sedimentation, and human activities, emphasizing the interconnectedness of climate systems across different regions and time scales. This study not only sheds light on the complex Holocene climate dynamics in the Eastern Mediterranean but also elucidates early human interactions with the coastal environment, providing crucial historical context for the region.
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1. Introduction

Since the Paleolithic era, the eastern Mediterranean (EM) region has been a landmark in human population migration passages from Africa and their expansion to Europe (e.g., Oppenheimer, 2009). Later, as navigational skills advanced, it became a maritime crossroads and appointed great civilizations that relied on the exploitation of marine resources (e.g., Brennan et al., 2012). The exploration of new environmental conditions and resources and the discovery of improved climatic conditions have been suggested as causes of early human migrations (e.g., Müller et al., 2011). In addition, the preference for living in coastal locations is attributed to greater biodiversity, mild climatic conditions, highly productive conditions for flora and fauna, availability of marine resources, and navigability (SPLASHCOS).

Changes in sea level, both eustatic and isostatic, as well as local tectonics, have all had significant impact on coastal geography over time. The rise in temperature after the Last Glacial Maximum (LGM) and during the last Interglacial, caused sea level rise and drowned ancient coastal settlement sites, burying crucial knowledge about human civilization and evolution (Bailey and Flemming, 2008). In recent years, technological advancements in marine remote sensing combined with the ability to locate and map the submerged coastal zone, as well as the discovery of well-preserved underwater archaeological finds, have increased scientists' interest in locating and studying submerged coastal sites of archaeological interest. Underwater archeological sites are highly valued in the humanities and geological sciences as they can yield long-term records concerning both the evolution of human and his civilization as well as changes in environmental conditions (SPLASHCOS). Because of their significance, they have piqued the interest of national, European and global organizations that aim to their investigation and management (UNESCO, ICOMOS, Valletta Treaty).

Depending on the local topography, geology, and hydrodynamics, the post last glacial marine transgression resulted in the formation of a dynamic range of successive environments ranging from lowlands to lagoons and shallow bays, as well as deeper shelf settings (Benjamin et al., 2017; Brunović et al., 2020; Flemming et al., 2017). The development of shallow marine habitats, such as lagoons and semi-enclosed bays, was driven by topographic configuration
(including sill depths), sediment, freshwater, and organic supply. These resulted in a succession of abiotic (lithology, (Emmanouilidis et al., 2020; Vött, 2007)) organic and inorganic chemistry and minerals (Brunović et al., 2020; Vött, 2007), oceanography (Rohling et al., 2015; Sergiou et al., 2022), and biotic (faunal (Haghani et al., 2016; Triantaphyllou et al., 2014) and floral (Koutsodendris et al., 2015)) conditions. Sediments deposited in favorable sites can store informative proxies regarding the variation of the above-mentioned parameters and serve as archives for predicting the evolution of the environment, the climate, and the relative sea level changes of the examined area over time (Lambeck & Purcell, 2005).

Valuable and accurate information about climate and environmental changes over time, such as the investigation of the drought episodes frequency, can be inferred through the study of the sediment record. Sediments, whether found in lakes, rivers, oceans, or glaciers, accumulate over time and trap various materials and particles, including organic matter, minerals, and microorganisms. Within the marine realm, such information can be greatly archived either in the sediments of deep basins or in restricted marginal environments such as semi-enclosed basins (Aleman et al., 2014). This type of environments are usually connected to the open sea through narrow straits, governed by a barrier (sill) which act as controlling mechanism for allowing or preventing water inflow during the various eustatic cycles, transforming them into either restricted marine basins or to isolated water/land bodies accordingly (Aleman et al., 2014; Hoyle et al., 2021) (Figure 1). Analyzing these sediments through methods applied in paleoceanography and palaeoclimatology allows scientists to reconstruct past climate conditions and understand the background triggering mechanisms through cross-correlation of the various climatic records. This understanding is essential for accurate climate modeling, forecasting future climatic scenarios to develop effective climate mitigation and adaptation measures (IPCC, 2023), and adds to a better understanding of cultural heritage.
Figure 1. Holocene sedimentary filling of the Arguin Basin. Depths are given according to the modern sea level (Aleman et al., 2014).

The Aegean Archipelago, with millennia of human history, at the crossroads of three continents, acting as an interplay between the northern and southern climate systems, it is a highly important region for the investigation of changes in climate and the ancient world (Brennan et al., 2012; Finné et al., 2011). In addition, the geomorphological configuration of the Aegean islands coastal zone is an outcome of the fluctuations in climate and sea level, transforming the coastal zone over time. The aforementioned reasons highlight that a marine geoarchaeological research in the Aegean region is particularly valuable for shedding light on matters like the migration of prehistoric populations, the selection and construction of coastal infrastructure, and the evolution of coastal geomorphology in response to regional tectonics and climate shifts.

In this thesis, a multi-disciplinary methodological approach that uses marine geophysics, non-acoustic techniques, and sediment core analyses, is implemented in the significant archaeological coastal area of Vathy bay, in Astypalea island, South Aegean Sea (Figure 2).
The methodology followed in this thesis contributed to the paleogeographic, paleoenvironmental, and paleoclimatic reconstruction of the investigated area, as well as the detection of the submerged archaeological site. This interdisciplinary approach enabled to understand the extent of the environmental exploitation by the ancient human societies in this particular location, within the critical period of Holocene, during which ancient human civilizations and advancements developed laying the foundations for modern societies.

**Figure 2.** Map of the Eastern Mediterranean region, the location of the study site, and sediment core ASTC1. The bathymetric data were obtained from GEBCO ([https://download.gebco.net](https://download.gebco.net)) (accessed on 15 January 2021)).

### 1.1. Thesis Objectives

The main objectives of this thesis are:

- The general palaeogeographical, paleoenvironmental, and paleoclimatic reconstruction of Vathy bay over time.
• The detection of the submerged antiquities in the investigated area and to assess the potential for human exploitation of the environment in the past.
• The documentation of landscape successions and link them to sea-level change and direct climate change.
• To address the accurate chronological framework of the various changes through a high-resolution age-depth model.
• To address drivers in common with other records from eastern Mediterranean region and the world.
• To trace cyclical patterns of aridity within the Holocene.

1.2. Marine remote sensing

Coastal zones have been important hubs of human activity since the Paleolithic period. Understanding how coastlines changed over the geological time frame through the reconstruction of their palaeogeographical evolution has provided valuable insights into human-environment interactions, and ancient human cultures and migrations (Bailey & Flemming, 2008). Multidisciplinary studies comprising geoscientists and archaeologists in the Mediterranean region investigate historic harbors as places of well-preserved geoarchaeological records. These studies aim to the understanding of occupation history, human use and exploitation of the Mediterranean environment (Marriner & Morhange, 2007, 2008), the prediction of relative sea level changes involving the tectonic contribution (Flemming, 1996; Blackman, 2005), the response of the deltaic deposits to the coast (Vött, 2007a) in association to the climatic changes (Marriner et al., 2013) and the effects of natural hazards to the coastal zone (Vött, 2007b).

Marine geophysical techniques have been widely used in underwater archaeological studies regarding the detection and investigation of archaeological sites such as ancient shipwrecks (Quinn et al., 2002; Papatheodorou et al., 2005; Sakellariou et al., 2007) due to the ability to investigate and map seabed and subsurface features at high speeds and regardless of water depth or visibility (Dellaporta et al., 2002). Furthermore, they have also been extensively employed in research aimed at reconstructing coastal paleogeography at submerged sites of archaeological importance, primarily by detecting and mapping the preserved palaeo-shorelines and by examining the local stratigraphy and Late Quaternary geology (Van Andel
The underwater remote sensing techniques most commonly applied to reconstruct the topographic relief through time and to detect submerged antiquities employ: (i) single and multi-beam echo-sounders (ii) side scan sonar (acoustic imaging), (iii) laser line scan (optical imaging) (iv) subbottom profiler, (v) marine magnetometer and (vi) undersea vehicles (Figure 3) (Georgiou et al., 2021; Papatheodorou et al., 2011).

1.3. Climate and environmental setting in the Eastern Mediterranean and the Aegean Sea during the Holocene

Important information on patterns of climate variability at regional and global scales in the Mediterranean area has been obtained from a number of paleoclimate studies (Abrantes et al.,
2012; Lionello, 2012). Its semi-enclosed configuration and the relatively short residence time of its water masses make it especially responsive to external forcing. As evidenced by many studies (Krijgsman, 2002; Picotti et al., 2014), it has been regarded as a unique natural laboratory for paleoenvironmental research. Additionally, Durrieu de Madron et al. (2011) and the references therein have designated it as a "hotspot" for global change research.

The Mediterranean region is extremely vulnerable to climatic changes due to its latitudinal position where the southern and northern climate systems intersect (Lionello et al., 2006, Lionello, 2012). The primary teleconnections influencing and regulating the climatic regime of the Eastern Mediterranean are mainly comprised of the North Atlantic Oscillation (NAO), East Atlantic Pattern (EA), the Siberian High-Pressure system, and the African Monsoon system (Barnston and Livezey, 1987) (Figure 4). The NAO, which centers near Iceland and the Azores, is the primary influencing element that, in general, governs the route of the previously stated systems. Because of the strengthening of the Azores high pressure system and the weakening of the Icelandic low, positive (negative) NAO phases provide colder temperatures in the southern Mediterranean and drier (wetter) conditions in the northern Mediterranean.

**Figure 4.** Circulation patterns affecting eastern Mediterranean climate regime with the broader study area highlighted as yellow box. Abbreviations (NAO) and (ITCZ) refer to North Atlantic Oscillation pattern and Intertropical Convergence Zone respectively (Emmanouilidis et al., 2022; Fleitmann et al., 2007; Ivanochko et al., 2005).
(Xoplaki, 2002; Trigo et al., 2006). Wetter periods are generally influenced by the northward movement of the intertropical convergence zone (ITCZ) and the intensification of the Asian monsoon system, which results in Northern Hemisphere summer and winter insolation peaks and minima respectively (Kutzbach et al., 2013; Milner et al., 2012; Toucanne et al., 2015; Stockhecke et al., 2016). Winter precipitation in the eastern Mediterranean can be influenced by both El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), but their impacts can vary depending on several factors, including the strength and phase of the ENSO and NAO events. During El Niño events (warm phase of ENSO), the eastern Mediterranean tends to experience wetter and cooler conditions in winter, while La Niña events (cold phase of ENSO) are associated with drier and warmer conditions. However, the relationship between ENSO and eastern Mediterranean precipitation is not always straightforward and can be modulated by other climate influences.

Special emphasis was placed on paleoclimate reconstruction over the last 20 ka. The Last Glacial Maximum (LGM) has resulted in significant climate and palaeoceanographic restructuring; the most notable of these are the Younger Dryas (YD, 12.9-11.7 ka), the Bölling Allerød (B-A, 14.7-12.9 ka) transition, the Holocene Climatic Optimum (HCO, ~9-5 ka), the 8.2 ka event, the termination of the African Humid Period (AHP, ~5 ka), the 4.2 ka event, the Medieval Climate Anomaly (MCA, ~1.0-0.75 ka), and the most recent Little Ice Age (LIA, ~0.65-0.15 ka) (Figure 5) (Finné et al., 2019; M Geraga et al., 2010; Katrantsiotis et al., 2019; Marino et al., 2009; Eelco J. Rohling et al., 2019; Triantaphyllou et al., 2009). These

![Figure 5](image_url)  
**Figure 5.** Global-scale Holocene temperature variations showing the major warm and cold periods (Cuffey & Clow, 1997; Fitchett, 2019)
transformations have provided valuable insights into current climate variability (Schmittner et al., 2011).

The best documented links at the onset of the Holocene period between the Mediterranean climate and the southern monsoonal system concern precipitation maxima linked to increased Nile River outflows triggered by a monsoonal intensification over north Africa between 9 and 6 ka (Hennekam et al., 2014). The consequent alternations of the EM oceanographic regime triggered the deposition of the sapropel layer S1 in the marine realm, a layer that is basically recognized by the high organic carbon content in the marine sediments (>2%, (Kidd et al., 1978)). Most of this knowledge originates from studies on deep water marine sediments from sites deeper than 200–300 m water depth in the EM (F. J. Jorissen et al., 1993; E. J. Rohling et al., 1993; E. J. Rohling & Gieskes, 1989; Shaw & Evans, 1984). These sites remained underwater even during the Last Glacial Maximum (LGM) when the sea level reached the lowest point of 125 m below the present, whereas the sites shallower than 125 m experienced subaerial conditions (Kapsimalis et al., 2009; Lambeck et al., 2014) (Figure 6). The end of the last glacial period was accompanied by general climatic improvement and continuous sea level
rise, which finally contributed to significant alternations of the coastal landscape and the gradual submergence of the ancient coastal zone (Benjamin et al., 2017; Brunović et al., 2020; Flemming et al., 2017; Simaiakis et al., 2017). This transition has been well documented in the EM, particularly in its northern parts (Aegean, Ionian, and Adriatic Seas), which have a complex basin topography (Brunović et al., 2020; M. Geraga et al., 2000; M Geraga et al., 2010; Maria Geraga et al., 2005; Kouli et al., 2012). Rates of the Holocene Sea level rise were initially rapid (global mean sea level rose from 61 m to 4 m below present-day sea level) between 11.7 ka and 6.7 ka (Lambeck et al., 2014). Regional sea-level rise and coastal drowning trajectories are affected by additional isostatic (Lambeck & Purcell, 2005) and tectonic factors (Benjamin et al., 2017; Desruelles et al., 2009; Evelpidou et al., 2010; Pavlopoulos & Theodorakopoulou, 2010; Perdue & Koprivnjak, 2007; Sivan et al., 2001).

The Holocene is punctuated by a series of climatic anomalies associated mostly with cold spells in high-latitude areas and/or aridification in low-latitude areas (Bond et al., 1997; deMenocal et al., 2000) and globally (Mayewski et al., 2004). These events have been identified either as series of ice-rafted debris (ICR) documented in sedimentary sequences (Bond et al., 1997) pinpointed at ca. 1.4, 2.8, 4.2, 5.9, 8.1, 9.4, and 11.1 ka, and as Rapid Climate Changes (RCCs, Mayewski et al., 2004) centered at 9-8 ka, 6-5 ka, 4.2-3.8 ka, 3.5-2.5 ka, 1.2-1.0 ka, and 0.6-0.15 ka. The RCCs partially coincide with the ICR events, and their trigger mechanisms involve changes in orbital parameters, variations in solar activity, atmospheric-oceanic interactions, and volcanic aerosol production (Bond et al., 2001; deMenocal et al., 2000; Mayewski et al., 2004). Their climatic signature as well as the exact
time of their occurrences is variable among the globally investigated sites (Mayewski et al., 2004; Wanner & Bütikofer, 2008).

In the eastern Mediterranean (EM) and the surrounding region (Figure 7), climatic anomalies within the Holocene have been observed through the study of variable material; marine sediments by the study of microfauna, microflora and stable isotopes (i.e. Aegean Sea: Casford et al., 2001; Geraga et al., 2010; Gogou et al., 2016; Kotthoff et al., 2008; Marino et al., 2009; E. J. Rohling et al., 2002; Levantine Sea: Hennekam et al., 2014; Schmiedl et al., 2010) and by the study of granulometric, geochemical and mineralogical parameters (i.e. Aegean Sea: Emmanouilidis et al., 2022; Hamann et al., 2008; southern margin of eastern Mediterranean: Hennekam et al., 2014; Zielhofer et al., 2017 and references therein), lake sediments (i.e. Turkey: Eastwood et al., 2007); Balkans: Lacey et al., 2015; Giovanni Zanchetta et al., 2018) pollen records (i.e. Roberts et al., 2011 and references therein), speleothems (i.e. Balkans: Finné et al., 2017; Levant area: H. Cheng et al., 2015) and microcharcoal content of sediments (Turner et al., 2008). In the northern latitudes of the EM, Holocene climatic anomalies are usually observed as terrestrial cooling of about 4 °C and drops in sea surface temperatures of about 2 °C resulted from intensification of Siberian High (pressure) conditions in winter/early spring (Mayewski et al., 2004; E. J. Rohling et al., 2002; Eelco J. Rohling et al., 2019 and references therein). Furthermore, many studies document increases of aridity during the Holocene climatic anomalies, in northern and lower latitude areas of the eastern Mediterranean associated with weakened summer monsoons over the Arabian Sea and tropical Africa, and/or variations of the North Atlantic oscillations (Arz et al., 2006; Fleitmann et al., 2003). These arid events reinforced significant archaeological changes observed in these regions (i.e., Berger et al., 2016; Clarke et al., 2016; Finné et al., 2017; Gogou et al., 2016 and references therein).

Paleoclimate data from other proxy studies, suggest that the region has experienced dramatic climate changes in the past including large-amplitude glacial-interglacial changes and millennial- to decadal-scale climate fluctuations (e.g., Bar-Matthews et al., 2003; Bar-Matthews and Ayalon, 2011). Several cycles of climate change have been identified, including periods of warming and cooling in ice- and sediment- core records. Bond cycles are characterized by fluctuations in climate conditions, with increased deposition of ice-rafted debris (IRD) in North Atlantic sediments and occur approximately every 1,500 years. Changes
in solar radiation, particularly in the form of solar minima (periods of reduced solar activity), might play a role in triggering these centennial-scale climate shifts. The Bond events were found to manifest as drought events in the EM during the Holocene, occurring approximately every 1500 years (Cheng et al., 2015). An oscillation with a period of about 2100-2500 years in 14C concentration, known in the literature as the Hallstatt cycle (Vasiliev & Dergachev, 2002), has been found in various paleoclimatic records spanning the Holocene (Scafetta et al., 2016, and references therein). This 2100–2500-year oscillation has been suggested to have an origin of three kinds: astronomical, solar, and Earth’s endogenous. Another, major climate variability in the Holocene was found to occur in a ~500-year cycle and is possibly linked to solar variations and interactions among climate systems. A ~500-year cycle in solar activity, inferred from global atmospheric $^{14}$CO$_2$ production variation, might have driven North Atlantic, North Pacific and North America terrestrial climates (Stuiver et al., 1993, 1995; Yu and Ito, 1999; Chapman and Shackleton, 2000; Hu, 2003; Zhao et al., 2010). However, it remains to be seen whether these periodic paleoclimate changes is global or regional signals in the Holocene.
Figure 7. World map showing the location of the climate archives used in this study. The Greenland Ice core record (GRIP and GISP2), the Eastern Mediterranean marine sediment cores from Astypalea, S. Aegean Sea (ASTC1) and southeastern Levantine Basin (PS009PC), the Jeita cave speleothem record from Lebanon, the lacustrine sediment core from Chew Bahir basin, S. Ethiopia, and the speleothem record from Sanbao cave, China. The gridded data for the map construction were taken from GEBGO database (https://download.gebco.net).

