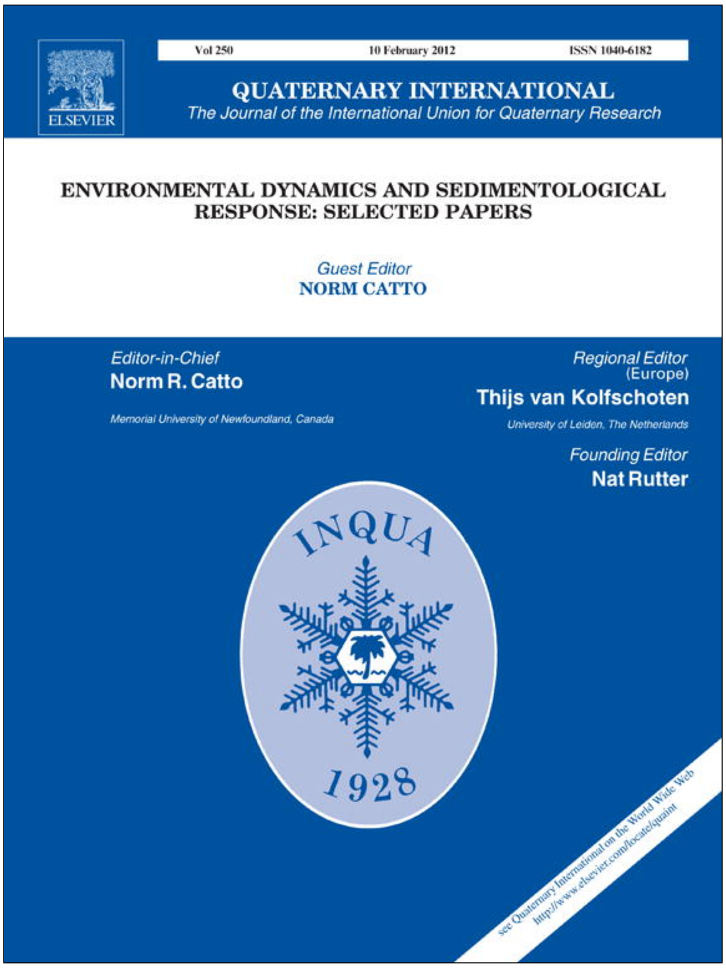
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A palaeogeographic reconstruction of the seafront of the ancient city of Delos in relation to Upper Holocene sea level changes in the central Cyclades

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ABSTRACT

Palaeogeographical reconstruction of the seafront of the ancient city of Delos is based on the recording and study of all available indicators of sea level change. Contemporary submerged beachrock formations and presently submerged areas of ancient human activity, including ancient coastal constructions, indicate the phases, vertical direction, extent and time frame of the changes. The sea level along the coasts of Delos has risen by a total of 2.15 m since the end of the Hellenistic period. This change occurred during two successive distinct phases of submersion, initially by 1.35 m and then by another 0.80 m. The sea's transgression into the ancient coastal zone by a width of at least 30 m radically altered parts of its geomorphology and resulted in the submersion of the ancient sea defences.

1. Introduction

Among the key indicators for previous sea levels are presently uplifted or submerged positions of coastal archaeological sites and structures, sea notches, beachrock formations and changes in the sedimentary stratigraphy of coastal sediments. Combined, they permit the interpretation both of quantitative changes in relative sea level over time, and of the extent of recent tectonic deformation of the coasts, thus allowing for palaeogeographical reconstructions of coastal sites. Multiple studies of coastal sites in Greece, with analysis of archaeological, sedimentary, and geomorphological evidence, reveal recent subsidence of the coasts in the following areas: the Ionian Sea; the western, southern, and eastern coasts of the Peloponnese; the Saronic Gulf and Attica; the southwestern coast of Evia; the Sporades; East Crete; Karpathos; as well as the coasts of Asia Minor, where vertical tectonic subsidence movements prevail. Conversely, coastlines affected by uplifting movements include the following: the southeastern coasts of Kefallonia; Antikythera; the northern coast of the Peloponnese; the northern coast of Evia; the west coast of Crete; the eastern coast of Rhodes; and the northwestern coast of Samos (Flemming, 1978; Mourtzas, 1990; Pirazzoli, 2005) (Fig. 1a).

Evidence is also available for the Cycladic archipelago, the eastern part of which includes Delos. In the western Cyclades, sea level changes during the Upper Holocene submerged the coasts of Kea in three different phases by ca. 5.50 m, 3.90 m and 1.50 m, respectively. These changes caused sea transgression along the shores of the island, varying from 8 m to 78 m, depending on the coastal morphology (Mourtzas, 2010). Subsidence movements also prevail along the shores of Andros, which has resulted in the submersion of several architectural phases of the extensive harbor of ancient Palaiopolis to a depth of 2.70 m (Mourtzas and Palaiokrasa, in preparation). Subsidence of about 5.50 m during the last 5500 years has been noted on the shores of Antiparos in the central Cyclades (Morrison, 1968), while on Mykonos and Rheneia it reached a depth of 3.60 m during the last 4000 years, 2.50 m over the last 2400 years, and 1.0 m for the last 1000 years (Desruelles et al., 2009).

2. Methodology

The present study focused on four key aspects: 1) location, depth and course of submerged sea defences; 2) formation of the respective beachrock phases, and the depth of the top and base of each beachrock formation; 3) morphology and depth range of the underwater coastal area; and 4) delineation of the extent and depth of ancient human activity in the now submerged areas. The latter was determined by studying the distribution of both ancient pottery shreds and ancient structures.