1.4. Sea level change and tectonism in the Aegean region

Relative sea-level changes in combination with changes to alluviation processes, tectonic movements and other climatic changes have altered the initial environmental status of the Aegean coastal sites (Pavlopoulos & Theodorakopoulou, 2010). The eustatic and isostatic deviations during the last glacial-interglacial cycle had as a consequence a total sea level rise of about ~120 m (Lambeck and Purcell, 2005; Lykousis, 2009). The subsequent changes in coastal geography were inevitable and were the ones that led to the Aegean Island configuration and the sea transgression. Furthermore, the coastal geomorphology was affected by the intense tectonics of the Aegean plateau causing vertical displacements of the coastline. These coastal displacements in the Southern Aegean are linked to submergence (for example Amorgos, Mykonos) but also emergence/uplift (for example Nisiros, Rodos) with rates reaching up to 1.24 mm/yr and 2.4 mm/yr respectively (Pavlopoulos et al., 2011). At the submerged coastal regions, it is expected that ancient remains will exist today below sea level.

The tectonics of the Aegean region are highly complicated with other regions experiencing submergence and other been prone to uplift. Little is known about the tectonic influence in the Astypalea region. Our study area (Vathy bay) lies at the NE Astypalea, an island just above the Aegean volcanic arc which forms the southeastern margin of the Santorini-Amorgos Shear Zone. According to seismic studies in this region, the Astypalea island was found to experience general uplift prior to and during the Quaternary (Figure 8) (Nomikou et al., 2018; Tsampouraki-Kraounaki et al., 2021). Other formations such as beachrock formations, notches, and other evidence from archaeological sites across the Aegean Sea coasts have been related to episodic coastal uplift and/or subsidence events during the Holocene (Evelpidou et al., 2010).
1.5. Regional oceanographic setting

The northeastern Mediterranean margin, represented by the Aegean Sea, is subdivided into two basins with different hydrographic characteristics (Theocharis et al., 1999): the north and south Aegean. Within the Aegean, the Eastern Mediterranean Deep Water mass forms (V Lykousis et al., 2002; Zervakis et al., 2000). The study region is located within an N-S gradient from subhumid to arid climate conditions. In the north, river systems from surrounding landmasses, as well as the Black Sea region, impact circulation. In the south, water masses exchange with the EM through the Cretan straits. The south Aegean basin is considered a

Figure 8. (A): Detailed map of the active fault network in Santorini-Amorgos Shear Zone. Teeth on the faults indicate the downthrown side. Half arrows show the sense of lateral motion. (B): Tectonic and kinematic map of Santorini-Amorgos Shear Zone. Dextral oblique rifting results from dextral strike-slip motion in NE-SW direction and extension in NW-SE direction. Red arrows show the direction of motion in respect to stable Eurasia, modified after Kreemer and Chamot-Rooke, 2004. (C): Drawing explaining the kinematic of dextral oblique extension with the rift axis running at 30° in respect to the rifting direction (Tsampouraki-Kraounaki et al., 2021; Withjack & Jamison, 1986).
typical oceanic margin environment, lacking large terrigenous (fluvial) supplies (Poulos et al., 2009). The documented productivity rates within the euphotic zone are very low according to measurements at 200 m water depth (Stavrakakis et al., 2000), and the sediments are poor in organic carbon, with a mean value of around 0.34% (Lykousis, 1991). The Aegean Sea contains highly saline water, with an average value of 39.2% and average temperatures of 16 °C in winter and 25 °C in summer (Figure 9). Eustatic sea-level fluctuations, along with complex tectonics, have dominated the sedimentary processes and the palaeogeographical evolution of the Aegean region (Kapsimalis et al., 2009; Lykousis et al., 2005; Pavlides & Caputo, 2004; Perissoratis & Consipoliatis, 2003; Piper & Perissoratis, 1991), with almost 50–60% of the present Aegean Sea bottom being exposed during the Last Glacial Maximum (Lykousis, 2009).

**Figure 9.** After Rohling et al., 2015. Key features of the Mediterranean. a. Bathymetric map with most important geographic names. b. Winter sea surface temperature distribution (Locarnini et al., 2010) and schematic surface circulation pattern (arrows, Pinardi et al., in press). c. Summer sea surface temperature distribution (Locarnini et al., 2010). d. Annual sea surface salinity distribution (Antonov et al., 2010). e. Annual temperature distribution at 250 m.
m and schematic circulation pattern of LIW (arrows, Pinardi et al., in press). f. Annual salinity distribution at 250 m (Antonov et al., 2010).

Vathy bay is 2 km long and 0.5 km wide, covering an area of 0.8 km2. The maximum water depth is 10 m. The bay has a flat floor, and it is semi-isolated from the south Aegean Sea by a narrow and shallow strait/channel of 1 km length and 150 m width and a 4.7 m deep sill. Maximum temperature in July is between 25.8 and 26.8 °C and salinity ranges between 38.6 and 38.8 psu. Vathy bay is surrounded by hills that provide some shelter from strong winds and waves. No evidence of Holocene fluvial input is known. Nowadays, the bay serves as a port, as it provides protection against wind and high waves. The island is sparsely populated but has a long and important human occupancy record dating back to 6 ka (Vlachopoulos, 2016).

1.6. Geological setting

The geological setting of the Astypalaia island is made up of both alpine formations of Mesozoic and Late Cenozoic age, as well as meta-alpine formations, which were formed after the end of the alpine orogeny (23 million years ago) (Ring, 2001; Chatzaras, 2010). It is occupied with External Hellenides rock formations (Marnelis and Bonneau, 1977; Marnelis, 1986; Ring, 2001) and among the central and eastern Aegean islands, is the one studied less. The wider area of the northeastern Astypalea, where our study area is located, is mainly composed of black rudist-bearing limestones and dolomitic limestones of Upper Cretaceous period (Senonian-Maastrichtian age) and constitute the bedrock of the area. Such rock formations can be dissolved physically by water or chemically by water enriched with carbon dioxide forming karst features such as caves, sinkholes, or dolines. Paleocene-Middle Eocene limestones and Upper Eocene-Oligocene sandstones are also present at the easternmost part, overlapping the Upper Cretaceous bedrock through overlap-faults. Talus scree and coastal deposits of Quaternary age are found laterally of Vathy bay and are linked to normal fault activity (Figure 10, IGME, 1986). No evidence of Holocene fluvial input is known.
1.7. Archaeology and Human Occupation

Vathy bay is located at the northeastern part of the Astypalea island, which since prehistoric times has held an important strategic geographical position at the crossroads of the Eastern Mediterranean maritime trade routes, linking the Greek peninsula, Asia Minor, the Middle East, and Egypt. At 105 BC a treaty with Rome was signed, as seen in an inscription found on the island, declaring the island as "civitas foderata", a free colony of Rome, ensuring sovereign equality between Rome and Astypalaia (Sherk, 1984; Vlachopoulos and Matthaiou, 2013). Archaeological excavations have revealed traces of ancient settlements, including pottery fragments and artifacts, indicating the island's ancient history since at least the Late Neolithic period (Vlachopoulos, 2013, 2014, 2015a, b, 2016a, b, c, 2017, 2018, 2019a, b, 2020a, b, 2021, 2022a, b, 2023a, b; Vlachopoulos and Angelopoulou, 2019). A modern discovery by the Ephorate of Antiquities of the Dodecanese brought to light the existence of a unique infant pot burial cemetery at Kylindra, located at the Astypalea castle’s foothill, constituting the largest infant cemetery in the world, in which 2700 newborns and small
children were buried in ceramic pots between approximately 750 B.C. and Roman times (Hillson, 2009). Other findings include a Mesolithic burial (~10th-9th mill. BCE) in the Negros Cave which highlights a further earlier presence of ancient humans on the island which also represents one of the oldest (Efstathiou, 2023).

The region where the research of this thesis took place, the Vathy bay, is a naturally protected peninsula controlling the narrow access from the open sea to the homonymous gulf on the north-west rocky coast of Astypalaia, thus ensuring complete surveillance over a large region. A series of archaeological excavations part of the “Vathy Astypalaia Archaeological Project” (https://vathy.project.uoi.gr/vathy_astypalaia_arch_project_eng/) conducted by the Archaeological society of Athens and the University of Ioannina under the direction of Professor Vlachopoulos, at the western part of the bay, at the Elliniko cape, initiated in 2011 and continue up to the present. This project brought to light significant evidence of the ancient human civilization on the cape (Vlachopoulos and Angelopoulou, 2019; Vlachopoulos, 2014,2015a, b, 2016a, b, c, 2017, 2018, 2019a, b, 2020a, b, 2021, 2022a, b, 2023a, b). A 7–8-acre acropolis with boulder-built circuit walls and megalithic retaining walls was erected in the 3rd millennium BCE at the easternmost point of the Pyrgos promontory, which is located on Cape Elliniko (Figure 11). In the late 4th century BCE, a tower and its surrounding ancillary facilities were built on the headland's top level. Numerous monuments and artefacts have
been discovered in Vathy as a result of the intensive surface survey since 2012 and the systematic excavation since 2014 (Vlachopoulos, 2023a, b). These efforts further establish the Early Cycladic elements while also point to influences from other areas of the Aegean.

**Figure 11.** Figure Top: Aerial photograph of the Pyrgos peninsula. The prehistoric citadel occupies the easternmost tip of the promontory (Cape Elliniko). Bottom: topographic plan with surface constructions (Vlachopoulos & Angelopoulou, 2019).

The recovery of Early Cycladic marble figurines and numerous rock engravings of spirals, oared ships, daggers, arrows, axes and other motifs over a wide area of dolomitic limestone on the cape, both quarried, built and in natural state identify Vathy as a significant site of the Final Neolithic/Early Bronze Age Aegean, with intense Cycladic features (Figure 12) (Vlachopoulos, 2019). Archaic (6th c. BCE) and classical (5th c. BCE) inscriptions were also located on the peninsula indicating that human activity continued in later centuries.

**Figure 12.** Rock carvings found on cape Elliniko (Tsigkas et al., 2020). On rows from top to bottom we see the carving of “Dion”, “Ship” and the “Dagger”. The uninterpreted and interpreted rock surfaces are on the left and right column respectively.

The data provided by the surface analysis and the continuous excavations since 2011 by the archaeologists on the site, support the prehistoric occupation of the cape during two successive periods or phases (Vlachopoulos and Angelopoulou, 2019). The first is dated by features pointing to the latest Neolithic or Early Bronze Age I, including three marble figurines and infant pot burials. The
second inhabitation phase is dated at Early Bronze Age II, and includes abundant motifs of rock art, such as the oared ships, the daggers and the spirals, despite their typological attribution to Early Bronze Age II, at Vathy date earlier, to the transition from the 4th to the 3rd mill. BC, as recent excavation in the citadel showed (Vlachopoulos et al. 2023a, b).

Many of the above mentioned findings terminate into the sea and prelude a possible expansion of these constructions under the sea. To this direction a marine geoarchaeological research was critical to be conducted in the bay, in order to assess whether there are submerged structures of the ancient acropolis.
2. Materials and Methods

2.1. Survey timeline

The methodological scheme followed in this PhD dissertation was implemented in three main directions, and was carried out by the Oceanus Lab, of the Department of Geology, University of Patras, Greece. The first direction includes the detailed geophysical-marine remote sensing survey of the area of interest to reconstruct the paleogeography of the bay over time. The second direction refers to the ground truthing, based on the results of the interpreted seismic data to trace submerged remains and structures of archaeological interest, as well as to map the occurring marine habitats of the bay. The third direction refers to the sediment core proxies to unravel the paleoenvironmental and paleoclimatic history of the bay in relation to other records from EM and the Northern Hemisphere. The two first directions employ marine remote sensing techniques, while the third one includes techniques applied on sediment core data.

The chronicles of the surveys took place in three time-phases (Figure 13). The first phase A took place in July 2016 and included the general mapping of the acoustic/geomorphological properties of the seafloor and the stratigraphy of the survey area. The second phase B occurred in July 2018, and included marine geophysical mapping of specific areas of interest with a higher resolution and the acquisition of one sediment core considering the results of phase A. The third phase C took place in July 2019 and involved the visual recording of the areas of interests indicated in phase B. This downscaling methodological approach represents a powerful tool to extract more detailed, accurate, and site-specific information when studying coarser-scale data sources like in this case (Figure 14).
Figure 13. Tracklines followed during the three time-phases (July 2016/2018/2019) of the survey in Vathy bay.

2.1.1. Marine Remote Sensing

For the implementation of the marine geophysical survey a specially modified research vessel meeting the survey needs was deployed. A dense network of seismic lines was produced to obtain seafloor morphology and seismic stratigraphy (Figure 13). The retrieved data helped us reconstruct the seismic stratigraphy of the upper 10 m of sediments below the sea floor and helped to select a favorable coring location where the maximum sedimentary sequences could be penetrated/retrieved. The overall equipment used for the acoustic and sediment data acquisition included the following equipment:

- An ELAC Seabeam SB1185 multi-beam echo sounder (MBES) with maximum depth range of 300 m (Figure 14). Maximum swath coverage is 153° and the maximum number of sounding is 126 per swath. The post processing of the acquired data was made in Hypack software. Multibeam echosounder produces a
number of sonar signals, or beams, that propagate from the sonar head in a fan, thus
recording bathymetry and amplitude measurements of the surveyed seafloor area.
Systematic coverage of the seabed using multibeam echosounder provides clear
images of the morphology of the seabed as well as man-made targets on the seafloor.

- A side scan sonar (SSS) with a dual frequency (100 and 500 kHz) towfish EG&G
  272TD with a digital recording unit Edgetech 4100P topside and Kevlar cables of
  50, 150 and 200 m length (Figure 14). The post processing of the acquired SSS data
  was made in ISIS Triton software. Side scan sonar produces acoustic images called
  sonographs which portray the seafloor texture and seafloor morphology. A higher
  frequency gives better resolution but less range with the modern systems having
  capability to resolve objects of 20 cm or less. The pulses are sent in two separate
  fan-shaped beams which are directed down to the seafloor either side of the tow-
  fish. The interpretation of the sonographs (Blondel, 2009) is based on the acoustic
  reflectivity (i.e., the coarser sediment material returns stronger acoustic signal) and
  on specific acoustic criteria (i.e., the presence of acoustic shadow, the parameters
  controlling the shape and the acoustic signature).

- Two sub-bottom profiling systems (S) were also used for surveys (Figure 14): A
  3.5 kHz Chirp type sub-bottom profiling system (Kongsberg Geopulse),
  provided a maximum penetration of 10 m, with a 5-10 cm resolution. An Innomar
  SES-2000 compact sub-bottom profiler with a 1-5 cm resolution, which provided
  more details regarding the inner structure of the sedimentary units that were also
  recognized in the chirp profiles. The Innomar SES-2000 S enabled the extraction
  of the average pulse length (measured in µs) of the stratigraphic sequence with a
  traced signal resolution of 1 cm, at the exact coring location which was used for
  seismic-sediment core data correlation. The post processing of the acquired S data
  was made in ISIS SBI and in ISE Innomar software. A subbottom profiling system
generally provides an acoustic profile of a narrow section of the subbottom beneath
the path over which the device is being towed. The signals are reflected off the
seafloor surface, the interfaces between strata and specific features that maybe
buried in the sediments (Darmuth, 1975). The strength of this reflection is governed
by the reflection coefficient.
• For the seabed inspection/visualization a remote operated vehicle (R.O.V) SubSeaTech Guardian with an acoustic positioning USBL system allowing location of a target relative to a reference unit on the surface was used (Figure 14). The underwater visual data were georeferenced via MATLAB programming language.

• Positional data on vessel was provided by a Differential Global Positioning System (DGPS) G.P.S Hemisphere Vector VS101 GPS Compass with two multipath-resistant antennas, differential including L-band, Beacon and SBAS (WAAS, EGNOS, MSAS, etc.) with ≤0.5m accuracy. The exact underwater position of the ROV was achieved by utilizing a Blueprint subsea X150 USBL acoustic transponder attached to it.

**Figure 14.** The downscaling methodological scheme during the three time-phases of the geoarchaeological survey in Vathy Bay. The maps on the left show the investigated areas per period, while on the right, we see the equipment used and their products through the three time-phases.
2.2. Sediment core acquisition and proxies

One sediment core was retrieved from the central part of the bay in July 2018 (Figure 15). The 3.2 m-long sediment core ASTC1 (lat. 36.618878°–long. 26.405795°) was obtained with a diver-operated piston coring system at 9 m water depth with 30kg hammering weight blocks adjusted on it (Figure 15). A series of standard sedimentological and geochemical analyses were performed on ASTC1 core samples, such as grain size analysis, determination of total organic carbon (TOC) and total nitrogen (TN), sediment color (CIE-b*) (Avaatech Color Line Scan Camera), inorganic geochemistry, and stable isotopes.

![Figure 15. The retrieved sediment core ASTC1 from Vathy bay (top) and the diver-operated coring system (bottom). The white rectangle shows the penetration limits of the coring system in the seismic stratigraphy.](image)

2.2.1. Standard sedimentological techniques

Grain size determination was carried out on 108 samples, which were analyzed and classified based on Folk and Ward’s (1957) nomenclature. The grain size measurements were made using a Malvern Mastersizer Hydro 2000 at the Laboratory of Sedimentology, University of Patras. Prior to measurement, bigger fragments, mainly biogenic (shells), were removed by
wet sieving each sample at 1 phi. The sedimentological statistical parameters, such as mean, sorting, skewness, and kurtosis, were calculated using Gradistat V.4 software (Blott & Pye, 2001). The carbonate fraction was not removed, so the grainsize also includes the bioclasts smaller than 1 phi.

Sediment color data were retrieved with an Avaatech XRF core scanner equipped with a Color Line Scan Camera at the Royal Netherlands Institute for Sea Research (NIOZ). This system produces both visual color images (core photo scan) and color data in RGB and CIEL*a*b* (L*, a*, b*) color space of that part of the core that is also ‘seen’ by the XRF. The set of reflectance data obtained from the sediment core on the visible light band is then automatically transferred into coordinates of color in the CIE La*b* chromaticity space (Nagao & Nakashima, 1992). Here, we use only the b* record, which is the color reflectance of the yellow to blue axis. This intact technique may provide various physical and geochemical indications in paleoenvironmental studies (Giosan et al., 2002; Heslop & Dillon, 2007; Ji et al., 2005; Rein & Sirocko, 2002; Weltje et al., 2015; Wu et al., 2017), especially when used in combination with other proxies. The applied resolution used here in the ASTC1 core was 0.07 mm, while the minimum cross-core area that can be defined is one pixel in size, which is less than 0.1 mm.

2.2.2. Qualitative micropaleontological analysis

In total, 40 sediment samples > 355 µm were qualitatively scanned for mollusk fauna, where common and dominant species were noted, as well as the occurrence of species with specific autecological traits (Table S1). Similarly, 60 sediment samples > 125 µm were scanned for benthic foraminifera species shown in Table S1.