In this study, these key aspects have been mapped and schematically reconstructed at a scale of 1:2000 where possible. During the underwater survey, their depth from present sea level was recorded. All measurements were collected during periods of low wave energy using mechanical methods. Records were corrected for

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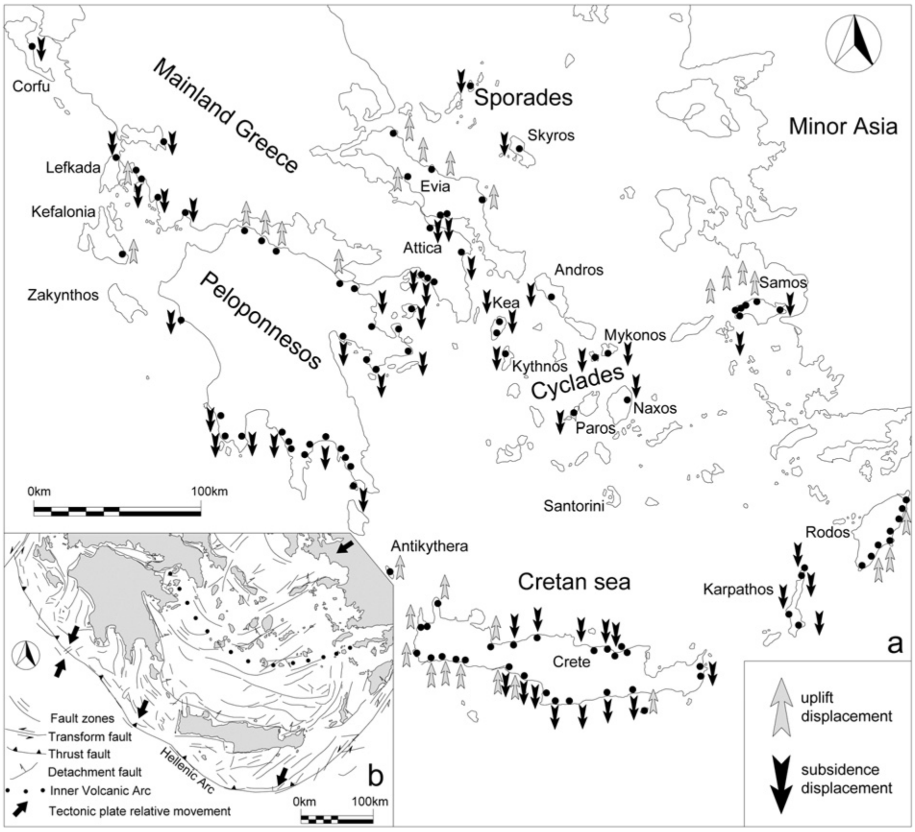

Fig. 1. (a) Uplifting and submerging coastal archaeological settlements and constructions, marine notches and beachrocks in the Hellenic area. (b) Geodynamic frame of the Hellenic Arc (after Papanikolaou, 2010).

tide effects using the data of the Hellenic Navy Hydrographic Service, which at the time of the surveys varied between +0.02 m and +0.06 m. The amplitude of the astronomical tide in the coasts of Delos, as well as in the area of the central Aegean, hardly exceeds 6–10 cm (Stiros and Pirazzoli, 2004; Lycourghiotis and Stiros, 2008).

Beachrocks are lithified beach sediments in the intertidal and supratidal zones, resulting from the precipitation of mainly calcium carbonates due to physicochemical and microbiological activity, under high temperature conditions and possibly with the presence of meteoric water (Alexandersson, 1969; El-Sayed, 1988; Gischler and Lomando, 1997; Kelletat, 2006; Vousdoukas et al., 2007). Based on surveys in the Aegean area, the beachrock cementation processes occur in a zone between the lower tidal level and the higher margin of the sea wave spray. They are formed during periods of tectonic and eustatic stability of the sea level and thus they represent the fossilized seaward part of the deposits of an older depositional coast. Positive or negative sea level change potentially forms successive beachrock outcrops. Their submerged or uplifted modern position reflects different past sea levels and the respective ancient coastlines (Mourtzas, 1990).

Consequently, the measured depth of the base of beachrocks coincides with the lower tidal level of the corresponding older sea level, and can be used as a reliable indicator for the determination of an average older sea level. Assuming that periods with important meteorological tides (surges etc), which may be very important and long-lasting in the Aegean, have a mean tidal range of 0.20 m (Stiros and Pirazzoli, 2004, 2008), an increment of +0.10 m to the measured depth of the beachrock base was adopted to determine the mean ancient sea level. Furthermore, the dating of beachrock can be determined on the basis of archaeological remains that have become incorporated into the formations. After the definition of the older sea levels, maps and bathometric data predating the extensive past interventions at the seafront connected with the excavations, as well as the ensuing natural processes, were used as aids in the palaeogeographical reconstruction of the ancient coastline and the assessment of the type of sea defences constructed along it.

3. Geotectonic setting

The geotectonic and geodynamic evolution of the Hellenic area over the past 13 Ma (Le Pichon and Angelier, 1979; Angelier, 1980) is closely related to the collision and subduction of the African tectonic plate and the remains of the ancient Tethys Ocean under the Eurasian tectonic plate along the Hellenic arc (Papazachos and Comninakis, 1969, 1978; McKenzie, 1970, 1972; Ritsema, 1970; Dewey et al., 1973; Papazachos, 1974; Le Pichon and Angelier, 1979) (Fig. 1b). Convergence and interaction between these tectonic plates has resulted in the dismemberment of the Eurasian plate into the Adriatic, Aegean, and Anatolian plates (McKenzie, 1970, 1972; Roman, 1973; Karnick, 1975). There is intense seismic activity in the area surrounding the Aegean Sea, with seismic hypocenters that seem to follow an amphitheatrically shaped Benioff seismic zone dipping 35° towards the Aegean (Comninakis and Papazachos, 1982).

The Hellenic Trenches, at the front of the Hellenic Arc, are comprised of an arc-shaped system of radiating troughs with extent from 390 km to 450 km, delimiting the Aegean Tectonic Plate (Angelier, 1980). Compressive tectonic stresses prevail in its western part (Hsu and Ryan, 1973; Got et al., 1977; Stanley, 1977) while extensional stresses dominate its central and eastern parts (Peters and Huson, 1985; Peters, 1985).

The inner volcanic arc with calc-alkalic volcanism has developed parallel to the outer Hellenic Arc, also following a small convex arc with a length of approximately 250 km (Fytikas et al., 1976; Angelier, 1980). Between these, the Cretan Sea forms a closed rectangular marginal basin with depths of up to 2 km, which has sunk under extensional forces resulting in the thinning of the Aegean plate (Jongsma, 1975; Angelier, 1979; Mercier et al., 1979; Angelier et al., 1982).

The Cycladic region, with a lithospheric thickness of 28–30 km, is located behind the inner volcanic arc in the center of the Aegean lithospheric plate. This underwent clockwise block rotations as a result of extensional forces (Avigad et al., 1998). It is considered to be an "aseismically deformed area", because seismic activity is limited to minor localized earthquakes of magnitude <2 on the Richter scale (McKenzie, 1972; Morelli et al., 1975; Papanikolaou et al., 1981; Papazachos, 1990). This peculiar behavior of the Cyclades is probably due to the existence of a very closely spaced geometric fracture framework within the metamorphic rocks, preventing strain accumulation. Thus, energy release manifests itself in continuous deformations creeping along the fracture planes (Papanikolaou et al., 1981).

4. Geomorphological characteristics and geological structure of Delos

The island of Delos is located in the central Cyclades. Oriented on an N–S axis, it has an elongated shape, with a length of 5 km, a width of ca. 1.30 km and a total area of 3.43 km^2 (Fig. 2). The island's topography is characterized by hilly relief with low hills separated by small relatively flat areas. The highest point on Delos is Mount Kynthos, with an altitude of 112 m, located on the eastern side of the central part of the island. In the northern section, Gamila hill has an altitude of 53 m, whereas in the south, Kato Vardia ridge reaches 82 m above sea level.

The main plain of the island, in its NW part, extends in a NE direction, stretching towards the eastern coast of the island at Gourna Bay. The coasts of Delos are steep, forming narrow peninsulas at the northern and southern extremities of the island, as well as small bays, such as Gourna Bay, in the NE, Skardana Bay in the NW, and Fournoi Bay in the SW.

Geologically, the island of Rheneia represents the western extension of Delos. Between the east and west coasts, respectively, of the islands is the narrow Strait of Delos, in the north of which lie the rocky islets of Mikros Rematiaris and Megalos Rematiaris.

The geology of the island is simple. Eruptive granite rocks are found on the larger part of the island, and the alpine formations of the "Southern Cyclades Islands" Unit (Papanikolaou, 1986), comprised of schists and gneisses with thin intercalations of marble, form the northern peninsulas of Morou and Morti. Limited occurrences are also present north of Mt. Kynthos and east of the ancient stadium.

Isoclinal and open folds, with NW–SW axes, cleavages, planes and schistosity, lineations due to the orientation of mineral constitutes and small-scale thrusts represent the alpine deformation phases of the metamorphic rocks of the island. Small-scale tensile faults with NE–SW and NW–SE directions represent the younger tectonic deformation phases.

5. Historical framework

According to Herodotus, the first inhabitants of Delos were Carians who settled on the top of Mt. Kynthos around 2500 BC. Approximately a thousand years later, a Mycenaean settlement developed in a small valley by the sea (1580–1100 BC). After the collapse of the Mycenaean civilization around 1100 BC, Ionians inhabited the island and turned it into a prestigious religious center before 540 BC. The island was designated as the seat of the Delian League and its treasury from 478 BC, until the funds were moved to the Athenian Acropolis in 454 BC. Delos remained effectively under Athenian control until 314 BC, when it was declared free by the Commonwealth of the Islands, a coalition of independent islands founded by Antigonos. It thus was placed under the leadership of local elites until 250 BC, when a period of Macedonian rule followed, lasting until 166 BC, during which the island prospered as a commercial and transit center. Following the Roman occupation, the island was once again granted to the Athenians. During this time it was strengthened as a counterweight to Rhodes, its proclamation as a free port assuring the apex of its prosperity. Later, Delos' fate followed that of many other Greek cities: it became a theater for political and military confrontations which resulted in its repeated destructions at the hands of King Mithridates in 88 BC and 69 BC during his campaigns against Rome. After these destructions, Delos declined in importance both for the Ptolemaic kingdom and the Roman administration (Hadjidakis, 2003).

Beginning in 1873, and still ongoing, excavations by the French Archaeological School have uncovered much of ancient Delos. During the early years of these explorations, however, some important historical evidence along the ancient coast was destroyed. Uncontrolled dumping of excavation debris irreparably altered its morphology, depriving subsequent researchers of important evidence for palaeogeographical reconstruction.

6. Previous views on sea level changes, palaeogeography of the coasts and formation of the ancient city's seafront

On the basis of a comparison with other ancient harbors, Ardaillon (1896) suggested that the harbour of Delos should be divided into the "Sacred Harbour" to the north and the "Commercial Harbour" to the south. A series of submerged aligned granite blocks formed a compact breakwater at the northern side of the "Sacred Harbour". No docks for disembarking have been found in this area. Ships appear to have entered the protected basin of the harbor and would have been pulled onto the sandy shore in front of the "Portico of Phillip V" and the Sanctuary. The "Commercial Harbour" is divided into two separate small basins, connected by a channel. A series of separate commercial stores along the edges of the "Commercial Harbour" may suggest the presence of private docks for loading/unloading along the coast. Located to the north of the harbor was a 120 m long complex of warehouses, related to the commercial area of the "Sacred Harbour" and the Roman Agora. A pocket located between the dock of the warehouses and a breakwater of aligned blocks, protecting the coast from northern winds and waves, allowed the approach and the loading/unloading of ships.