2.2.3. C\textsubscript{org} and N

Variations in nitrogen and organic carbon content in the ASTC1 core were measured with a Fisons NA1500 CN elemental analyzer at Earth Sciences Utrecht University. An average 10 cm sampling resolution was established for 42 samples. Prior to measurement, a series of pretreatments was made. First, the samples were freeze-dried, ground, and precisely weighed. To eliminate the carbonate fraction, the carbonates were removed through mechanical shaking of the sample with 1 M HCl (twice for 4 and 12 h) (for details, see (van Santvoort et al., 1996)).
Then they were washed 4 times with demineralized water, centrifuged, dried in the oven (3 days at 60°C), and weighed again before being measured at the CN analyzer. The organic carbon content calculation was based on the equation $C_{\text{org}} = C\% \times (M2/M1)$, where $C\%$ is the result of the CN analyzer (decalcified sample), $M1$ is the sample weight before decalcification, and $M2$ is the sample weight after decalcification.

2.2.4. XRD

To define the mineral composition within the lithological units of ASTC1 sediment core we performed X-ray powder diffraction analysis (XRD) on 13 selected samples. The sampling was made by considering the inorganic specific geochemical ratios given by the XRF measurement, and thus we did not use a steady sampling interval. Samples were then ground (<10 µm) in a vibration disc mill using an agate grinding set mortar and randomly mounted in a sample holder. The XRPD data were collected at the Minerals and Rocks Research Laboratory, Department of Geology, University of Patras, under a Bruker D8 Advanced Diffractometer, using Ni filtered Cu-Kα radiation, operating at 40 kV and 40 mA and employing a Bruker Lynx Eye fast detector. Samples were step-scanned from 2° to 70° with a step size of 0.015° (2θ). For the identification of crystalline phases, the DIFFRACplus EVA (Bruker-AXS, Madison, WI, USA) software was used, based on the ICDD Powder. The identification was made based on the first and most intense peak (Brindley and Brown, 1980), while their determination was semi-quantitative considering the spikes of the mineral reflections.

2.2.5. Inorganic geochemistry

The inorganic geochemistry of ASTC1 was also measured with an Avaatech XRF (X-Ray Fluorescence) core scanner at the Royal Netherlands Institute for Sea Research (NIOZ). Prior to measurement, a protective film was placed at the part where the scan would take place. Core scanning was performed at 10, 30, and 50 kV with a step of 1 cm, and the system’s detection limits ranged between Mg and Pb. Although this approach has semi-quantitative results, it can provide reliable records of the relative variability in downcore elemental composition.
2.2.6. C and O isotopes

The stable oxygen and carbon isotopic compositions of selected benthic microfossils were measured following the standard procedures of the Isotopes laboratory, Geosciences, Utrecht University. Due to the downcore coexistence of structured and homogenized sedimentary groups, the sampling interval applied in this study had to be adapted to the presence/absence of inner structures or the obvious transition in sediment texture. Sediment samples were extracted every 5 to 10 cm on average and were initially wet sieved with a 63 and 125 µm sieve, dried in an oven for 24 h, but due to big bioclasts occurrence, the 125 µm samples were extra dry sieved with a 355 µm sieve fraction. The microfossils measured for stable isotopes were the ones collected from >125 µm sieve fraction (>125 and <355) and were in majority well preserved and predominantly benthic with a total absence of planktonic species, so this study is focused on the variability of shallow water benthic species. A fraction above 355 µm was used for macroscopic observations. Residues contained gastropods, bivalves, some benthic foraminifera, and ostracods, as well as charophytes with thalli encrustations and gyrogonites. Hand-picked microfossils showing no signs of diagenetic alteration were selected under a Nikon SMZ800 electron microscope. Among the occurring species throughout the core, one infaunal and two epifaunal genera/species where selected, where the most abundant, such as Ammonia spp. tests (mainly Ammonia tepida, shallow infaunal sediment), Quinqueloculina spp. tests (epifaunal), and ostracods (Cypridoidea) tests (epifaunal), were selected from >125 µm fraction (plate 1) for stable isotope analyses. The 91 calcite tests were then treated twice with deionized water and ultrasound shaking before being dried in the oven. Afterwards, a specific amount of the samples (20–50 µg) and the standards (20–50 µg of IAEA and NAXOS) were weighed and flashed before being measured with an isotope ratio mass spectrometer (IRMS) with different preparation systems (gas chromatography-based Gas Bench II system) that each provide the analyte in a stream of helium gas, hence continuous flow. This analysis was conducted at the Isotopes Laboratory, Utrecht University. The standard deviation of the measured samples was better than 0.05‰ for δ^{13}C and better than 0.1‰ for δ^{18}O.

2.2.7. Chronology - Radiocarbon C14 dating.

The age model of core ASTC1 was based on 20 bulk \(^{14}\text{C}_{\text{org}}\) measurements and one \(^{14}\text{C}\) accelerator mass spectrometry (AMS) measurement on benthic foraminiferal tests of the species Ammonia tepida (Figure 16, Table 1). The \(^{14}\text{C}\) analysis for the shell test was carried
out at the Radiochronology Lab C.E.N. ULAVAL in Canada, whereas the $^{14}$C dates were conducted at ETH-Zurich. The Marine20 and Intcal20 data sets were used for calibration (Heaton et al., 2020), and a ∆R of $-58 \pm 85$ years was adopted based on measurements of recent mollusk shell material in the Aegean basin (Marino et al., 2009). A zero ∆R was applied to the non-water-logged samples of the sediment core.

**Figure 16.** Calendar $^{14}$C dates measured along the two sections of the ASTC1 sediment core.
<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>(^{14}\text{C}) Age (yr B.P.)</th>
<th>Calendar Age (Cal yr)</th>
<th>Material</th>
<th>Lab Code</th>
</tr>
</thead>
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<tr>
<td>0.5</td>
<td>623 ± 65</td>
<td>59 ± 322</td>
<td>Bulk sediment</td>
<td>BCd1</td>
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<tr>
<td>2.5</td>
<td>418 ± 65</td>
<td>104 ± 350</td>
<td>Bulk sediment</td>
<td>BCd2</td>
</tr>
<tr>
<td>25</td>
<td>1206 ± 51</td>
<td>708 ± 750</td>
<td>Bulk sediment</td>
<td>BCd3</td>
</tr>
<tr>
<td>40.5</td>
<td>3105 ± 72</td>
<td>2123 ± 1169</td>
<td>Bulk sediment</td>
<td>BCd4</td>
</tr>
<tr>
<td>49</td>
<td>2417 ± 53</td>
<td>2426 ± 1083</td>
<td>Bulk sediment</td>
<td>BCd6</td>
</tr>
<tr>
<td>66</td>
<td>3365 ± 56</td>
<td>3441 ± 924</td>
<td>Bulk sediment</td>
<td>BCd7</td>
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<tr>
<td>77</td>
<td>4185 ± 56</td>
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<td>Bulk sediment</td>
<td>BCd9</td>
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<tr>
<td>87</td>
<td>4663 ± 57</td>
<td>4447 ± 638</td>
<td>Bulk sediment</td>
<td>BCd12</td>
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<tr>
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<td>5584 ± 59</td>
<td>5414 ± 614</td>
<td>Bulk sediment</td>
<td>BCd13</td>
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<tr>
<td>139</td>
<td>5810 ± 60</td>
<td>5717 ± 405</td>
<td>Bulk sediment</td>
<td>BCd16</td>
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<tr>
<td>151</td>
<td>5555 ± 60</td>
<td>5857 ± 344</td>
<td>Bulk sediment</td>
<td>BCd17</td>
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<tr>
<td>159</td>
<td>5930 ± 60</td>
<td>5968 ± 309</td>
<td>Ammonia spp.</td>
<td>AMSC14</td>
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<tr>
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<td>5995 ± 309</td>
<td>Bulk sediment</td>
<td>BCd18</td>
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<td>319</td>
<td>8305 ± 66</td>
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<td>BCd32</td>
</tr>
</tbody>
</table>

**Table 1.** The \(^{14}\text{C}\) data used to construct the Age Model.
3. Results

The results of this dissertation are presented in two directions. The first one refers to the palaeogeographical reconstruction of Vathy bay, the archaeological indications within the marine part of the examined area, and the evidenced seafloor habitats and types based on the marine remote sensing techniques within subchapter 3.1. The second direction concerns the reconstruction of the paleoenvironmental and paleoclimatic conditions of the bay based on sediment core data within subchapter 3.2.

3.1. Geophysical data

3.1.1. Bathymetry

The total bathymetry of the study area was created based on the interpolated digitized seafloor surface data collected with a chirp Subbottom Profiler. The produced bathymetry of the bay shows a smooth seafloor morphology, with a relative flat bottom and maximum depth of ~10 m (below modern sea level) which is evidenced in the central and eastern part of the bay (Figure 17). Based on the bathymetry and the revealed geomorphology of the bay, the seafloor can be distinguished into three morphological units: a) the inner bay region, which is characterized by a smooth relief and maximum depth of ~10 m and slope rates between 0° and 1°, b) the inner and shallow part of the straits (communication channel) at the south-western part, with depths ranging between 0 and 8 m, and seafloor slope rates strongly varying mainly in the nearshore part, showing values up to 20°, while in the central axis of the straits the slope rates exceed 20°, and c) the outer and deep part of the straits at the south and westernmost part, with depths >8 and <50m, with seafloor slope rates less than 16°. The mean seafloor slope rates across the northern, southern, eastern, and western margin of the inner bay area are 5°, 3°, 4°, and 14° respectively. The seafloor configuration of the straits forms a bathymetric barrier (sill) with an average minimum depth of 4.7 m which separates the inner bay area from the open Aegean Sea (Figure 18). The average minimum depth of the sill was determined through bathymetry and a depth profile graph across the central axis of the straits.
Figure 17. The bathymetric map of the Vathy bay, based on the seismic data collected with the chirp-type subbottom profiler.

Figure 18. Depth profile graph of the bathymetric barrier produced along the central axis of the straits.
3.1.2. Sea-floor morphology

The synthesis of the backscatter acoustic signal collected with a side scan sonar led to the construction of two mosaic maps, an overall mosaic map of the of the Vathy bay seabed covering an area of 0.7 km², with lower frequency (100 kHz, Figure 19) and a higher frequency (500 kHz) mosaic map centered around the cape Elliniko and the straits (Figure 20). These mosaic maps present the seabed surface in a two-dimensional aspect based on acoustic criteria. In the overall acoustic mosaic map, three acoustic types (AT) were distinguished based on their backscatter intensity. The determination of their spatial distribution led to the production of an acoustic-type map of the bay (Figure 21). The first acoustic type (AT1) presents low backscatter intensity (dark tone) because of the weak reflected echoes on a seabed covered by loose fine-grained sediments (Figure 21, AT1). AT1 has a very wide spatial distribution and covers almost the entire bay except for the nearshore areas. This acoustic type refers to an area of 0.5 km², covering 71% of the bay. The second acoustic type (AT2) shows medium to high backscatter intensity and is detected peripherally to AT1, and represents seabed covered by seagrass meadows and/or coarse-grained/rocky seabed (Figure 21, AT2). The third acoustic type (AT3) presents very high backscatter intensity and is a result of the very strong reflection of the echoes on rocky seabed (Figure 21, AT3). AT3 is restricted close to the shoreline, peripherally to the bay and to the straits. The total area occupied by medium and high backscatter intensity (AT2 and AT3) amounts to 0.2 km² or 29% of the total area. The spatial distribution of the three acoustic types is positively correlated with depth distribution in the bay, showing a water depth dependent relationship.
Figure 19. A general mosaic map of Vathy bay based on the side scan sonar data with a frequency of 100 kHz.

Figure 20. A mosaic map of the offshore area around cape Elliniko based on the side scan sonar data with a frequency of 500 kHz.
Figure 21. Acoustic types identified through the side-scan mosaic map of the survey area.

3.1.3. Seismic stratigraphy

The investigation of the bay was accomplished with two subbottom profiler systems (3.5 kHZ chirp and SES Innomar S) and yielded high-resolution seismic profiles, which depict the geological stratigraphy of the accumulated sediments in the Vathi basin over the geological time (Figure 22). The interpretation of the seismic profiles, based on the characteristics of the acoustic reflections and the stratigraphic relationships, allowed the study of the structure and geometry of the sedimentary formations-units deposited in the basin and enabled the reconstruction of the sedimentary environment.

Six main seismic reflectors (R0, R1, R2, R3, R4 and R5) were identified on the seismostratigraphic profiles and were detected in most of the transects throughout the bay (Figure 22). These main and discrete seismic reflectors represent subsurface interfaces with significant differences in physical properties (e.g., density, water content) and mainly in sediment composition (e.g., lithology). The six acoustic reflectors determine the borders of
discrete seismo-stratigraphic facies identified across the profiles. R0-reflector represents the seabed surface while all the other, R1-R5, represent the sub-surficial reflectors. The acoustic basement of the seismic sequence is represented by R5-reflector which marks the penetration limit of the acoustic waves. Their division is based on the acoustic characteristics (continuity, clarity, amplitude) and the frequency of occurrence of internal seismic reflections.

**Figure 22.** Bathymetric map of Vathy bay, showing the location of the seismic line AA`. High-resolution seismic profile (SES Innomar S) of the AA` transect (location marked on the bathymetric map) with a 5.5x vertical exaggeration of the sedimentary basin of Vathy (the
uninterpreted above and the interpreted below). The interpreted seismic profile shows the main reflectors (R0-R5) and the seismic facies (SF1-SF5) detected within the seismic stratigraphy.

Five main seismic facies (SF1–SF5) with different acoustic reflections were identified (Figure 22), each of which represents a specific and distinctive depositional environment. Both the seismic reflections and the seismic facies were recognized in the Chirp and SES Innomar seismic profiles. Due to the higher resolution given by the SES Innomar profile, we chose to present the seismic facies on the best representative seismic profile across the AA` transect which encounters a ~10 m thick sedimentary sequence in the Vathy bay (Figure 22). The AA` transect crosses the central part of the strait and the basin from west to east and overlies the ASTC1 core sight. The five seismic phases are enclosed between the six main seismic reflectors (R0, R1, R2, R3, R4 and R5) and are listed from lower (older) to upper (younger), as follows:

- **SF5** displays acoustically transparent structure and overlaps the acoustic basement, it refers to the deepest deposited sediments in the basin and its basis is the limit of the penetration ability of the S (Chirp and SES Innomar). This unit may represent homogeneous sedimentary deposits (e.g., shale, limestone, or sandstone) which do not create strong acoustic contrasts with adjacent layers. Seismic acoustic transparency may also be attributed to high water content porosity.

- **SF4** overlies SF5 and is semi-transparent with some weak and horizontal seismic reflectors occurring at the eastern part of the basin. The features of this unit may be attributed to variability in lithology, and/or mixed depositional conditions which could be related with fault activity. The chaotic semi-transparent feature noticed in the eastern part of this seismic unit may also attributed to mass transported sediments, debris flows, and may suggest a dynamic sedimentary setting.

- **SF3** overlies SF4 and is characterized by horizontal dense laminated seismic reflectors. These parallel internal seismic reflections may often indicate fine-grained sedimentation, cyclical deposition, and/or variation in sedimentation rate. The preservation of this feature within the seismic stratigraphy can provide important information on the paleoenvironmental conditions as it is commonly associated with low energy depositional environments (e.g., deep marine basins or quiet shallow marine settings), and/or anaerobic conditions on the seafloor which can be further linked to the presence of organic rich layers.
SF2 and SF1 overlie SF3 and show a chaotic acoustic pattern, with the last one being semi-transparent (Figure 22). The two last seismic facies are divided by the seismic reflector R1. The semi-transparent acoustic feature within SF1 may indicate higher dynamic of the sedimentary setting compared to the SF2. This feature is common among the present marine environments representing pelagic sedimentation.

All seismic facies (SF1–SF5) show onlap termination against the slope of the acoustic basement (Figure 22). The lower seismic facies (SF5 and SF4) present particularly anomalous morphology in contrast to the upper three SF3-SF1. This may indicate possible tectonic activity which led to this morphology, but due to the absence of core data within these units, we can’t provide accurate information on the tectonic parameters. The presence of a depression on the R5-reflector as seen in seismic profiles northern of the AA’ transect BB’ (Figure 23) may also prelude another factor affecting the evidenced morphology. This factor may be related to karstic formations such as dolines, usually found in karstic limestones, which represent the lithological bedrock of the Eastern Astypalea.
Figure 23. Bathymetric map of Vathy bay, showing the location of the seismic line BB’. High-resolution seismic profile (SES Innomar S) of the BB’ transect with a 5.5× vertical exaggeration of the sedimentary basin of Vathy (the interpreted above and the uninterpreted below). The interpreted seismic profile shows the geometry of the reflectors within the detected seismic facies and highlight features recognized such as onlap termination, erosional unconformity, bathymetric depression, and a possible fault.

3.1.4. Paleobathymetric maps

Five paleobathymetries of Vathy bay were produced based on the interpolated digitized reflectors (R5 to R1, Figure 24) of the Chirp S seismic profiles. The paleobathymetries are presented from the deeper (older) to the shallower (younger) showing the transformation of the basin morphology.

The older paleobathymetry of R5 reflector, which represents the acoustic basement of the basin, shows an anomalous morphology. The basin presents a deepening trend towards the east, with maximum depth of 20 m (Figure 24-R5). Two depocenters are revealed in this paleobathymetry, one in the central part of the basin with a depth of 18 m, and another one in the eastern part with a 20 m depth. The depocenter of 18 m is of smaller diameter than the one of 20 m, and represents the depression seen in Figure 23.

The paleobathymetry of R4 reflector presents a deepening trend towards the east with maximum depth of 16 m (Figure 24-R4). Its morphology is developed in plateau-like shape. At the south-eastern part of this paleobathymetry, a round shaped depocenter is evidenced and can be also seen at the eastern part of the AA` seismic profile.

The upper three paleobathymetries of R3, R2, and R1 show an almost flat morphology in contrast to the lower R4 and R5, with maximum depths of 14 m, 12 m, and 10 m respectively. The produced paleobathymetries show an overall infill trend of the basin towards the west with maximum sediment thickness centered at the eastern and central part of the bay as seen in the produced sediment thickness map (Figure 25).
Figure 24. Paleobathymetries of the seismic reflectors from older to younger (R5 to R1) of Vathy bay.