Négris (1904), observing the submerged antiquities at the coasts of Delos and Rheneia, concluded that the sea level had risen about 2.50 m since antiquity, causing a transgression of the sea onto formerly dry land. Cayeux (1907) rejected Négris (1903) opinion regarding the rise of the sea level in the Eastern Mediterranean during the historical period and proposed instead that the presently submerged remains of ancient coastal constructions at Delos had originally been constructed below sea level. The shift in the coastline of the ancient city's western seafront was therefore the result of human-made fills, placed during antiquity for the purpose of reclaiming land. According to Cayeux (1907), a detailed investigation in the area of the "Sacred Harbour" allowed him to identify two earlier coastlines which lay to the east of the modern one (Fig. 3). The oldest coastline he identified dates to the 8th century BC, follows the western edge of the Sanctuary, and was located at a distance of 70 m roughly east of the modern shore. The newer

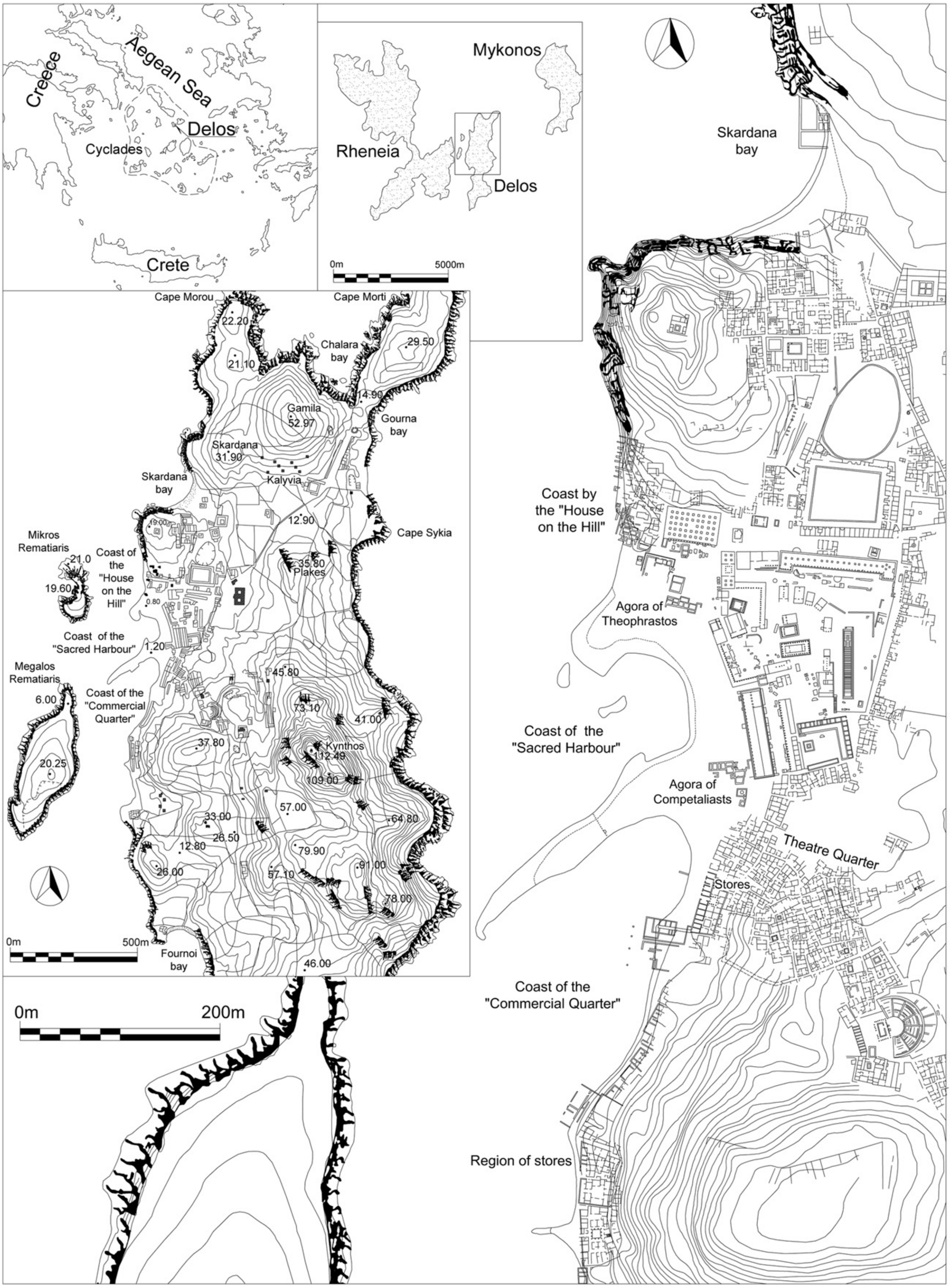

Fig. 2. Location map of the Cyclades, the Delian archipelago and Delos.

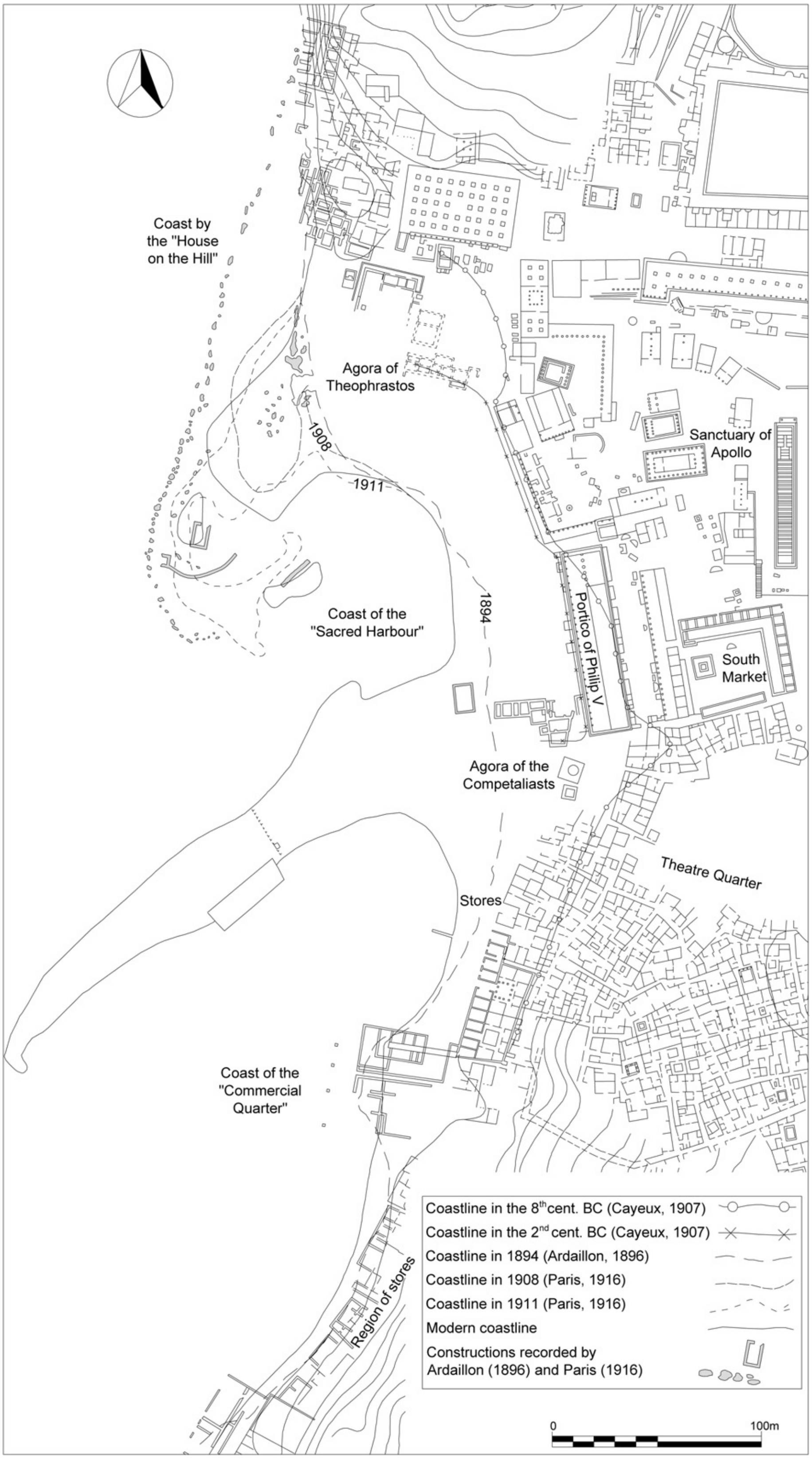

Fig. 3. The development of the coastline at the seafront of the ancient city of Delos from 2nd century BC until today, as recorded by Cayeux (1907), Ardaillon (1896), and Paris (1916).

coastline dates to the 2nd century BC, was located about 60 m from the modern one, and follows the western edge of the "Portico of Phillip V", which was founded on deposits of marine origin. The fills which formed the "Agora of Theophrastos", constructed or at least completed by the end of the 2nd century BC, also cover marine sediments similar to those deposited at the edges of the "Sanctuary" prior to the 8th century BC. According to Cayeux (1907), many sewer-drains which end in the area of the "Sacred Harbour" are interrupted under the sand of the old coast at a distance of 2 m or 3 m beyond their exits from the western edge of the Sanctuary; furthermore, they are covered by marine organisms. Structural and decorative elements of buildings fallen at the western limits of the Sanctuary into what was sea already at that time are also covered by marine organisms.

According to Cayeux (1907), the warehouses in the "Commercial Quarter" south of the "Sacred Harbour" were built on artificial fills, while the docks and jetties of the ancient port facilities, which are interrupted abruptly at sea level, had their foundations below sea level, and their present position does not prove sea transgression. He also observed that Roman hydraulic concrete was used to ensure the durability of these structures against sea erosion. He further argued that if these ruins were foundations or parts of the superstructure of ancient buildings, traces of mosaic floors or pavements would occur. Based on these assertions, which have been thoroughly rejected by Dûchene et al. (2001), Cayeux concluded that the sea level on the coast of Delos remained constant from antiquity until today.

According to Paris (1916), the port facilities along the western coast of Delos comprise five harbor basins. The northernmost, formed by two interdependent basins, is delimited by the "Agora of Theophrastos" to the north and the "Agora of the Competaliasts" to the south. Its access to the sea was ensured by an opening in its SW, about 130 m wide, between the large western breakwater and a considerably smaller one to the south. A large breakwater, 100 m in length and constructed of granitic blocks placed successively at a depth of 2.0 m–3.0 m, entirely protected the harbor against strong winds and currents. For a length of 65 m, it extends SW, then turning S and SE, ending at an almost right angle to its initial orientation.