Figure 25. Sediment thickness accumulation map of the Vathy basin.
3.1.5. Areas of archaeological interest and ground-truthing

The underwater landscape surrounding Cape Elliniko, where the archaeological site is located, is of particular interest in terms of geomorphological configuration. More specifically, the underwater extension of the cape is characterized by two terraces (step-like seabed forms) at a water depth of -2 m. and -4 m., respectively, as seen in the high-resolution slope map produced by the MBES (Figure 26). The terrace at -2 m. forms a small, slightly inclined (~2.7°) area, peripheral to the cape, while the terrace at -4 m. forms an extended almost horizontal (~1.7°) area (Figure 26). This stepped-like underwater extension of the cape is of particular palaeogeographical interest, as under lower sea level conditions in the past, might have been subaerially exposed, making it possible to be exploited by human populations of those times. This can be further supported by the fact that the onshore archaeological remains (yellow outlines, Figure 17), especially the ones placed on the coastline, terminate in the sea as can be seen through the onshore topographic features, indicating the presence of a distant former coastline.

Figure 26. Slope map based on the MBES bathymetry around the cape Elliniko showing the terraces at -2 m and -4 m depth (underwater rocky terraces) and the onland archaeological establishments.
To assess whether an underwater expansion of the archaeological remains is possible we examined the higher frequency (500kHz) backscatter intensity data of this area. The backscatter data of the seabed showed three areas of high interest which have a distinct acoustic character on the mosaic map (Figure 27). The first area is located northern of the cape and contains three conical rubble structures. The second area is placed eastern of the cape and contains structures of sub-linear geometry or features presenting geometric configuration. The third area is evidenced at the southern part of the straits and refers to a linear configuration with significant expansion of about 200 m at 1.5 m depth, developed parallel to the southern coast.

Figure 27. Areas of interest (highlighted targets with yellow color) detected on the 500kHz mosaic map of the area around cape Elliniko.

The examination of the seismic profiles in this area pointed out another area of interest including a formation slightly buried under the sea floor which is not evidenced on the mosaic map (Figure 28). The spatial expansion of this formation was determined through the digitization in the seismic profiles crosscutting this area. Its range is 60 m long and 15 m wide following a linear geometry and extends from 8 to 8.5 m depth eastern of the cape following the seabed topographic relief (seen in Figure 26). It is presented as a prolonged, continuous,
intense reflection and creates acoustic shadow to the underlying layers which is a feature produced by dense material with different lithological composition than the surroundings and interrupts the continuity of the stratigraphy. This linear formation is incorporated within the uppermost SF1 of the seismic stratigraphy and does not ascend to the seafloor. This raises the scenario of a non-natural origin but rather points out a man-made configuration.

**Figure 28.** Location of the buried target on the mosaic map.

All four areas of interest were further examined through underwater visual inspection with an ROV. The visual inspection showed the presence of cubic-shaped boulders in linear configuration at the southern part of the straits, which could indicate a submerged construction (e.g., wall) developed parallel to the southern coast. Northern of the cape, three conical rubble structures were determined to be comprised of cubic-shaped boulders. At the north- and south-eastern to the cape area stones in geometric configuration and curved boulders were also detected and point out either possible submerged archaeological remains or collapsed products of the onshore constructions. These stone plinths have the regularity of Hellenistic isomorphic structures (Vlachopoulos 2020, fig. 7), connected to the tower and the accompanying building,
(see Vlachopoulos 2023a). The derived visual data were accurately positioned and plotted on a map (Figure 29) which led to a first classification of the main seabed sub-types. Nine different seabed sub-types were identified and are presented in Table 2. These data also enabled the construction of a classification map of the detected seabed sub-types showing their spatial distribution (Figure 30).

**Figure 29.** Accurate position of the visual data of the three areas of interest plotted on the mosaic map and their visual display.

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<tr>
<th>Seabed sub-type</th>
<th>ROV snapshot</th>
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<tr>
<td>T1. Sandy seabed with sparse vegetation</td>
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</tr>
<tr>
<td>T2. Sandy seabed with scattered stones and sparse vegetation</td>
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<tr>
<td>------------------------------------------------------------</td>
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</table>


T5. Seabed with boulders

T5. Seabed with boulders
T6. Seabed with geometrically arranged stones or boulders.
T6. Seabed with geometrically arranged stones or boulders
Table 2. The nine seabed sub-types identified in the area where the underwater visual inspection took place.

3.2. Sediment core analyses

3.2.1. Core-chronology

Bayesian age-depth modeling was performed using the R package Rbacon (v.2.3; Blaauw and Christen, 2011) (Figure 31). Calibrated radiocarbon dates are reported as “cal. BP” (before present, this is before 1950), according to Mook and van der Plicht (1999). The radiocarbon measurements indicate that the sediment core spans the Holocene time interval (Table 1). The
core bottom is dated at 9.1 ka cal. BP, whereas the core top has an age of 100 years cal. BP. The sedimentation rates decreased upward from 53 to 20 cm/ka (Figure 31).

![Figure 31. Bayesian age-depth model for ASTC1 sediment core in cal yr.](image)

### 3.2.2. Sedimentary units

Sedimentary Units Macroscopic observations, together with sedimentological, color reflectance, and geochemical data, suggest that the core ASTC1 consists of three main Lithological Units LU-I to LU-III (Figure 32).

The uppermost LU-I extends from a 0 to 80 cm core depth, and it comprises grayish brown to very dark grayish brown sandy mud. Within LU-I, the Fe values decline upwards, while the Ca values and the b* record are in general high. Microscopic observations revealed the frequent presence of glass shards in the sediments of this unit. Based on the proposed age model, the LU-I spans the time interval between 4.1 ka and the present.

LU-II extends from 80 to 160 cm core depth, and it comprises very dark greenish gray and very fine silt to sandy mud. The base of LU-II is characterized by low values of Ca and b* record, which mark the transition between this unit and the underlying LU-III. The values of
Ca increase toward the top of the unit, while the values of Fe show an opposite trend. The timing of the deposition of unit II is estimated to be between 6 and 4.1 ka. LU-III extends from the base of the core (320 cm) up to 160 cm, and it comprises a very fine to silt grain size of dark olive brown sediments.

LU-III is characterized by a laminated pattern, in contrast to the more homogeneous upper and middle LU-I and LU-II. In addition, frequent short-scale variability in the values of Ca, Fe, and b* records, is observed within LU-III. The base of this unit is estimated at 9.1 ka.

Figure 32. Correlation diagram between seismic (left) and lithostratigraphic units of ASTC1 sediment core (right). The seismic profile (total thickness) includes the core position and the different seismic facies, SF1–SF5, based on the pulse length. The lithological units are defined on the downcore *b color reflectance record, the grainsize, Ca, and Fe XRF counts. The calendar ages of the sediment core obtained in this study have been assigned to the depth axis.
The downcore variations in the above-mentioned proxies (grain size, values of Ca and Fe, and values of b* record) were compared to the pulse length variation retrieved at the core site. An uncertainty of 1–5 cm is implemented by the seismic profile and the extracted pulse length according to the instrument’s specifications; thus, the correlation to the sediment core units is not linear. The comparison showed that lithological units I to III correlate well with seismic facies 1 to 3, respectively, on the seismic profile (Figure 32). The higher amplitude (large pulse length) recorded in SF1 most probably corresponds to the higher density of the sediments of LU-I. In contrast, the fine-grained sediments and the low densities in LU-III correspond to the low pulse length recorded in SF3.

3.2.3. Carbonate Precipitates

To evaluate the types of carbonate precipitation at the core site, the variations of the Sr/Ca and Mg/Ca ratios were examined. In shallow water marine carbonates, a high Sr/Ca ratio often represents the occurrence of aragonite (Kinsman, 1969; Rothwell et al., 2006). High-Mg calcite and aragonite content is usually found in sediments lying under oversaturated water columns, such as in shallow water depth basins and/or at low latitudes (Kinsman, 1969; Wilkinson & Given, 1986). In the ASTC1 core, the downcore variations of these ratios revealed two different carbonate mineral precipitates (Sr-rich and Mg-rich), and their dominance in specific intervals allowed for a further distinction of the lithological units into subunits (Figure 33). Units III and II were divided into subunits IIIA-IIIC and IIA-IIB, respectively. The highest Mg/Ca values are recorded in subunits IIIC (8–9.1 ka) and IIB (5.4–6 ka), while the highest Sr/Ca values are recorded in IIIA (6–7.3 ka) and IIIC (8–9.1 ka). Although the two carbonate precipitates occur individually, they co-occur in subunit IIIC, presenting a mixed carbonate precipitate pattern. On the other hand, the high Sr/Ca ratio in IIIA suggests that the water conditions were in favor of aragonite formation in the Vathy basin between 7.3 and 6 ka, possibly in the presence of discrete concretions (white laminae) (Figure 33). Notably, samples taken from IIIB and IIB, which correspond to low and zero values of both Sr/Ca and Mg/Ca, contain abundant calcified remains of charophytes, such as cortex and thalli encrustations and gyrogonites (Figure 34c–e). In closed or semi-closed water bodies, precipitation of high-Mg calcites (high values of Mg/Ca (Kelts & Hsü, 1978)) and/or aragonites (high values of Sr/Ca (Bayon et al., 2007)) could be of inorganic origin associated with increases in salinity under enhanced evaporation (Brunović et al., 2020; Kelts & Hsü, 1978; Koutsodendris et al., 2015) and/or of biogenic and
biological processes associated with algal blooms and removal of CO\textsubscript{2} (De Choudens-Sánchez & Gonzalez, 2009; Sondi & Juračić, 2010).

**Figure 33.** Synthetic plot of ASTC1 sediment core proxy record. From bottom to top: Sr/Ca (cps) and Mg/Ca (cps) geochemical ratios, total organic carbon content (%TOC) and TOC/TN (%), stable isotopes (\(\delta^{13}\text{C}\) and \(\delta^{18}\text{O}\)), the chronologically adjusted lithological units of ASTC1, and their boundaries marked with the dashed gray line. Red color refers to Ammonia spp., green to ostracods, and purple to Quinqueloculina spp. Dots represent the absolute values of \(\delta^{13}\text{C}\) and \(\delta^{18}\text{O}\) whereas the colored lines refer to the 5-point running average. The black line refers to the 5-point running average of the mean \(\delta^{13}\text{C}\) and mean \(\delta^{18}\text{O}\) values. Three point running averages (thick line) were also calculated for Mg/Ca, Sr/Ca, C\textsubscript{org} and C\textsubscript{org}/N.

### 3.2.4. Mollusks and Foraminifera

Observations made on the mollusk and benthic foraminifera of core ASTC1 are provided in Table S1. LU-I contains diverse mollusk fauna in the upper part (1–50 cm) and intermediate-low diverse and less abundant marine fauna in the lower part (50–75 cm). The mollusk faunas
in this unit are dominated by *Varicorbula gibba*, *Nucula nucleus*, *Acanthocardia paucicostata*, *Parvicardium exiguum*, and smooth *Dentaliidae*, indicative of a shallow marine seafloor with high organic content and potentially (seasonal) hypoxic conditions (Fuksi et al., 2018). *Bittium reticulatum*, *Rissoa parva* s.l., and *R. membranacea* s.l. commonly occur in the upper part (typically but not exclusively suggesting subaqueous vegetation), while the abundance of *Abra alba* s.l. in the lower part of LU-I indicates fine-grained soft bottoms (Leontarakis et al., 2008). Benthic foraminifera assemblages are dominated by epifauna and epiphytic species (*Quinqueloculina* spp., *Peneroplis* spp., *Rosalina* spp., *Planorbulina* spp.) (Barmawidjaja et al., 1995; Debenay & Payri, 2010; Faber, 1991; Frontalini & Coccioni, 2011), and infauna species (*Ammonia* spp., *Melonis* spp.) that favor high organic matter and tolerate dysoxia (Barmawidjaja et al., 1995; Jorissen et al., 2018). The lower part of unit I, an increase in infauna/epifauna ratio is observed suggesting a reduction of oxygen conditions in the bottom waters (Dimiza et al., 2016).

Common mollusk species in subunit IIA include *Rissoa parva* s.l., *Parvicardium exiguum*, and *Acanthocardia paucicostata*. The upper part of this subunit (80–90 cm) contains a low-intermediate diverse fauna dominated by *Varicorbula gibba*, while other species, such as *Bittium reticulatum*, *Abra alba* s.l., *Nucula nucleus*, and *Pussilina inconspicua* s.l., also occur. The faunal composition of the lower subunit IIA (91–110 cm) is slightly variable and dominated by *Abra alba*, while some *Cerastoderma glaucum* s.l. occurs at the base. Subunit IIB contains faunas entirely dominated by *Cerastoderma glaucum* s.l., and a few *Abra alba* fragments also occur. These species have been found in the littoral zones of carbonate-rich freshwater or brackish shallow water lakes ((Khanaqa et al., 2013) and references therein). *Cerastoderma glaucum*-dominated populations are often found in euryhaline or in mesohaline settings, and they can dominate in lagoons, saline lakes, and estuaries (Rohling et al., 2002). Within this subunit at 139.5 cm depth, a layer consisting of *Characeae* occurs that lacks marine shells (Figure 34c–e). Benthic foraminifera assemblages also present low abundance and low diversity in subunit II. Dominant taxa are *Ammonia* spp. and *Quinqueloculina* spp., while *Miliolinella* spp., *Melonis* spp., and *Triloculina* spp. are also present. These genera have been linked to inner shelf environments, from brackish to hypersaline lagoons ((Murray, 2006) and references therein).
Figure 34. (A, B) mollusc fragments, (C) Gyrogonite (Charophyte oogonial cell), (D) Calcified remains of a charophyte cortex (thalli encrustation), (E) Calcified Charophyte cortex and Gyrogonites, (F) Bivalve (*Acanthocardia paucicostata*), and carbonate aggregates, (G) Clastic grains and fish bones.

Some mollusk species were found only in upper unit III (subunit IIIA), mainly dominated by *Varicorbula gibba*, and some *Cerastoderma glaucum* s.l., occurring at 174.5 and 231.5 cm. The presence of other mollusk faunas is rare, mainly found at the top of IIIA (161.5 cm), including the species *Rissoa parva* s.l., *R. membranacea* s.l., *Nucula nucleus*, *Bittium reticulatum*, and *Acanthocardia paucicostata*, which were also present at the younger units of ASTC1 core. Benthic foraminifera specimens were observed only in IIIA, and when they were
present, they usually belonged to the genera of *Ammonia* spp., *Quinqueloculina* spp., *Melonis* spp., *Haynesina* spp., and *Rosalina* spp.

Below subunit IIIA, no fossils were found (Figure 34) apart from very few ostracods and charophytes (oospores and gyrogonites) in subunit IIIB and upper IIIC (at 270, 285, and 295 cm depth).

### 3.2.5. Organic Carbon Accumulation and Source

The Organic Carbon (C$_{\text{org}}$) content varies between 0.1–2% in total and follows a general upward decreasing trend throughout ASTC1. Enriched C$_{\text{org}}$ (>0.5%) values have been recorded within unit III and subunit IIIB (9.1 to 5.4 ka), and upper unit I (0.8 ka to present) (Figure 33). The highest C$_{\text{org}}$ values were observed at around 6.1, 6.9, and from 7.6 to 7.4 ka. C$_{\text{org}}$/N ratio varies from 0.6 to 12.4 throughout the ASTC1 record, suggesting a mixed marine/terrigenous type of organic matter (Meyers, 1993) for the bigger part of the studied interval (Figure 33). The highest C$_{\text{org}}$/N values (>10) occur in subunits IIIC, IIIB, and IIB, suggesting a terrestrial organic supply (Meyers, 1993, 1994) for these intervals (9.1–7.3 and 6.1–5.4 ka).

### 3.2.6. XRF-Factor Analysis and XRD results

To investigate the distribution of the elemental concentrations along the core we applied factor analysis (FA) on the XRF counts and compared these results with specific elementary ratios and the XRD data (Figures 35, 36). The first four factors are considered to be significant and explain ~83% of the dataset variability (Figures 35, 36, Table S3). The first factor (FS1; explained the 54.1% of the total variance, Table S3) includes Al, Si, K, Ti, Cr, Ba, Fe, Co, Cu, Zn, Ga, Rb, Y, Zr, Rb and Pb which are commonly considered as terrigenous indicators (Zabel et al., 2003) with positive loadings, and Ca, Sr and As with negative loadings. Ca and Sr are chemically similar and are major constituters in carbonate sedimentation (Cuellar-Martinez et al., 2017, and references therein), while As is probably associated with volcanic formations surrounding the study area (Nordstrom, 2002) or pyrite authigenesis (Thomson et al., 2006). Therefore, FS1 depicts the intervals of the core sediments where the presence/absence of carbonates is significant. The downcore variations of the FS1 scores show that the high concentrations of carbonates (negative scores) occur within the LU-IIIA and IIIB and LU-I and the lowest values (positive scores) in LU-II and IIIC (Figure 36). In an attempt to investigate...
the nature of the carbonate sedimentation we used the following element ratios: the Ca/K ratio, as an index for the biogenic carbonate contribution, since K is mainly related to illite; Sr/K and S/Ca ratios, as indexes for the authigenic carbonate sedimentation, since aragonite is rich in strontium while gypsum rich in S; and the Ca/(S+Sr) ratio to depict the detrital carbonate fraction, since aragonite and gypsum are removed (Neugebauer et al., 2016, 2015). Within the LU-III, the values of these ratios fluctuate in accordance with the subunits and show high values of S/Ca in the subunit LU-IIIC and frequent alternations of the ratios S/Ca and Sr/K in the LU-IIIA (Figure 36). These observations coincide with the XRD measurements and suggest the presence of gypsum and alternations of gypsum and aragonite within LU-IIIC and LU-IIIA, respectively (Figure 36). On the other hand, the detrital carbonate fraction (high Ca/(S+Sr)) characterizes the subunit LU-IIIB. The biogenic carbonate fraction also contributes to the LU-IIIA and LU-IIIB, and partially coincides with brief intervals where microfauna shells were observed (suppl. Table S1: Noti et al., 2022). However, the most significant contribution of biogenic carbonate sedimentation is found within LU-I where the record presents constantly high values of Ca/K and Sr/K (Figure 36). The XRD measurements indicate that these high Sr/Ca values are linked to the presence of aragonite. The high biogenic carbonate fraction within this interval can be explained by the high abundances of microfauna assemblages within LU-I of which the dominance of benthic species related to dysoxia or seasonal anoxia may explain the aragonite precipitation (Noti et al., 2022).