Four roughly rectangular harbor basins, located in a succession south of the major one, are entirely artificial, of small extent, shallow and insufficiently protected along a straight coast without any engulfment. They are separated by four sizable artificial breakwaters oriented at 90° to the shore. A sixth and smaller harbor basin seems to have been created behind the fifth one, intruding into the land. The docks were developed at the seafront of the city. They begin 180 m north of the "Sacred Harbour" and surround the successive basins. Their total length varies between 1100 m and 1800 m, their width from 3 m to 11 m, and their height is estimated at 1.0 m to 1.20 m, although a wooden extension where the seabed descends to greater depths is probable. The total capacity of the port facilities is estimated by Paris (1916) to have been between 250 and 300 small-sized vessels. Finally, he suggested that at Skardana Bay, the length of the ancient harbor reaches up to 60 m, its eastern extremity now submerged under recent coastal deposits. He also described partly submerged remains of an ancient building on the northern part of the coast, now embedded in marine conglomerate.

Papageorgiou-Venetas (1981) drew a plan of the bay with the likely outline of the ancient breakwater. Its remains, which have accumulated at the base of the underwater slope, are made up of sizable granitic pillars located at depths between 2.50 m and 7.0 m. The foundations of an ancient building at the northern extremity of the sandy shore are also shown in the plan.

Bernier and Dalongeville (1988) separated the beachrock formations on coasts of Rheneia and Delos into two categories. The first includes cemented coastal deposits comprised of sands, pebbles and shells rich in magnesium calcite as cementing material. The second is largely comprised of archaeological remains from the Hellenistic period (c. 200 BC) cemented in quartzo-feldspathic sands and cobbles. Their concretion is a result of a cyanobacterial process in the intertidal zone, trapping local micrite.

The foundations of buildings containing a tank coated with hydraulic mortar at their center, originally constructed on dry land at the edge of a steep coast near the "House on the Hill" north of the "Sacred Harbour", are today submerged below sea level at a depth of 1.33 m (after Dûchene et al., 2001). On the northern shore of Rheneia, the now submerged tombs of the Hellenistic necropolis led to the conclusion that, during its operation, sea level was considerably lower than today, with a difference of as much as 2.50 m to 2.00 m.

Dûchene et al. (2001), refuting Cayeux' (1907) views on sea level stability, reinterpreted the deposits considered by him as marine in origin, on which his reconstruction of the 8th century BC shoreline was based. According to Dûchene et al. (2001), even though these deposits are locally composed from elements of marine origin, their nature is nevertheless aeolian and they were deposited on dry land during periods of low sea levels. Laboratory analysis of gastropods from similar deposits at Rheneia provides evidence that these are of Pleistocene age, 13,640 ± 950 BP (Dûchene et al., 2001).

Desruelles et al. (2009) ascertained that the area of the central Cyclades has subsided during the last 6000 years. Investigating the beachrocks of the Mykonos-Delos-Rheneia group of islands, they identified three different sea levels. The oldest, dated to around 2000 BC, was about 3.60 m lower than the present one, whereas the two more recent ones, dated to 400 BC and AD 1000, were lower by 2.50 m and 1.0 m, respectively.

7. Historical seismicity of the Cyclades area and its possible correlation with the phases of coastal submersion on Delos

Possibly due to the destruction and abandonment of Delos after 69 BC, there are no historical sources to correlate seismic events, vertical subsidence movement sand sea level changes along its coasts. The seismic history of the island is limited to two reports of such events, occurring in the late 5th and early 4th centuries BC, with a time span of 60 years between each report (Guidoboni, 1994).

Thucydides refers to the 431 BC earthquake, indicating that it struck the island just before the start of the Peloponnesian War, and considered it an omen for future events. Probably, this earthquake was a contributing factor toward the second "purification" of Delos by the Athenians in 426 BC. During this ritual act, tombs were removed, thus reviving the religious authority of the island and establishing Athenian prestige among the Greeks during a politically critical time (Guidoboni, 1994).

The 373 BC earthquake is mentioned by Seneca in "Naturales Quaestiones" who records a statement by Callisthenes referring to it "among many prodigies that announced the great quake that destroyed Helike in Achaia". Callisthenes, however, "wishes Delos to be understood as stable because it is on the coast and has hollow cliffs and porous rocks to provide an outlet for the air caught in them. That is why islands have firm ground and why the closer cities lie to the sea, the safer they are" (Guidoboni, 1994). These reported seismic events predate the construction of the submerged buildings from the late 2nd and early 1st century BC, which must therefore have been submerged later than the Hellenistic period.

For the period between the abandonment of Delos and the beginning of the main archaeological excavations, five major earthquakes in the area of the Cyclades are reported (Papazachos and Papazachou, 1989) and can be correlated with the two phases of coastal subsidence. These are: The Santorini earthquake of

46 BC ($M = 6.0$), which caused a tsunami affecting the coast of Crete; the earthquakes of 1650 and 1707, also centered at Santorini ($M = 6.8$ and $M = 6.0$, respectively), accompanied by volcanic eruptions, lava flows and a great tsunami that struck all the Cycladic islands, especially neighboring Paros, but also remote Kea; the 1862 Milos earthquake ($M = 7.0$) which was felt across the whole of southern and central Greece; and finally the strong earthquake at Santorini in 1866 ($M = 6.2$) which was again accompanied by volcanic activity and lava flows.

8. Indications of Late Holocene sea level changes

The submerged beachrock formations which appear to have developed in two different phases, the submerged foundations of buildings along the NW shore of the island, and variations of the groundwater level within the archaeological site are the main indications for Upper Holocene sea level changes along the coasts of Delos.

Incorporated into the older phase of the beachrock formation are building foundations and structural materials from the Hellenistic period (Paris, 1916; Bruneau, 1972; Dûchene et al., 2001). These include carved architectural members such as column drums and capitals and are encountered up to maximum depths of 1.30 m to 1.50 m. The different phases of the evolution of the sandy coast from Hellenistic times until today are represented schematically in Fig. 4. They comprise: initial formation of the coast when the sea level was lower than it is today (Fig. 4a); abandonment of the area (Fig. 4, b); cementation of coastal deposits in the intertidal and supratidal zones, incorporating ancient remains, and the formation of the older phase of beachrocks (Fig. 4c); subsidence of the area during a vertical paroxysmic tectonic event and the formation of the newer phase of beachrocks, incorporating in its turn the archaeological remains located in the intertidal and supratidal zones after the submersion of the area (Fig. 4d); and finally renewed submersion of the coast, including the total subsidence of the two beachrock phases (Fig. 4e).

The rise of the aquifer horizon inside the archaeological site is directly related to the Upper Holocene sea level changes. In the area between the "Agora of Theophrastos" and the "Portico of Phillip V" at a distance of ~50 m from the coast, the rise of the sea level has created a swampy area. The presence of the swamp is not consistent with the use of the area or the methods of building foundation in antiquity.

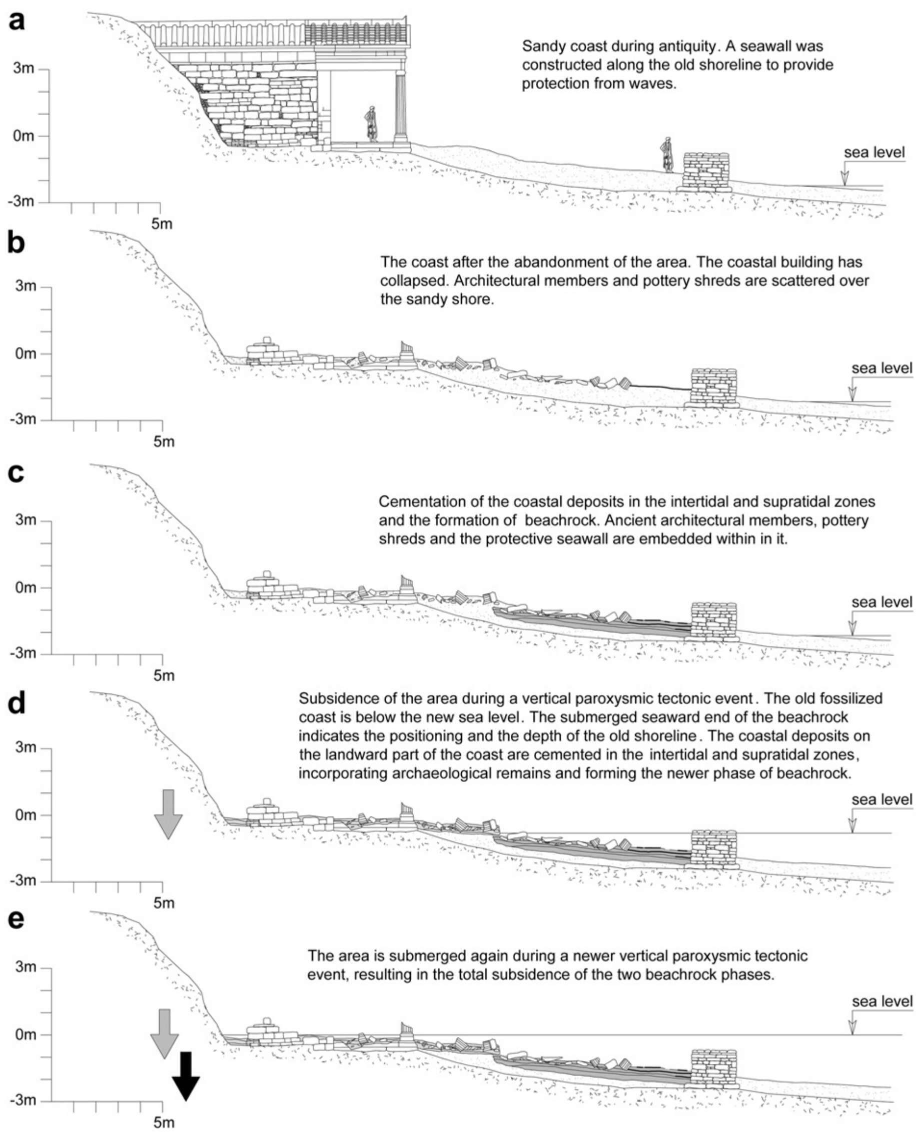

Fig. 4. Graphic representation of the development of the coast in conjunction with sea level changes from antiquity until the present.

9. Underwater indicators of palaeogeographic changes along the NW coasts of ancient Delos – results

The coastal zone of the archaeological area of Delos has a total length of 2.3 km, all of which was examined in the course of this study. It was divided into four distinct sections, so as to facilitate underwater survey along the coasts (Fig. 2).

9.1. Skardana Bay

Skardana Bay is located in the northern part of the study area, where the Inopos meets the sea at the end of a small valley. It is an area exposed to strong northern winds and intense waves, and is oriented along a main NE–SW axis. It has a broad entrance of 220 m width, a coastal length of 325 m, and depth that never exceeds 15 m. Its northern and southern coasts, with a total length of 195 m, are rocky and steep and display evidence of intensive sea erosion. Their height does not exceed 10 m and has a slope grade of ca. 45%. The central stretch of this coast is sandy, with a length of 130 m, a width of 27 m and a slight gradient of 10% towards the sea (Fig. 5).

The beachrock formation developed in the northern half of the sandy beach. Its length reaches ca. 80 m and its width 27 m. It is comprised of strongly cemented coastal deposits which incorporate the remains of an ancient building and many pottery shreds. The top of the formation at its west end is located at depths of 1.30 m and its base at depths of 1.70 m, respectively. The formation slopes downwards gradually to the west, with a low gradient. Beyond its edge, the gradients of the seabed increase to 10% for the next 30 m and to 35–40% for the following 5 m to the west. The morphology of the sandy seabed further offshore is smooth, preserving a 5% gradient towards the NW. Rocky blocks, among them columns or column fragments and pottery shreds, have accumulated in this steep section of the seabed. The rocky fill covers the whole front of the old sandy beach which has been cemented into beachrock for a length of ca. 90 m. The width of the fill reaches 34 m, following the increased gradients of the seabed it covers, with a maximum depth of its top and base of 3.55 m and 6.80 m, respectively (Figs. 5 and 6).