The second factor (FS2; explained the 12.6% of the total variance, Supplementary Table S3) includes as significant variables the XRF counts of Cl, Br and I. All these elements are considered as salinity indicators. The downcore variations of the FS2 are high within LU-II and LU-I (Figure 36), suggesting a marine influence at the core site at that time. This observation correlates well with the microfauna assemblages which suggest the presence of a lagoon at the core site within LU-II which later on within LU-I, developed into a marine bay (Noti et al., 2022). The third factor (FS3; explained the 6.5% of the total variance, Table S3) included the XRF counts of Mg, Mo and S. All these elements are associated with sediments rich in organic material (Algeo & Lyons, 2006; Nieto-Moreno et al., 2011). The high values of FS3 correlate well with the enhanced presence of pyrite (Huerta-Diaz & Morse, 1992; Łukawska-Matuszewsk et al., 2019) and the increased C_{org} content (Noti et al., 2022) within LUIII A & B (Figure 36), suggesting enhanced accumulation of organic matter. The fourth factor (FS4; explained the 4.5% of the total variance, Supplementary Table S3) included only
the XRF counts of Mn. Although, Mn is considered as a redox-sensitive element and usually is involved to depict diagenetic processes in the marine sediments (Raiswell & Canfield, 2012), it is also related to detrital sediments since Mn oxyhydroxide precipitates are dispersed within sediments in the form of coatings of detrital particles (i.e., Bayon et al., 2004). High values of FS4 observed mostly within LU-IIIB (Figure 36) and correlate well with strong presence of quartz, suggesting a detrital source for this element.

**Figure 35.** XRD mineral phases measured in ASTC1 sediment core. The sample name indicates the sampled depth on the sediment core.
Figure 36. From left to right: Factor scores FS1 (terrigenous vs carbonates) and FS2 (marine influence), geochemical ratio Ca/K (biogenic Ca), Sr/K and aragonite, S/Ca and gypsum, Ca/(S+Sr) (detrital), factor scores FS3 (rich in $C_{org}$ sediments) and FS4 (detrital)
geochemical ratios of Ca/(S+Sr), Sr/K, S/Ca, Ca/K, XRD results (aragonite, gypsum, pyrite, plagioclase, quartz) and the factor scores FS1, FS2, FS3, FS4 of ASTC1 record.

3.2.8. XRF- Elements and elemental ratios

The main patterns in the elemental composition of the Astypalea core (Figure 37) indicate that the sediments are dominated by an opposing decreasing trend of the terrigenous sourced elements, such as Aluminum (Al), Silicium (Si), Titanium (Ti) and Zircon (Zr), and increasing trend of carbonate elements, such as Strontium (Sr) and Calcium (Ca). A sharp transition between the terrestrial and carbonate elemental concentrations occurs around 6.0 ka, which marks the boundary between LU-II and LU-III of which the latter is characterized by a laminated interval with up to 2% C_{org} concentrations.

Sr and Ca show a high similarity along the record (Figure 37) except for two brief periods between 8.0 and 7.4 ka, where probably an additional detrital source of Calcium may have enriched the Ca values with respect to Sr, which is usually used as marker for biogenic origin as it is incorporated into aragonite (Foubert & Henriet, 2009; Richter et al., 2006). The close resemblance between the Si and Al records indicates furthermore that there is no clear evidence for large changes in biogenic silica production.

Ti and Zr are known to be enriched in aeolian dust from the Sahara Desert (Guieu & Thomas, 1996; Wehausen & Brumsack, 2000) and both have been used as a dust proxy in the Mediterranean region when they are divided by Al (Jimenez-Espejo et al., 2008; Lourens et al., 2001; Rodrigo-Gámiz et al., 2011). Accordingly, we chose to compare the trends of two elemental ratios, the Ti/Al and Zr/Si to investigate possible changes in dust input at the site (Figure 37). Clearly, both ratios show a high similarity and a general increasing trend towards the present with maximum values between 3.5 and 2.5 ka (Figure 37).
3.2.9. Stable Isotopes

The stable isotope data of *Ammonia* spp., *Quinqueloculina* spp., and ostracods comprise the past 7.3 ka of the ASTC1 sediment core (Figure 33). There appears to be relatively large variability between the individual samples in both δ¹³C and δ¹⁸O values, which may point to a large seasonal imprint on the picked and analyzed specimens. To derive a clearer picture of the isotopic trends within the Vathy bay over the past 7.3 ka, we applied a five-point running average. Evidently, the δ¹³C and δ¹⁸O trends derived from this approach show that the
individual microfauna followed a highly comparable (similar) pattern during the Holocene (Figure 33).

Unit I and subunit IIIA are characterized by mean δ\(^{13}\)C ratios of −2 to 0‰ and become more negative downwards in unit II, especially at its basal subunit IIB (−4 to −2‰) (Figure 7). Similarly, the average δ\(^{18}\)O ratios of unit I and subunit IIIA are generally high (i.e., an average value of 0.4 to 0.8‰) compared to those of unit II (i.e., ranging between −0.1 to 0.2‰). The δ\(^{13}\)C and δ\(^{18}\)O ratios became higher toward the top of the core (Figure 33).

Offsets in the isotopic signal between Ammonia spp. and Quinqueloculina spp. have been attributed to a combination of vital effects and seasonal differences in the timing of shell calcification (Austin & Scourse, 1997; Scourse et al., 2002, 2004; Woods et al., 2019). Scourse et al. (2004) showed that Ammonia batavus calcifies during the same period as Quinqueloculina seminulum (September) when stratified conditions occur in a continental shelf environment. When conditions change to mixed conditions, Ammonia batavus calcifies during spring or early summer. Epifaunal taxa are commonly close to the isotopic signature of bottom water δ\(^{13}\)C DIC whereas infaunal taxa bear a strong pore water signal, which is marked by depleted δ\(^{13}\)C (Cheng et al., 2015; Fontanier et al., 2006; Grossman, 1984; Mackensen et al., 2004; Martin et al., 2003; McCorkle et al., 1990, 1997; Rathburn et al., 1996; Roeser et al., 2016; Schemmel et al., 2017; Schmiedl et al., 2004).

3.2.10. Spectral analysis

We applied spectral analysis on the detrended Ti/Al and Zr/Si time series to evaluate if they are determined by cyclic variations (Figure 39). This analysis revealed the prevalence of three major frequencies within our record, of which a 2493-2685-year cycle dominates the signal (highest power; 99% c.l.), followed by a 1091-1396-year cycle (90% c.l.), and 521–553-year cycle (95-99% c.l.) (Figure 39).
**Figure 38.** Spectral analysis results of the detrended time series of: (left top and bottom) Ti/Al and Zr/Si detrended record of ASTC1 sediment core, and (right top and bottom) the 20-pt moving averaged GISP2-K record (Mayewski et al., 2004) and stacked North Atlantic Ice indices (Bond et al., 1997) between 0 and 9 ka. The brown shaded areas indicating the spectral results obtained from the Multi Taper Method (and Lomb Scargle for the North Atlantic Ice Indices) in ACycle (M. Li et al., 2019) and the solid black lines are those obtained from the standard Blackman-Tukey power estimates in AnalySeries (Paillard et al., 1996). The red solid curves indicate the MTM (LS) (AR1) confidence levels at 99%, the red dashed lines at 95% and red dotted lines at 90%.

To further investigate the cyclic patterns in the Ti/Al and Zr/Si time series, we extracted their main spectral components using a Gaussian filter centered at their peak frequency (Figure 40). In the first panel of each figure, we have plotted the fourth order polynomial fit used for detrending. In the 2nd – 4th panels, we have subsequently plotted the extracted ~2500-year, ~1200-year and ~525-year components (red dashed lines). In both Zr/Si and Ti/Al time series, all filtered components reveal an increasing amplitude towards the present (red lines of the first panel), indicating that their variability increased during the Holocene. The lowest variability is found in LU-III between 6 and 8 ka (Figure 40). The two proxy records show an almost in-phase relationship for all three filtered signals.
**Figure 39.** Comparison between the major cycles (dashed red lines) identified in the Zr/Si and Ti/Al time series as overlays to their original detrended series (black solid lines). The original Zr/Si (grey shaded area) and Ti/Al (black solid line) records are shown in the left panel (first panel) including their fourth order polynomial fit as indicated by red dotted and solid lines, respectively. The second, third, and fourth panel refer to the 2500-yr, 1200-yr, and 525-yr filtered components of the two proxies respectively.
4. Discussion

4.1. Paleoenvironmental Evolution

Combining all proxies enabled the documentation of several phases within the depositional system and its biota and the identification of the driving mechanism of environmental change. More specifically, the sediments of the lower LU-III represent a transition from a terrestrial to a water-logged environment. The absence of any shells in subunit IIIC (9.1 to 8 cal ka) indicates the development of a terrestrial environment isolated from the open sea (Figure 41). This is further supported by terrestrial organic matter with high C$_{org}$/N values (Figure 33). On the seismic profiles (Figure 22), the strong reflections of uneven surfaces recorded at the base of the SF3 provide evidence for the deposition of high-density, subaerial exposed, and eroded sediments, along at least an area between the core site and the sill of the bay (Figure 22).

In the overlying seismic phases SF1–SF3, the acoustic signal amplitude decreases (Figure 22). Internal reflections are horizontal, suggesting subaquatic sediment deposition. This change correlates with a shift in the biological content occurring in the sediment samples of subunit IIIB. Episodic presence of Charophyta (Figure 34) in the examined samples from subunit IIIB, indicative of freshwater conditions (Martin et al., 2003), implies the establishment of an ephemeral pond/lake, at least at the core site between 8 and 7.3 cal ka. Within this interval, the organic carbon content is elevated, and thus may indicate low rates of organic matter metabolism under intense water stratification and/or high rates of organic matter flux. High organic matter intervals mostly coincide with high C$_{org}$/N ratios, suggesting an increase in terrestrial organic supply. In addition, minor fluctuations of Sr/Ca and Mg/Ca ratios coincide with high C$_{org}$ content suggesting that within this interval the precipitation of Sr-rich and Mg-rich calcites in the sediments of the pond/lake was favored at times of anoxic bottom water conditions or enhanced lake productivity ((Roeser et al., 2016) and references within).

These short-scale environmental changes may be linked to minor climatic fluctuations in the area. According to the proposed age model, it is estimated that subunit IIIB was deposited between 8 and 7.3 cal ka, an interval where previous studies have shown EM humidity fluctuations (i.e., N. Aegean Sea (Schemmel et al., 2017); Lebanon, Jeita Cave (Cheng et al.,
within a general warm period (Rohling et al., 2019). These climatic conditions contributed to an oceanographic regime that led to the deposition of the second sub-sapropel S1b in the EM (7.9–6.5 ka, Hennekam et al., 2014). Increased precipitation at the Vathy bay area likely enabled the establishment of an ephemeral pond/lake, where the high temperature would have enhanced water stratification, oxygen deprivation, and organic matter accumulation.

**Figure 40.** Reconstruction of the different basin phases within the 9.1 ka time interval. Each phase represents the lithological unit of the ASTC1 sediment core. Global mean sea level, following Lambeck et al. (2014).
During the successive deposition of subunit IIIA, organic matter accumulation increased (Figure 41), and marine/euryhaline shells occurred at 7.3 ka (Table S1), indicating that marine conditions had been established.

The mollusk and benthic assemblages are of low abundance and low diversity, and the laminated character of subunit IIIA indicates the prevalence of low oxygen conditions on the seafloor. In addition, high values of Sr/Ca ratio together with heavier δ¹⁸O values point to the establishment of high salinity waters (Ariztegui et al., 2010). Within this interval (7.3–6.2 ka), arid conditions have been reported in the Anatolia region (Cheng et al., 2015; Clarke et al., 2016; Eelco J. Rohling et al., 2019). The studied area also experienced aridity during this period, with the high evaporation rates inducing the precipitation of aragonite, pointed out by the high Sr/Ca ratio, in this newly established marine environment (Koutsodendris et al., 2015 and references therein).

This contrasts with the findings of the overlying subunit IIB (6–5.4 ka), where the mollusk and the benthic foraminifera assemblages suggest the establishment of a lagoonal environment (Murray, 2006; Ben Dor et al., 2019 and references therein). The depletion in the δ¹⁸O values and the cease in the precipitation of aragonite (low values of Sr/Ca ratio) imply a reduction in salinity in the waters (Ariztegui et al., 2010). Previous studies have shown an increase in humidity and a decrease in temperature during this interval (Rohling et al., 2019; Cheng et al., 2015). Thus, an increase in the freshwater supply together with low temperature, along with the elevated increase in the water depth, may have altered the former hypersaline marsh into a lagoon.

The continuous sea level rise led gradually to the dominance of marine waters over low salinity waters. This signal started to be observed within subunit IIA. There, the increase in the abundance and diversity of mollusk and benthic foraminifera assemblages, together with an enrichment in the stable oxygen isotope values, suggests the prevalence of more saline waters and more oxygenated seafloors. In addition, from IIA onwards, the low values of C<sub>org</sub>/N ratio suggest that the organic matter is of marine origin (Perdue & Koprivnjak, 2007). As for subunit IIA and onwards, the seafloor environmental conditions do not present any influence by the sea level changes but rather appear to be regulated mainly by the internal oceanographic conditions developed in the bay. The dominance of benthic foraminifera and mollusk species

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that tolerate dysoxia and/or favor high organic matter contents suggests that stressful bottom conditions prevailed in the Vathy bay from 5.4 to 4.1 ka, corresponding to the deposition of subunit IIA and the lower part of unit I. An improvement in the bottom water oxygen concentration is suggested for the last 4 ka in the bay, based on the dominance of microfauna sensitive to oxygen availability. The high-water depth (−0.5 m) reached at 2.5 ka (Lambeck et al., 2014) may have enhanced the water circulation in the bay, bringing fresh oxygenated waters from the open sea, and thus improving the seafloor conditions.

4.2. Global Sea Level and Flooding of the Bay

According to the proposed age model of the present study, subunits IIIC and IIIB were deposited from 9.1 to 7.3 ka. Within this interval, the models for the global eustatic sea level change show that the sea level rose from −27 m (at 9.1 ka) to −8 m (at 7.3 ka) (Benjamin et al., 2017; Lambeck et al., 2014). Such sea levels are well placed below the present depth of the sill (−4.7 m) suggesting that the bay (and the core site) was isolated from the open sea for the total period of the depositions of IIIC and IIIB (Figure 42). This observation further supports the nature of the depositional environments attributed previously to subunits IIIC and IIIB (land and pond/lake, respectively). On the contrary, the 4 m difference between the global mean sea level stand and the depth of the sill at the time of the onset of subunit IIIA (7.3 ka) cannot explain the inundation of the sea according to the eustatic sea-level curve as far as the core site.

To explain this earlier than expected sea inundation in the bay, regional and/or local scale factors should be further investigated. Onlap geometries of the upper sedimentary sequences recorded in the inner basin could indicate differences in the rate of sediment supply and/or differences between the rate of sea-level fluctuations and the rate of local tectonic-induced vertical displacements (Vail et al., 1997). For instance, tectonic studies have shown that the entire central Aegean region experienced a general uplift during the Quaternary (Nomikou et al., 2018; Tsampouraki-Kraounaki et al., 2021). However, more specific archaeological data, beach rock formations, and rocky notches from the south Aegean region and the Minor Asia coasts have provided evidence of both subsidence and uplift events of variable magnitude during the Holocene (Bailey & Flemming, 2008; Benjamin et al., 2017; Desruelles et al., 2009; Flemming et al., 2017; Lykousis, 2009; Piper & Perissoratis, 2003; Poulos et al., 2009) linked to intense regional tectonic activity (Piper & Perissoratis, 2003). Although an overall specific
trend (subsidence or uplift) is not provided for the SE Aegean Sea, and for the Astypalea area in particular, their recording indicates that they may produce relative sea level changes that may be incompatible with the already predicted eustatic-isostatic ones (Benjamin et al., 2017; Lambeck et al., 2014; Spratt & Lisiecki, 2016). Following this approach, the scenario of the relative sea level changes of episodic or summarized over time character seems to be plausible and responsible for the earlier-than-expected marine flooding of the bay.

**Figure 41.** Graphical depiction of the evolution of the Bay through time, considering the environmental conditions and the sea level state.

An alternative scenario that could explain the earlier-than-expected flooding of the Vathy basin may involve the possibility of a sea entrance linked with a tsunami. Although the island is situated in an area where earthquakes have triggered tsunamis in the past (Karkani et al.,
2022), the steady presence and the increasing abundance of all taxa associated with saline
waters, from 7.3 ka onwards, suggest that a marine inundation related to a tsunami should be
most likely excluded.

Finally, a likely explanation is that the massive carbonate formations (limestones) on the
island and the associated karstification may have induced the prevalence of sea in the bay,
independent of sea levels. This karstification, in turn, could have formed underground channels
connecting the bay to the open sea, thus establishing a marine lake environment in the bay
between 7.3 and 6.8 ka. Such seawater seepage through karstified sill contributes to the
establishment of brackish marine lake conditions, as shown by other cases on the Dalmatic
coasts (Brunović et al., 2020). The large variability in the C$_{org}$/N ratio in IIIA suggests that the
basin’s connectivity to the Aegean may still have been vulnerable to small changes in sea level
and the freshening of the basin, either by being influenced by karstic communication or by
higher precipitation.

4.3. Climate Evolution and Human Inhabitation

Sapropel S1 is the most well-documented deposition in the marine sediments of the eastern
Mediterranean during the Holocene, related to climatic change (Rohling et al., 2002, 2015). In
our records, the deposition of S1 coincides over time with LU III, dated between 9.1 and 6.0
ka. LU III is rich in organic carbon content (C$_{org}$) (~1.2–2%) and favors Sr-rich (authigenic)
carbonate formation (Sr/Ca) (Figure 33). It is striking that the timing of subunits IIIA and IIIB
corresponds to the second part of the Sapropel S1, the S1b, which was deposited between 7.8
and 6.1, on average, in the EM, while subunit IIIC should coincide with the upper part of the
S1a and the short interruption that was found in the S1 at around ~8.2–7.9 ka (Hennekam et
al., 2014; De Lange et al., 2008; Incarbona et al., 2019). LU IIIA and LU IIIB are characterized
by a laminated pattern. Such parallel laminations are usually recognized in lacustrine or semi-
enclosed water basins, where depositional and hydrodynamic processes favor their formation
and preservation (Koutsodendris et al., 2015; López-Merino et al., 2016; Morellón et al., 2016)
and may be linked to climatic variability. LU III is rich in organic carbon content (C$_{org}$) (~1.2–
2%) and favors Sr-rich (authigenic) carbonate formation (Sr/Ca) (Figure 33). The shallowest
occurrence of sapropel layer S1 in EM sediment cores is found in water depths of ~120 m
(Perissoratis & Piper, 1992), apart from a core (GM2) in the Marmara Sea, where sapropel S1
was found at a water depth as shallow as 37 m (Çağatay et al., 2009). Since the laminated section of ASTC1 was formed when there was no full marine connection, it is highly unlikely that this interval represents an even shallower expression of sapropel S1 in the EM. Instead, due to its timing, it may have been plausible that besides changes in global mean sea level, regional and circum-Mediterranean climatic conditions (Marino et al., 2007, 2009; Rohling et al., 2002) may have played a pivotal role in the formation and preservation of this laminated feature.

In this light, the gradual increase in δ¹⁸Omean values from the upper subunit IIA until the top of LU-I may prelude either the gradual increase of marine water into the Vathy basin (Figures 41 and 42) or the gradual decrease in precipitation in the Eastern Mediterranean (Bar-Matthews et al., 1997; Frisia et al., 2006) or increased aridity in the Aegean (Rohling, et al., 2002a, b). The latter has been suggested by several planktonic δ¹⁸O records of EM (Bar-Matthews et al., 1998, 1999; Grant et al., 2012). At present, however, we cannot distinguish between what part of the δ¹⁸Omean signal is related to this aridification trend in the region and what relates to the relatively larger marine influence within the bay throughout the Holocene. The evolution of the landscape conditions from hinterland to brackish and to coastal environments seems to be conducive to the human settlement in the area. Archeological investigations have shown that settlements of human occupation in the Vathy region go back to at least the Late Neolithic Period at 6 ka (Vlachopoulos, 2016). It is an interval that is generally characterized by relative sea-level stability and human expansion into coastal areas (Griggs, 2017; Devillers et al., 2019). According to several studies, coastal areas characterized by fertile soils and constant freshwater supply, as are the deltaic environments, were more conducive to human settlement and the development of societies and trades along the coasts (Devillers et al., 2019). Similar conditions were developed at Vathy during that period. In our records, during the Late Neolithic period, the Vathy was already connected to the Aegean Sea, though this interval coincides with the establishment of brackish conditions related to the subunit IIA, thus contributing to the sedentarization of humans in the site.

4.4. Holocene increases in aridity in the Eastern Mediterranean

The geochemical data derived from the FA and the ratios of the elements together with the mineral data from the XRD measurements present similar trends and indicate fluctuations in
the sedimentation at the core site since 8.7 ka. The alteration in the site’s evolution was both accompanied by sea level rise and climate change (Noti et al., 2022). During the deposition of LU-IIIC (8.7-8 ka), under lower sea level (-27 to -13 m below present), the core site was isolated from the open sea and authigenic carbonate sedimentation was dominant. Based on all proxy evidence, the accumulation of detrital material increased between 7.3-8 ka (LU-IIIB). This interval is associated with increased humidity in Aegean region as pointed out by studies in marine and terrestrial records (i.e., Geraga et al., 2010; Schemmel et al., 2017) and corresponds to the later phases of the African Humid period. This shift to wetter conditions is attributed to increased boreal insolation and the northward shift of the Intertropical Convergence Zone (ITCZ, i.e., deMenocal et al., 2000). The high aragonite and gypsum percentages found in LU-IIIA between 7.3 and 6 ka are most likely associated with increases in salinity under enhanced evaporation in isolated and restricted water bodies (Koutsodendris et al., 2015), when the connection between the Vathy basin and the open sea was gradually being developed (Noti et al., 2022). On the other hand, the occurrence of pyrite together with the increased values of organic material and biogenic fraction indicators, may also provide evidence for a biological origin of the carbonate precipitates (Sondi & Juračić, 2010) in this subunit. After 6 ka, the salinity indicators and the biogenic fraction present increasing trends and reflect the permanent connection of the study area to the open sea, forming at the initial phases a lagoon (LU-II; 6-4.1 ka) and then a bay (LU-I, 4.1-0 ka, Noti et al., 2022).

Beyond the impact of the sea level rise, the examination of the retrieved sediment record depicts that climatic variability also resulted in changes on the geochemistry record of the study area. In order to further investigate the climatic variability, we focused on the records of the Ti/Al and Zr/Si ratios whose fluctuations as discussed previously (section 3.2) represent long- and short-term changes in dust supply and thus could be associated with aridity intensification. During LU-I & LU-II, a general increasing trend of both ratios, together with a general enrichment in the δ¹⁸O values (Noti et al., 2022) suggest an increase in dust supply and in aridity at the core site, over the last 6 ka. Around that time drier conditions and/or increases in dust flux started to be recorded in the Balkans (Finné et al., 2019; Longman et al., 2017 and references within), in Anatolia region (on speleothems, Cheng et al., 2015), and marine sediment data i.e., Hennekam et al., 2014; Schmiedl et al., 2010) and in North Africa region (Palchan & Torfstein, 2019). This shift to drier conditions in the eastern Mediterranean has been attributed to the southward migration of the ITCZ during the middle and late Holocene.
(i.e., Fleitmann et al., 2003). The retreat of monsoonal rains by the end of the African Humid Period resulted into the onset of Saharan desertification (deMenocal et al., 2000). From about that time (Ehrmann et al., 2017) and up to present Sahara constitutes a major source of dust influx to the eastern Mediterranean region (Avila et al., 1998; Beuscher et al., 2020; Ginoux et al., 2012).

In the Astypalea record, though, short term fluctuations in both Ti/Al and Zr/Si ratios, suggest brief oscillations of increased terrigenous supply associated most probably with increases in aridity. High values of both Ti/Al and Zr/Si ratios cluster at around 8.4 ka, 8.1 ka, 7.7 ka, 4.9 ka, 4.6 -4.2 ka, 3.8 ka, 3.3-2.4 ka, 1.8-1.5 ka and 0.6-0.3 ka (Figure 43). Previous studies of high resolution datasets from lake sediments (Peloponnese: Emmanouilidis et al., 2022; Katrantsiotis et al., 2019; Unkel et al., 2014; Turkey: Eastwood et al., 2007), speleothems (Peloponnese: Finné et al., 2014, 2019; Leb-anon: H. Cheng et al., 2015) and marine sediment cores (North Aegean Sea: Gogou et al., 2016; Hamann et al., 2008; Western Greece: Koutsodendris et al., 2017; Israel: Hennekam et al., 2014) have shown numerous arid events, in the EM within the Holocene, and several of these events appear at intervals similar to our record, although the exact time of their occurrence is variable among the records probably due to small dating uncertainties. Among them, the most widely documented arid events are those centered at 8.2 ka, 6-5 ka, 4.2 ka, 3.5-2.5 ka, 1.2-1 ka and the 0.65-0.15 ka and some of them are globally referred as the Holocene “Rapid Climate Change” events (RCCs, Mayewski et al., 2004, and references therein). However, the main RCCs expressed in the EM, and specifically in the Aegean Sea records are those between 8.6-8.0 ka, 6-5.2 ka, and 3.1-2.9 ka, which are relevant with the increases suggested by our record. Other severe millennial events in the EM associated with increased aridity are centered at 5.3-4.2 ka and 2.8-1.4 ka as shown by the high resolution δ18O record on cave speleothems from the south-eastern Mediterranean region (Jeita cave, Cheng et al., 2015) and the events around 7.7 ka and 1.8 ka which coincide with aridity intensification mostly evidenced in cores from the north-eastern Mediterranean region (Aegean Sea, Carpathians and Turkey; Finné et al., 2019; Longman et al., 2017; Triantaphyllou et al., 2016)
Figure 42. From left to right, the GRIP δ¹⁸O from the Greenland ice core (blue line), the Sanbao cave (central China) δ¹⁸O record (red line), the Jeita cave δ¹⁸O record (black line), the Ti/Al (orange line) downcore variation of the PS009PC Levantine marine sediment core, the Chew Bahir PC1 in the eastern Africa showing the dust variability (green line), and the Ti/Al (red line) and Zr/Si (black line) downcore variation from the ASTC1 marine sediment core in Astypalea, South Aegean Sea. The grey shaded areas represent the arid intervals found in ASTC1 record.
These arid events appear to have impact on civilizations developed in Balkans (i.e., Berger et al., 2016; Finné et al., 2017) as well as in Anatolia and Middle East (i.e., Berger et al., 2016; Clarke et al., 2016). In our record, the time occurrence of the changes between arid and wet climatic conditions appear to almost coincide with main archaeological periods in Greece: the Late Neolithic period (~9-5 ka) coincides with a general humid period (~until 7 ka) followed by a transitional period (wet to dry, 7-5.5 ka (Desprat et al., 2013; Finné et al., 2011); the Early (5-3.9 ka) and the Late Bronze (3.5-3 ka) period which were more arid than the Middle Bronze period (3.9-3.5 ka, Finné et al., 2011). Enhanced aridity also characterized the Greek Dark Ages (3-2.6 ka, (Langgut et al., 2013; Ina Neugebauer et al., 2015; Roberts et al., 2011) while wetter conditions prevailed during the classical period (2.4-2.3 ka, Dean et al., 2015). The Roman period (2-1.6 ka) coincides with relative high levels of aridity which continued up to the early phases of the Byzantine period with several reported extremely cold seasons (1.6-0.7 ka) (Telelis, 2008; Elena Xoplaki et al., 2016). In the North Aegean though, the latter period is characterized by fluctuations in the SSTs and relative high river discharge (Gogou et al., 2016).

The most recent increase in aridity in our record occurs between 0.6 and 0.3 ka and probably corresponds to Little Ice Age (LIA) (Figure 43). Oscillations of humidity/aridity indicators corresponding to Medieval and LIA periods have been observed in the paleo-climatic proxies from Greece (Finné et al., 2017; Gogou et al., 2016; Hamann et al., 2008) and Levant region (Cheng et al., 2015). These studies suggest that the EM experienced reduced precipitation and drier conditions during the LIA, while the Medieval Climate Anomaly (MCA) is associated with relatively wetter conditions and increased humidity in certain parts of the EM. Our record also indicates decreased aeolian activity which may reflect wet climate conditions in the south Aegean Sea within the Medieval period (1.1-0.7 ka) and increased aridity within the LIA. In addition, our records suggest climatic fluctuation within the LIA with the aridity being interrupted for a short period around 0.5 ka. This interruption has been linked to an increase in humidity within the LIA, which was also evidenced in the North Aegean Sea at around 0.5 ka, pointing out the high hydroclimate variability within this period (Gogou et al., 2016). Within the LIA, glacier development/expansion occurred also in many Mediterranean mountain locations, while semi-permanent snowfields became established in the mountains of Greece, which are too dry for glacier development (Hughes, 2014). Drop in mean summer temperatures by 2-3 °C at around 0.35 ka in the Pirin Mountains, SW Bulgaria (Grunewald & Scheithauer, 2010), support further the dry scenario within the LIA across these
regions. Increased aridity is also inferred from central Anatolian Lake Nar Gooülü data (Dean et al., 2013), while frequent widespread freezing events between 0.35 and 0.02 ka also affected the Black Sea, Bosporus, Golden Horn, and Istanbul region (Yavuz et al., 2007). The main factors responsible for the winter cold and snow-falls within this region involved northerly airflow, with high pressure over northern Europe and lower pressure over the central or eastern Mediterranean (Xoplaki et al., 2001).

4.5. Global arid traces within the Holocene

To better understand the phase relations between the northern-, mid- and south- northern latitude sub-systems, we compare our record to those from five other sites with high temporal resolution and precise age control (Figure 43). These records are from Greenland (GRIP δ¹⁸O ice core record, Johnsen et al., 2001), from eastern China (speleothem δ¹⁸O record of the Sanbao cave, Wang et al., 2008), from central Africa (Chew Bahir PC1, Trauth et al., 2018), Ti/Al record from southeast Levantine Basin in the eastern Mediterranean (marine sediment core PS009PC, Hennekam et al., 2014), and from Jeita cave in Lebanon (δ¹⁸O on cave speleothems, Cheng et al., 2015) (Figure 43). The overall trend shown by the geochemical ratios Ti/Al and Zr/Si points to dust increase over the last 6-5 ka which agrees well with other trends seen globally, like in record from Africa (Chew Bahir), Greenland ice core record (GRIP δ¹⁸O) and the monsoon-related speleothem δ¹⁸O record of the Sanbao cave in central China (Figure 43). Prior to the aridification trend, all datasets suggest a wetter trend for the Early to Middle Holocene compared to the Middle-Late Holocene, suggesting a coherent climatic response across these regions (Figure 43), although decoupling between GRIP and Sanbao δ¹⁸O record is due to the stronger response of the latter to insolation forcing than the first (Dong et al., 2010). The increases in aridity though noticed between 8.7 and 8 ka in our record, couple with the cooler trend shown by the GRIP record and the Sanbao cave speleothems. This increase of aridity is possibly linked to the 8.2 cooling event, an event which had a global impact and affected various parts of the globe, such as North Atlantic, Europe, Asia, Africa, and South America (Blockley et al., 2012; Bond et al., 1997; Guo et al., 2000; Haug et al., 2001; Magny et al., 2003; Rein et al., 2005; Shanahan et al., 2015; Yao et al., 2017). There is ongoing debate among scientists regarding the exact timing and causes of the 8.2 ka cooling event, as well as its duration. Some suggest that the event began abruptly around 8.2 ka (Alley et al., 1997; Grootes et al., 1993; Haug et al., 2001; Kennett et al., 2000; Rasmussen et al., 2012; 2013).
2006), while others propose that it may have started earlier with the oldest scenario setting the initiation at 8.6 ka. There is also debate about the primary drivers of the cooling, with some studies suggesting changes in ocean circulation and freshwater input and others highlighting changes in solar radiation or volcanic activity. The climatic response of this cooling event in other records from the EM is marked by drier conditions and reduced precipitation (Develle et al., 2011; Staubwasser et al., 2003), increased aeolian activity and dust deposition (Develle et al., 2011; Torfstein et al., 2013). Thus, this shift appears to have affected synchronously all cross-correlated dataset used in this study, showing the teleconnection of the northern and southern latitudinal climatic systems. Next to this arid interval, a prominent increase of aridity seen in the ASTC1 around 7.7 ka seems to agree with a relative signal from south-eastern EM (Jeita Cave; H. Cheng et al., 2015). As previously mentioned above a similar trend has been recorded in records northern of the examined area (up to Carpathian region; Longman et al., 2017). This may reflect a northern origin of this event related to the intensification of the Siberian High.

The exact timing, however, of the various dry periods addressed by the global records may vary due to differences among the specific datasets, the location, as well as the methods used to reconstruct past climate and their resolution (Bond et al., 2001; Mayewski et al., 2004; Rasmussen et al., 2014). For example, some suggest that the Holocene Climatic Optimum came to end approximately at 6-5 ka when the climate conditions turned into more arid (Cullen et al., 2000; Kaniewski et al., 2010; Roberts et al., 2011), while others suggest that the onset of aridity occurred later, around 4-3 ka (Koutsodendris et al., 2013; Roberts, 2014). The compared records here show that the increase in aridity started at around 6 ka or earlier and continued until full arid conditions were reached at around 5 ka (Figure 6). This shift from wetter conditions within the Holocene towards aridity marks the most prominent ecological changes during the Holocene, with the termination of the African Humid Period (AHP). Some records reveal a more gradual transition, like in the ASTC1, Chew Bahir, Sanbao, and the GRIP record, and others support a more abrupt termination of the AHP, like in the PS009PC record and other marine archives (Hennekam et al., 2014; ODP 658C sediment core: deMenocal et al., 2000). The exact timing of the AHP termination is debated, basically due to the different location and their proximity to the governing climatic system. deMenocal et al. (2000) differentiate between two feedback mechanisms that could have amplified such a transition, a coupled vegetation-albedo feedback and ocean surface temperature-moisture feedback, as well as declining
summer insolation (Renssen et al., 2006), and the southward migration of the ITCZ (Sachs et al., 2018; Zhang et al., 2021).

The drying trend continues until around 2 ka, with the most prominent increase in aeolian activity seen in ASTC1 record centered around 2.8 ka. The period around 3 ka has been suggested to be the driest time of the Holocene in the EM (Finné et al., 2019) but, there is also multiple evidence, of draught and increased aridity during this period in several regions around the globe, including EM (Soreq Cave in Israel, Lake Van in Turkey, Bar-Matthews et al., 2003; Lamb et al., 2007; Lamb et al., 2007), Central Asia (Shihua Cave in northeast China, Ku & Li, 1998), Central America (Lake Chichancanab in the Yucatan Peninsula, Mexico, Hodell et al., 2005), and South America (Cueva Larga in Peru, Rein et al., 2005), and in other sediment cores from southeastern Greece (Gogou et al., 2016; G Zanchetta et al., 2013). Changes in the North Atlantic due to solar activity and/or freshwater input from melting ice sheets around 4 ka is suggested to be responsible for this long-term aridity and the subsequent weakening of the Indian monsoon system (Kathayat et al., 2018) following the 4.2 ka cold event. Some studies suggest that the decrease in precipitation during this period may be related to changes in large-scale atmospheric circulation patterns, such as the Intertropical Convergence Zone (ITCZ) and the North Atlantic Oscillation (NAO), as well as solar variability (Izdebski et al., 2016; Magny, 2013; Mayewski et al., 2004) and increased volcanic activity (Kobashi et al., 2017).

After that, the most recent aridity increases at 0.7 and 0.3 ka show a coupling with the global records. This most recent RCC (<0.6 ka) features bipolar cooling but a more variable response in humidity at low latitudes (Mayewski et al., 2004), with this interval appearing to be more complex than the classic “cool poles, dry tropics” pattern that typified the Pleistocene and most of earlier Holocene RCCs. However, here it seems that the climate response to this RCC was almost synchronous across the compared regions with cooler and drier conditions implied by the proxies.

4.6. Holocene climatic cyclicity

The Holocene has seen a complex interplay of natural factors that have driven cyclical patterns of climate change over time. Several cycles of climate change have been identified, including periods of warming and cooling in ice and sediment records. Here the application of the spectral analysis suggests that the Ti/Al and Zr/Si ratios of the ASTC1 sediment core are
non-stationary data, but present cyclicity referring to recurrence of dry/cold climatic conditions with main periodicities at ~2500, 1200 and 525 years within the Holocene (Figure 40). The frequency of the variability increases after 6 ka which is coincident with previous studies which show increase in the frequency of aridity events after the end of the African Humidity Period (Balkans: Finné et al., 2019; Anatolia and Middle east: Clarke et al., 2016). An oscillation with a period of about 2100-2500 years in 14C concentration, known in the literature as the Hallstatt cycle (Vasiliev & Dergachev, 2002), has been found in various paleoclimatic records spanning the Holocene (Scafetta et al., 2016, and references therein). This 2100–2500-year oscillation both in the cosmogenic radioisotope and in the climate, records have been suggested to have an origin of three kinds: astronomical, solar, and Earth’s endogenous. The comparison with the GISP2 record and the stacked drift ice indices shows an in-phase relationship within the 9 ka with a small offset though (Figure 44). The variability however within the ASTC1 proxies is

Figure 43. Gaussian Filter of ~2500 years applied on the detrended data from Drift ice indices in North Atlantic, GISP2 record and the ASTC1 (Ti/Al and Zr/Si) record. The green and blue bars refer to the glacial advance in Scandinavia and North America respectively. The numbered sections refer to the Bond events within the Holocene.
small prior to 5 ka, and thus better describes this section of our record showing a positive relation of the cooler conditions in the northern hemisphere with the intensification of the aeolian activity and/or drier conditions in the South Aegean Sea with a 2500-yr periodicity.

A second frequency of 1200-years was also recognized in the ASTC1 record. This cyclical pattern seen in the two proxies seems to be in phase with the GISP record especially for the last 3 ka, while for the older Holocene time interval an anti-phase relationship is displayed. This periodicity is close to ~1500-yr cyclicality as seen in the drift ice indices time series (Bond et al., 1997). This cyclicity is described by cooling and increased ice-raifting in the North Atlantic that occurs every 1500 years on average and is suggested to be driven by changes in ocean circulation and the freshwater release from ice sheets (Bond et al., 1997). Thus, implying that the cooler conditions described by Bond cycles and the Greenland ice record within the last 3 ka may be linked with an expression of drier conditions in the eastern Mediterranean region, as shown by the ASTC1 record (Figure 45).

**Figure 44.** Gaussian Filter of ~1100 years applied on the detrended data from Drift ice indices in North Atlantic, GISP2 record and the ASTC1 (Ti/Al and Zr/Si) record. The green
and blue bars refer to the glacial advance in Scandinavia and North America respectively. The numbered sections refer to the Bond events within the Holocene.

The spectral analysis of ASTC1 Zr/Si and Ti/Al time series also reveals a significant period of ~525 years over the Holocene, which may be linked with the reoccurrence of the Bond events or other events of similar frequency (Figure 46). A common periodicity of ~500 years during the Holocene is also found in solar activity (Cheng et al., 2015) and references therein, Greenland temperature (Stuiver et al., 1995), the North Atlantic Deep Water (NADW) circulation (Chapman & Shackleton, 2000), as well as temperature (Xu et al., 2014) and monsoon variability (Wang et al., 2005) in East Asia. Cave speleothems from Eastern Mediterranean (Cheng et al., 2015) and in China (Li et al., 2023), also show a significant ~500-yr and ~550-yr periodicity respectively in-phased with our ASTC1 ~525-yr cycle, suggesting that the ~525-yr cycle may be a large spatial-scale phenomenon. The above-mentioned observations imply teleconnections between a common forcing and various responses or feedback (Chapman & Shackleton, 2000). It is likely that atmospheric response to reduced solar irradiance may lead to coincident increase in North Atlantic drift ice, reducing the NADW intensity, cooling of both the ocean surface and high-latitude continent around North Atlantic and North Pacific, and weakening of the Asian monsoon (e.g., Hai Cheng et al., 2012; Emile-Geay et al., 2007; Xu et al., 2014), triggering cyclical patterns of higher dust supply in the South Aegean region. The potential mechanism might be attributed to the Atlantic Meridional Overturning Circulations (AMOC) changes. This is because a strengthened (weakened) AMOC will not only result in a temperature increase (decrease) in China, but also lead to a weakened (strengthened) anticyclonic circulation over the Mediterranean via changing the surface temperature, contributing to a long-term increase (decrease) in the wet season Mediterranean precipitation (e.g., Delworth et al., 2022; Stockhecke et al., 2016).
Figure 45. The Gaussian Filter of ~550 years applied on the detrended data from Drift ice indices in North Atlantic, GISP2 record and the ASTC1 (Ti/Al and Zr/Si) record. The green and blue bars refer to the glacial advance in Scandinavia and North America respectively. The numbered sections refer to the Bond events within the Holocene.

4.7. Geoarchaeological implications

The evolution of the landscape conditions from hinterland to brackish and to coastal environments seems to be conducive to the human settlement in the area. The Holocene, is an interval that is generally characterized by relative sea-level stability and human expansion into coastal areas (Griggs, 2017; Devillers et al., 2019). According to several studies, coastal areas characterized by fertile soils and constant freshwater supply, as are the deltaic environments, were more conducive to human settlement and the development of societies and trades along the coasts (Devillers et al., 2019). Similar conditions were developed at Vathy during that period. In our records, during the Late Neolithic period, the Vathy was already connected to the Aegean Sea, though this interval coincides with the establishment of brackish conditions
related to the subunit IIA. Thus, a freshwater source seems that contributed further to the sedentarization of humans in the site.

The marine geoarchaeological survey in Vathy area provided important results concerning the paleogeographical reconstruction especially the last 6.5 ka and enabled tracing archaeological remains which constitute the submerged archaeological scenery peripherally to the cape and into the straits. The chronological framework given by the high-resolution age model of the basin’s sediments revealed possible initiation of human interference in the bay back to 6.5 ka. The linear configuration at the borders of the -4 m terrace north of the cape, indicates that this construction was built at around 6.5 ka when the global mean sea level was of about 4 m lower than the present and might be related with maritime installations such as harbor walls, constraining the terrestrial area. This can be further supported by the archeological investigations in Vathy which showed that settlements of human occupation go back to at least the Late Neolithic Period, at ~6 ka (Vlachopoulos, 2016). Emblematic rock art representations of a long-oared ship and of the daggers, that decorate two monumental gateways of the 3rd mill. BCE (~5 ka) acropolis (Tsigkas et al., 2020), further support that the found structures represent maritime installations. Other findings from Negros cave indicate human presence on the Astypalea island during the Mesolithic period, dating back to 9 ka BCE (11 ka) (Efstathiou, 2023), representing also one of the older implications for human presence in the Aegean and Greek region. These findings indicate human occupational activities on the island further back in time which could highlight the scenario of earlier activities in the Vathy region. Another deeper construction extending until the 8.5 m water depth may indicate a further back in time (~7.4 ka) human intervention in the area, when the mean global sea level was of about this range. However, due to the fact that this finding is incorporated within the SF1/LU-I which goes back until 4.1 ka, when the sea level was 1.5 m lower than the present, contradicts the scenario of an earlier than 6.5 ka human intervention. The presence of such an installation instead, might have played the role of a slipway or boat launch ramp along which the vessels could be moved into or out of the water for their protection or maintenance, which explains its underwater presence.

The three conical rubble structures found north-western of the cape at 2 m water depth, adds extra evidence of an organized ancient harbor installation. These structures are valuable archaeological findings that indicate the presence of human activity in a specific area and
highlight the historical significance of this harbor. Cone piles are often used as foundations or protective structures for maritime installations such as piers, quays, or harbor walls, providing stability and support to the structures built on them, especially in areas with soft or shifting sediments (Graauw, 2022). The presence of conical rubble structures can also indicate navigational routes and the presence of safe harbors. In ancient times, mariners used recognizable landmarks, including these structures, for navigation. Their presence in certain locations can provide insights into ancient maritime trade routes. Such an example has been found in other coastal areas such Aegina (Georgiou et al., 2021), showing that this type of installation was widely used as port facilities in the Aegean Sea.

The submerged wall configuration at the southern part of the straits, lying at 1.5 m water depth raises the scenario of a construction which might have played the role of an observatory, guarding the entrance to the bay and the access to the acropolis. It could also indicate a construction enabling the constraining of the sea-water flow into the bay, and thus protecting the maritime installations, but this would be the case if it was found at the foot of the cape. Its position right across the cape and not at the foot rather supports the scenario of an observatory, due to a better monitoring of the incoming vessels to the bay from this angle.

In this direction the remains found on the sea floor between 4 m and the coastline and peripherally to the cape, which present a geometric configuration or are presented as sparse curved boulders, represent either remains of maritime installations such as docks or may indicate areas of collapsed blocks coming from the higher levels of the acropolis.

All these findings on the seafloor seem to be highly related to ancient maritime facilities that were built right by the sea level, rather than ancient human residences. The topographic map of the onshore remains shows a clear evidence of an acropolis dense structural tissue located on a safer level well above the sea surface.
5. Conclusions

Coastal restricted basins are sensitive recorders of both global sea level and regional scale climate changes and thus provide a reliable archive toward their reconstruction. The examination here was based on geophysical, visual, sedimentological, and geochemical data and enabled the reconstruction of the paleogeography, and the paleoenvironmental conditions of the bay, while also provided significant insights into the paleoclimate conditions through the Holocene in the South Aegean Sea, highlighting significant environmental and climatic changes. These changes appear to be modulated not only by the global/regional sea level rise but also by the general climatic pattern in the EM and the morphological features of the basin. It revealed also the submerged archaeological site around the cape Elliniko, while the dense grid of the radiocarbon analyses led to an accurate dating of the detected constructions and the possible ways of exploitation by the ancient humans.

The main outcomes of our research can be summarized as follows in two directions:

**Paleogeography, Paleoenvironment, and Paleoclimate:**

- The Vathy dataset provides valuable insights into the complex interplay of sea level changes, climate variability, and their impacts on sedimentation and climate patterns in the Eastern Mediterranean over the Holocene period and highlights the interconnectedness of climate systems across different regions and time scales.

- The cross-correlation of the seismic and sediment core data presents a causal link and suggests that the basin experienced three major environmental stages during the Holocene recorded as seismic facies (SF1-3) on the profiles and lithological units (LU I-III) in the sedimentary deposits.

- The environmental conditions changed gradually from completely isolated to the present shallow marine in the last 9.1 ka due to the post-glacial sea level rise.

- The onset of the marine influence, according to our findings, is placed at around 7.3 ka when the global mean sea level was at −8 m, ~3 m lower than the basin’s sill.
• Relative arid outbreaks were pointed out within the 7.3–6 ka interval, which favored Sr-rich carbonate precipitation in the basin, and a general aridification or less precipitation trend as of 4.1 ka till present. Wetter conditions were instead implied for the 9.1–7.3 ka and 6–5.4 ka intervals, which coupled with the general humid conditions in the Eastern Mediterranean at those times.

• The geochemical proxies of ASTC1 record provide high resolution climate reconstruction for the last 8.7 ka, showing a distinct pattern of environmental changes during the Holocene in the South Aegean region. These climate changes can be correlated to well-known aridity cycles recognized in other records around the Northern Hemisphere, due to its high-resolution chronological model.

• The general pattern shown by the ASTC1 record indicates an increase in dust and aridity during the last 6 ka, which fits with other worldwide trends documented in records from the Balkans, Eastern Mediterranean, eastern Africa, Greenland, and central China.

• According to the studied data, a rise in aridity began around 6 ka with evidence of a gradual trend as of 7 ka, and persisted until complete arid conditions were attained around 5 ka.

• The correlation of ASTC1 trend shows a high similarity regarding this mid-Holocene transition with records from southern latitudinal regions, which were influenced by the ITCZ's southern migration followed by a retreat of monsoonal rains by the end of the AHP.

• Short-term fluctuations in both Ti/Al and Zr/Si ratios indicate transient cycles of enhanced terrigenous supply, most likely related with increases in aridity, that correlate with Holocene "Rapid Climate Change" events (RCCs). Those focused during 8.5-8 ka, 3-2.5 ka (Dark Ages), and 0.6-0.3 ka (LIA) are the most prominent in our record.

• In terms of the contested Medieval Climate Anomaly and LIA eras, higher values of the two geochemical ratios imply generally arid conditions in the LIA, whilst low ratio values represent wet climatic conditions in the south Aegean Sea throughout the Medieval period (1.1-0.7 ka) and a brief wet interruption within the LIA (~0.5 ka).

• The correlation of the arid events evidenced in ASTC1 with other Northern Hemisphere records discussed in this study, indicate the AMOC changes as a common trigger
mechanism of the aridity seen in our record, except for the one centered at 7.7 ka which may be linked to Siberian High intensification. This cross-correlation demonstrates the relevance of the Aegean position functioning as an interplay between the various climatic systems.

- Finally, the spectral analysis indicates that the ASTC1 record exhibits cyclical patterns pertaining to the recurrence of dry/cold climatic conditions with key periodicities during the Holocene at 2500, 1200, and 525 years, which match with the Hallstatt and Bond cycles, and are expressed as periods of drier conditions and/or enhanced dust input which in many cases lead to cultural collapse and societal crisis.

**Geoarchaeology**

- The environmental transition gradually developed through several intermediate stages, as shown by this study, also providing important information on the climatic pattern of the Eastern Mediterranean region. The topography of the Vathy bay forms a natural well-protected area favoring the inhabitation of prehistoric humans. Since Neolithic times, the area has also offered freshwater sources, while the establishment of a series of water bodies contributed to the further exploitation of the associated ecosystems.

- The evolution of the landscape from hinterland to brackish and coastal environments provided stable conditions conducive to human settlement. Coastal areas with fertile soils and freshwater supply, such as deltaic environments, were particularly attractive for human habitation and societal development. Vathy, too, was connected to the Aegean Sea during the Late Neolithic period, facilitating sedentarization.

- The study used a high-resolution age model of the basin’s sediments, revealing possible human interference in the bay around 6.5 ka, earlier than the onshore archaeological indications. Evidence suggests maritime installations such as harbor walls being constructed during this time, indicating early human activity in the area.

- The findings from Negros cave on Astypalea Island indicate human presence during the Mesolithic period, dating back to 9 ka BCE. This discovery represents one of the older implications of human presence in the Aegean and Greek region, suggesting earlier human
occupational activities on the island, potentially shedding light on earlier activities in the Vathy region too.

• The various underwater detected structures and configurations, including linear constructions, conical rubble structures, and submerged walls, indicate ancient harbor installations, potentially serving as piers, quays, or observatories guarding the entrance to the bay.

• The presence of conical rubble structures suggests ancient navigational routes and safe harbors. Mariners likely used these structures as landmarks for navigation, indicating the existence of ancient maritime trade routes.

• The presence of collapsed blocks on the seabed suggests that the submerged structures were related to maritime facilities rather than human residences.
6. References


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Appendix

Supplementary Table S1. Micro- and macro-paleontological content of the examined sediment samples of the ASTC1 sediment core.
<table>
<thead>
<tr>
<th>Unit</th>
<th>DEPTH (cm)</th>
<th>FORAMINIFERA</th>
<th>GASTROPOD S-BIVALVES</th>
<th>OSTRACOD S</th>
<th>CHAROPHYTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,5</td>
<td></td>
<td>Ammonia spp., more Peneroplis spp., Elphidium sp., Quinqueloculina spp.,</td>
<td>Rissoa parva s.l., Rissoa membranacea s.l., Nucula nucleus, Bittium reticulatum,</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Triloculina spp., Discorbis sp., Ammonia spp., Adelosina spp., Milionela</td>
<td>Acanthocardia paucicostatum (Env: Shallow marine, Algal seafloor)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>spp., Spiroloculina spp.</td>
<td></td>
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</tr>
<tr>
<td>5.5</td>
<td></td>
<td>Ammonia spp., Elphidium spp., Quinqueloculina spp.</td>
<td>Varicorbula gibba and Bittium reticulatum. Common species are Nucula nucleus,</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Acanthocardia paucicostata, and Parvicardium exiguum. Other occurring species</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>include Rissoa parva s.l., Rissoa membranacea s.l., indet juvenile Veneridae,</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>indet. smooth Dentaliidae. Lucinids occur in low numbers, mostly Lucinoma borealis</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>(Env: Shallow marine, low energy, Seasonal bottom dysoxia or anoxia)</td>
<td></td>
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</tr>
<tr>
<td>10.5</td>
<td></td>
<td></td>
<td>Varicorbula occurs to dominates (Env: Semi isolated shallow marine)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td></td>
<td></td>
<td>Well preserved juvenile cypreaidid or ranellid gastropod (Env: Seasonal dysoxia)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td>Many benthic/miliolids, <em>Ammonia tepida</em> and <em>A. beccarii</em>, <em>Peneroplis</em> spp., <em>Elphidium</em> spp.</td>
<td>Yellowish-grey crumble with few well-preserved fragments of <em>Cerastoderma glaucum</em> s.l. (Env: Shallow marine)</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.5</td>
<td><em>Miliolids</em>, <em>Rosalina</em>, <em>A. tepida</em>, <em>A. beccarii</em>, <em>Elphidium</em> spp., <em>Peneroplis</em> spp.</td>
<td></td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.5</td>
<td></td>
<td><em>Varicorbula gibba</em> (Env: Semi-isolated shallow marine, seasonal dysoxia)</td>
<td></td>
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<tr>
<td>39.5</td>
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</tr>
<tr>
<td>40.5</td>
<td>Milolids, Rosalina spp., Ammonia tepida &amp; A. beccarii, Elphidium spp., Peneroplis spp.</td>
<td>Varicorbinula gibba and Bittium reticulatum. Common species are Nucula nucleus, Acanthocardia paucicostata, and Parvicardium exiguum. Other occurring species include Rissoa parva s.l., Rissoa membranacea s.l., indet juvenile Veneridae, indet smooth Dentaliidae. Lucinids occur in low numbers, mostly Lucinoma borealis (Env: Low energy, Seasonal bottom dysoxia or anoxia)</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41.5</td>
<td></td>
<td>Varicorbinula gibba (Env: Semi isolated shallow marine, seasonal dysoxia)</td>
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<td></td>
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</tr>
<tr>
<td>44.5</td>
<td>Ammonia spp., Elphidium spp., Quinqueoleculina spp.</td>
<td>Varicorbinula gibba and Bittium reticulatum. Common species are Nucula nucleus, Acanthocardia paucicostata, and Parvicardium exiguum. Other occurring species include Rissoa parva s.l., Rissoa membranacea s.l., indet juvenile Veneridae, indet smooth Dentaliidae. Lucinids occur in low numbers, mostly Lucinoma borealis (Env: Low energy, Seasonal bottom dysoxia or anoxia)</td>
<td>Yes</td>
<td></td>
<td></td>
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<tr>
<td>Depth (m)</td>
<td>Common Species</td>
<td>Other Common Species</td>
<td>Presence/Abundance</td>
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<tr>
<td>46.5</td>
<td>Quinqueloculina spp., Peneroplis spp., Tribulina spp., Discorbis spp., Ammonia spp., Adelosina spp., Millonella spp., Spiroloculina spp.</td>
<td>Varicorbula gibba, Bittium reticulatum is notably absent and Rissoo species are rare. Other common species are Acanthocardia paucicostatum, Parvicardium exiguum, Abra alba s.l., smooth Dentaliidae. (Env:seasonal dysoxia, turbidity)</td>
<td>No</td>
<td></td>
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<tr>
<td>49.5</td>
<td>Many benthic, Miliolids, Ammonia tepida and A. beccarii, Peneroplis spp., Elphidium spp.</td>
<td></td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51.5</td>
<td>Many benthic, Miliolids, Rosalina spp., Ammonia spp., Peneroplis spp., Elphidium spp.</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>55.5</td>
<td>Many benthic, Miliolids, Rosalina spp., Ammonia spp., Peneroplis spp., Elphidium spp.</td>
<td></td>
<td>No</td>
<td></td>
<td></td>
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<tr>
<td>56.5</td>
<td></td>
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<tr>
<td>Value</td>
<td>Remarks</td>
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<tr>
<td>59.5</td>
<td>Few benthics, <em>Vanicornula gibba</em>, <em>Bittium reticulatum</em> is notably absent and <em>Rissoa</em> species are rare. Other common species are <em>Acanthocardia paucicostatum</em>, <em>Parvicardium exiguum</em>, <em>Abra alba</em> s.l., smooth <em>Dentaliidae</em>. (Env: seasonal dysoxia, turbidity)</td>
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<tr>
<td>61.5</td>
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<tr>
<td>62.5</td>
<td><em>Miliolids</em>, <em>Elphidium</em> spp., <em>Peneroplis</em> spp., <em>Ammonia</em> spp., <em>Vanicornula gibba</em>, <em>Bittium reticulatum</em> is notably absent and <em>Rissoa</em> species are rare. Other common species are <em>Acanthocardia paucicostatum</em>, <em>Parvicardium exiguum</em>, <em>Abra alba</em> s.l., smooth <em>Dentaliidae</em>. (Env: seasonal dysoxia, turbidity)</td>
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<tr>
<td>66.5</td>
<td>Quite a few benthics, many <em>Miliolids</em>- <em>Ammonia</em> spp., <em>Peneroplis</em> spp., <em>Elphidium</em> spp.</td>
<td></td>
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<tr>
<td>69.5</td>
<td><em>Ammonia</em> spp., <em>Elphidium</em> spp., <em>Quinqueoloculina</em> spp. Yes</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>71.5</td>
<td><em>Cerastoderma glaucum</em> s.l., <em>Vanicornula</em> (Env: Semi isolated/very shallow marine or variable salinity, seasonal dysoxia)</td>
<td></td>
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<tr>
<td>Score</td>
<td>Benthic Species</td>
<td>Notes</td>
<td></td>
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<tr>
<td>72.5</td>
<td>Very few benthics. Quinqueloculina spp., Peneroplis spp., Tribulina spp., Discorbis spp., Ammonia spp.</td>
<td>Varicorbul a gibba, Bittium reticulatum is notably absent and Rissoa species are rare. Other common species are Acanthocardia paucicostatum, Parvicardium exiguum, Abra alba s.l., smooth Dentaliidae. (Env:seasonal dysoxia, turbidity)</td>
<td></td>
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<tr>
<td>74.5</td>
<td>Few benthics/ Miliolids, Ammonia spp., Astengerinata spp.</td>
<td>No</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>77.5</td>
<td>Ammonia spp., Elphidium spp., Quinqueloculina spp.</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>None to very few benthics mainly Quinqueloculina spp.</td>
<td>Varicorbul a gibba but also with common Parvicardium exiguum, Acanthocardia paucicostata, Rissoa parva s.l., Bittium reticulatum, Abra alba s.l., Nucula nucleus, Pussilina inconspicua s.l. (Env: Seasonal oxygen stress, alternating faunas)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>83.5</td>
<td>Few benthics</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>IIA</td>
<td>86.5</td>
<td>Varicorbul a gibba (Env: Semi isolated shallow marine, seasonal dysoxia)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>87.5</td>
<td>Miliolids, Ammonia spp., Peneroplis spp., Elphidium spp.</td>
<td>Varicorbul a gibba but also with common Parvicardium exiguum, Acanthocardia paucicostata, Rissoa parva s.l., Bittium reticulatum, Abra alba s.l., Nucula nucleus, Pussilina inconspicua s.l.</td>
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<td></td>
<td></td>
<td>Yes</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Line</td>
<td>Ammonia and Miliolids</td>
<td>Environment</td>
<td>Remarks</td>
<td></td>
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</tr>
<tr>
<td>88.5</td>
<td>Elphidium spp., Ammonia spp., Miliolids</td>
<td>(Env: Seasonal oxygen stress, alternating faunas)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>91.5</td>
<td>Ammonia and Miliolids</td>
<td></td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>99.5</td>
<td>many Ammonia beccarii and A. tepida, few Quinqueloculina seminula</td>
<td>Low-intermediate diverse faunas dominated by Abra cf. alba; Varicorbula gibba and Bittium reticulatum are notably absent. Other common species are Rissoa parva, Parvicardium exiguum, Acanthocardia paucicostata and in the lower samples Cerastoderma glaucum s.l. (Env: low water energy, marine, oxygenated, lower or variable salinity)</td>
<td></td>
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<tr>
<td>103.5</td>
<td>Ammonia spp. and Miliolids</td>
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<tr>
<td>109.5</td>
<td></td>
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<tr>
<td>120</td>
<td>many Ammonia beccarii, A. tepida, Quinqueloculina spp.</td>
<td>Cerastoderma glaucum s.l., Abra fragments occur. Some variable preservations styles but dominant preservation is translucent with coloration and fine details preserved. Also paired specimens of Cerastoderma. In the lower sample some fragments of Varicorbula gibba occur (Env: Lagoonal)</td>
<td>Yes</td>
<td></td>
<td></td>
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<tr>
<td>129.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>139.5</td>
<td>Ammonia beccarii, Quinqueloculina spp., broken benthic fauna,</td>
<td>No molluscs. Charophytic oogenesis, small (?insect larval) tubes (Env: variable salinity)</td>
<td>Yes</td>
<td>Yes (Lamprothamnium spp.)</td>
<td></td>
</tr>
<tr>
<td>IIB</td>
<td></td>
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<tr>
<td>149.5</td>
<td>mainly Ammonia spp.</td>
<td>Cerastoderma glaucum s.l., Abra fragments occur. Some variable preservations styles but dominant preservation is translucent with coloration and fine details preserved. Also paired specimens of Cerastoderma. In the lower sample some fragments of</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>159.5</td>
<td>only a few <em>Ammonia beccarii</em></td>
<td>Varicorbulina gibba occur (Env: Lagoonal)</td>
<td>No</td>
<td></td>
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</tr>
<tr>
<td>161.5</td>
<td>Quinqueloculina spp.</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>very few benthics mainly <em>A. beccarii</em>, <em>Nonion</em> spp., <em>Trioculina</em> spp.</td>
<td></td>
<td></td>
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<tr>
<td>170.5</td>
<td>Very few benthics, <em>Ammonia</em> spp., <em>Miliolids</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>174.5</td>
<td>Very few benthics,</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>181.5</td>
<td>No benthics</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>192.5</td>
<td>Very few benthics, <em>Ammonia</em>, <em>Miliolids</em></td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>199.5</td>
<td>Very few benthics</td>
<td></td>
<td></td>
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<tr>
<td>210</td>
<td>Very few benthics</td>
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<tr>
<td>211.5</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<td>216.5</td>
<td>No</td>
<td>No</td>
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<td>221.5</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>227.5</td>
<td>Many <em>Miliolids</em> big and small, few <em>Ammonia</em> spp.</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>231.5</td>
<td>Very few benthics mainly <em>Miliolids</em> broken bivalves</td>
<td>No</td>
<td></td>
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<tr>
<td>235</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Units</td>
<td>Depth cm</td>
<td>Fauna</td>
<td>Conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
<td>-------</td>
<td>------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>1.5</td>
<td><em>Rissoa parva</em> s.l., <em>Rissoa membranacea</em> s.l., <em>Nucula nucleus</em>, <em>Bittium reticulatum</em>, <em>Acanthocardia paucicostatum</em></td>
<td>Shallow marine</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Supplementary Table S2. Macrofauna content and the indicative environmental conditions.
| 5.5 | Varicorbula gibba and Bittium reticulatum. Common species are Nucula nucleus, Acanthocardia paucicostata, and Parvicardium exiguum. Other occurring species include Rissoa parva s.l., Rissoa membranacea s.l., indet juvenile Veneridae, indet. smooth Dentaliidae. Lucinids occur in low numbers, mostly Lucinoma borealis | Shallow marine |
| 10.5 | Varicorbula occurs to dominates | Semi isolated shallow marine |
| 12.5 | well preserved juvenile cypriaid or ranellid gastropod | Seasonal dysoxia |
| 14.5 | Yellowish-grey crumble with few well-preserved fragments of Cerastoderma glaucum s.l. | Shallow marine |
Varicorbula gibba and Bittium reticulatum. Common species are Nucula nucleus, Acanthocardia paucicostata, and Ranvicardium exiguum. Other occurring species include Rissoa parva s.l., Rissoa membranacea s.l., indet juvenile Venenae, indet. smooth Dentaliidae. Lucinids occur in low numbers, mostly Lucinoma borealis.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Behavior</th>
<th>Habitat</th>
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</thead>
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<tr>
<td>21.5</td>
<td>Low energy</td>
<td>Semi isolated shallow marine</td>
</tr>
<tr>
<td>25.5</td>
<td>Seasonal bottom dysoxia or anoxia</td>
<td>Low energy</td>
</tr>
<tr>
<td>30.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.5</td>
<td>Varicorbula</td>
<td>Semi isolated shallow marine</td>
</tr>
<tr>
<td>39.5</td>
<td></td>
<td>Seasonal dysoxia</td>
</tr>
<tr>
<td>40.5</td>
<td><strong>Varicorbula gibba</strong> and <strong>Bittium reticulatum</strong>. Common species are <strong>Nucula nucleus</strong>, <strong>Acanthocardia paucicostata</strong>, and <strong>Pavoncardium exiguum</strong>. Other occurring species include <strong>Rissoa parva s.l.</strong>, <strong>Rissoa membranacea s.l.</strong>, indet juvenile <strong>Veneridae</strong>, indet. smooth <strong>Dentaliidae</strong>. <strong>Lucinids</strong> occur in low numbers, mostly <strong>Lucinoma borealis</strong></td>
<td>Shallow marine</td>
</tr>
<tr>
<td>41.5</td>
<td><strong>Varicorbula</strong></td>
<td>Semi isolated shallow marine</td>
</tr>
</tbody>
</table>

Low energy
Seasonal bottom dysoxia or anoxia

Seasonal dysoxia
<p>| 44.5 | Varicorbula gibba and Bittium reticulatum. Common species are Nucula nucleus, Acanthocardia paucicostata, and Parvicardium exiguum. Other occurring species include Rissoa parva s.l., Rissoa membranacea s.l., indet juvenile Venenidae, indet. smooth Dentaliidae. Lucinids occur in low numbers, mostly Lucinoma borealis | Shallow marine |
| 49.5 | Crumble and/or travertine, some organics and (almost) no shells. Interpretation – uncertain. | Low energy Seasonal bottom dysoxia or anoxia |
| 51.5 | Varicorbula gibba, Bittium reticulatum is notably absent and Rissoa species are rare. Other common species are Acanthocardia paucicostatum, Parvicardium exiguum, Abra alba s.l., smooth Dentaliidae. | uncertain |
| 55.5 | Seasonal dysoxia | Turbidity |</p>
<table>
<thead>
<tr>
<th>Turbidity</th>
<th>Crumble and/or travertine, some organics and (almost) no shells.</th>
<th>uncertain</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.5</td>
<td>Varicorbula gibba, Bittium reticulatum is notably absent and Rissoa species are rare. Other common species are Acanthocardia paucicostatum, Parvicardium exiguum, Abra alba s.l., smooth Dentaliidae.</td>
<td>Seasonal dysoxia</td>
</tr>
<tr>
<td>61.5</td>
<td>Crumble and/or travertine, some organics and (almost) no shells.</td>
<td>uncertain</td>
</tr>
<tr>
<td>62.5</td>
<td>Varicorbula gibba, Bittium reticulatum is notably absent and Rissoa species are rare. Other common species are Acanthocardia paucicostatum, Parvicardium exiguum, Abra alba s.l., smooth Dentaliidae.</td>
<td>Seasonal dysoxia</td>
</tr>
<tr>
<td>66.5</td>
<td>Cerastoderma glaucum s.l. Varicorbula</td>
<td>Semi isolated/ very shallow marine or variable salinity/</td>
</tr>
<tr>
<td>67.5</td>
<td></td>
<td></td>
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<tr>
<td>69.5</td>
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</tr>
<tr>
<td>71.5</td>
<td></td>
<td>Seasonal dysoxia</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Seasonal dysoxia</td>
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</tr>
<tr>
<td>-----------</td>
<td>-----------------</td>
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</tr>
<tr>
<td>74.5</td>
<td>Varicorbula gibba; Bittium reticulatum is notably absent and Rissoa species are rare. Other common species are Acanthocardia paucicostatum, Parvicardium exiguum, Abra alba s.l., smooth Dentaliidae.</td>
<td></td>
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<tr>
<td>Seasonal oxygen stress</td>
<td></td>
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<tr>
<td>77.5</td>
<td>Varicorbula gibba but also with common Parvicardium exiguum, Acanthocardia paucicostata, Rissoa parva s.l., Bittium reticulatum, Abra alba s.l., Nucula nucleus, Pussilina inconspicua s.l.</td>
<td></td>
</tr>
<tr>
<td>Alternating faunas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>83.5</td>
<td></td>
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<tr>
<td>Semi isolated shallow marine</td>
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<tr>
<td>86.5</td>
<td>Varicorbula</td>
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<tr>
<td>Seasonal dysoxia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>87.5</td>
<td>Varicorbuta gibba but also with common Parvicardium exiguum, Acanthocardia paucicostata, Rissoa parva s.l, Bittium reticulatum, Abra alba s.l., Nucula nucleus, Pussilina inconspicua s.l.</td>
<td>Seasonal oxygen stress</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------------------------------------------</td>
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<tr>
<td>88.5</td>
<td></td>
<td>Alternating faunas</td>
</tr>
<tr>
<td>91.5</td>
<td>Low-intermediate diverse faunas dominated by Abra cf. alba; Varicorbuta gibba and Bittium reticulatum are notably absent. Other common species are Rissoa parva, Parvicardium exiguum, Acanthocardia paucicostata and in the lower samples Cerastoderma glaucum s.l.</td>
<td>Low water energy</td>
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<tr>
<td>99.5</td>
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<td>Marine</td>
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<tr>
<td>103.5</td>
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<td>Oxygenated</td>
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<tr>
<td>109.5</td>
<td></td>
<td>Lower or variable salinity</td>
</tr>
<tr>
<td>IIB</td>
<td>120.5</td>
<td>Cerastoderma glaucum s.l., Abra fragments occur. Some variable preservation styles but dominant preservation is translucent with coloration and fine details preserved. Also paired specimens of Cerastoderma. In the lower sample some fragments of Varicorbula gibba occur.</td>
</tr>
<tr>
<td>-----</td>
<td>-------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>129.5</td>
<td>No molluscs. Charophytic oogenia, small (?insect larval) tubes and ostracods</td>
</tr>
<tr>
<td></td>
<td>139.5</td>
<td>Variable Salinity</td>
</tr>
</tbody>
</table>
Cerastoderma glaucum s.l., Abra fragments occur. Some variable preservations styles but dominant preservation is translucent with coloration and fine details preserved. Also paired specimens of Cerastoderma. In the lower sample some fragments of Varicorbula gibba occur.

Proximity to Marine setting

IIIa 160-170 Crumble and/or travertine, some organics and (almost) no shells. uncertain

Supplementary Table S3. The 29 variables expressed by 4 strong factors explaining the ~83% of the total variance.

<table>
<thead>
<tr>
<th>Component</th>
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<th>Initial Eigenvalues</th>
<th>Extraction Sums of Squared Loadings</th>
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<td>% of Variance</td>
<td>Cumulative %</td>
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<td>59.044</td>
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<td>4.611</td>
<td>82.897</td>
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<td>3.243</td>
<td>86.140</td>
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<td>2.415</td>
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<td>12</td>
<td>.270</td>
<td>.930</td>
<td>96.556</td>
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<td>.338</td>
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<td>.016</td>
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<tr>
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<td>.003</td>
<td>.009</td>
<td>100.000</td>
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</table>

Supplementary Table S4. Rotated component matrix shows which variables are encountered in each component. The positive (negative) correlated are highlighted with green (red) color.

<table>
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<th>1</th>
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<th>4</th>
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<tbody>
<tr>
<td>Mgcnts10kV</td>
<td>.243</td>
<td>.142</td>
<td><strong>.763</strong></td>
<td>.072</td>
</tr>
<tr>
<td>Alcnts10kV</td>
<td><strong>.812</strong></td>
<td>-.186</td>
<td>.474</td>
<td>.076</td>
</tr>
<tr>
<td>Sicnts10kV</td>
<td><strong>.788</strong></td>
<td>-.203</td>
<td>.504</td>
<td>.080</td>
</tr>
<tr>
<td>Scnts10kV</td>
<td>.205</td>
<td>-.154</td>
<td><strong>.680</strong></td>
<td>-.294</td>
</tr>
<tr>
<td>Clcnts10kV</td>
<td>-.212</td>
<td><strong>.850</strong></td>
<td>-.327</td>
<td>-.074</td>
</tr>
<tr>
<td>Arcnts10kV</td>
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<td><strong>.715</strong></td>
<td>-.327</td>
<td>-.211</td>
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<td>Kcnts10kV</td>
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<td>-.057</td>
<td>.377</td>
<td>.068</td>
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<tr>
<td>Cacnts10kV</td>
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<td>.228</td>
<td>.004</td>
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<tr>
<td>Ticnts10kV</td>
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<td>-.041</td>
<td>.272</td>
<td>.019</td>
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<tr>
<td>Crcnts10kV</td>
<td>.692</td>
<td>-.375</td>
<td>.337</td>
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Supplementary Table S5. Component score coefficient matrix of the 29 chemical elements shows the weighting of variables to be used when computing saved variables of the components.

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<th>4</th>
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<tbody>
<tr>
<td>Mncnts30kV</td>
<td>0.070</td>
<td>-0.162</td>
<td>0.084</td>
<td>0.907</td>
</tr>
<tr>
<td>Fecnts30kV</td>
<td>0.912</td>
<td>-0.100</td>
<td>0.229</td>
<td>0.116</td>
</tr>
<tr>
<td>Cocnts30kV</td>
<td>0.836</td>
<td>-0.076</td>
<td>0.215</td>
<td>0.097</td>
</tr>
<tr>
<td>Nicnts30kV</td>
<td>0.624</td>
<td>0.463</td>
<td>0.436</td>
<td>-0.188</td>
</tr>
<tr>
<td>Cucnts30kV</td>
<td>0.840</td>
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<td>0.381</td>
<td>-0.006</td>
</tr>
<tr>
<td>Zncnts30kV</td>
<td>0.943</td>
<td>0.034</td>
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<tr>
<td>Gacnts30kV</td>
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<td>0.043</td>
<td>0.156</td>
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<td>0.380</td>
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</tr>
<tr>
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<td>0.835</td>
<td>-0.086</td>
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</tr>
<tr>
<td>Rbcnts30kV</td>
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</tr>
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</tr>
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<td>0.100</td>
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</tr>
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<td>0.032</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>1</th>
<th>2</th>
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<tbody>
<tr>
<td>Mgcnts10kV</td>
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<td>0.013</td>
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<tr>
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<td>0.258</td>
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Supplementary Table S6. Component transformation matrix of the 4 components.
Supplementary Table 7. XRD measurements.

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Supplementary Table 8. Aridity evidences throughout Holocene researches in the EM and the Balkans.
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