Assuming that the rocky fill, prior to its collapse, was considerably higher in antiquity and formed a pronounced ridge, it is probable that it created one or several offshore breakwaters, providing effective protection for the coast and the human activities on it (Fig. 6). The collapse of the protective structure over time into its present state, a pile of blocks, was probably caused by the intense wave action.

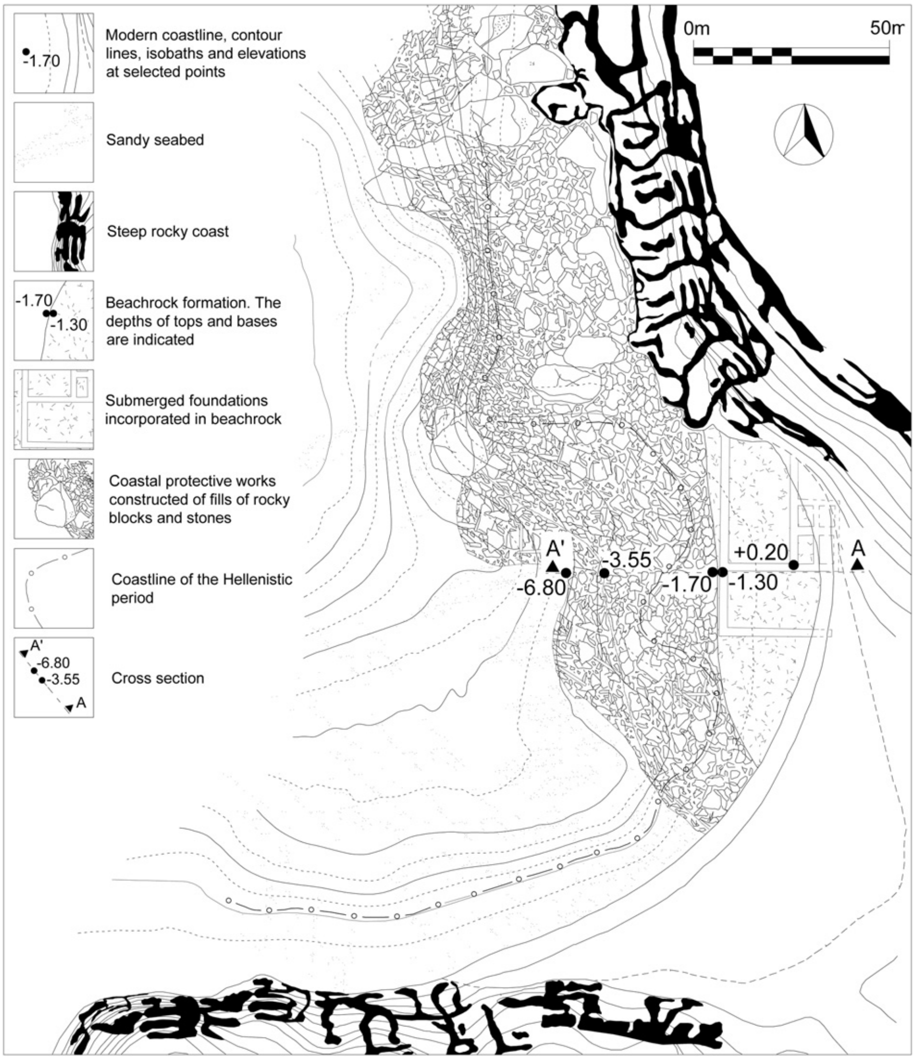

Fig. 5. Skardana Bay with graphic depiction of the seabed morphology, the coastal submerged beachrock formation and the foundations of ancient structures incorporated within in it, as well as the now submerged ancient fills for the protection of the coast.

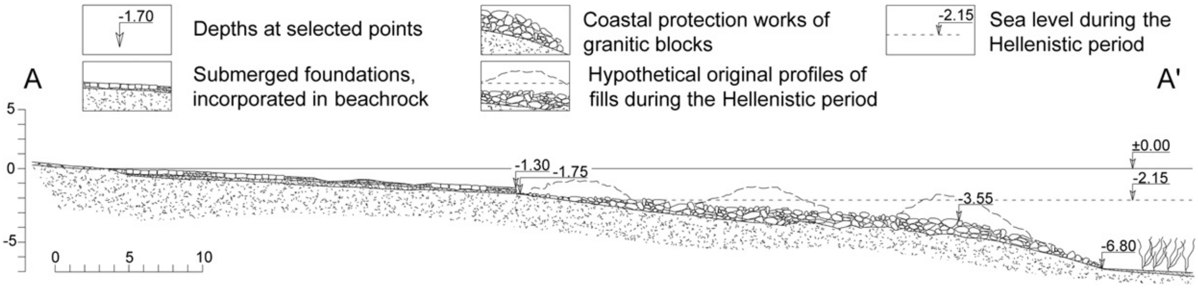

Fig. 6. Characteristic profile of the underwater area of Skardana Bay.

9.2. Coast by the "House on the Hill"

This roughly straight rocky coast starts directly beyond the southern end of Skardana Bay and ends north of the engulfment of the "Sacred Harbour". It has developed in the N–S direction and only at its southernmost part turns SW. In its northern part, 180 m long, the height of the steep rocky coast varies between 6 m and 9 m. Ancient buildings were located along the southern part, with a total length of ca. 200 m. The coastal morphology is quite gentle, with an altitude of up to 3m, and slope angles do not exceed 10° in the northern part and gradually reduce towards the south (Fig. 7).

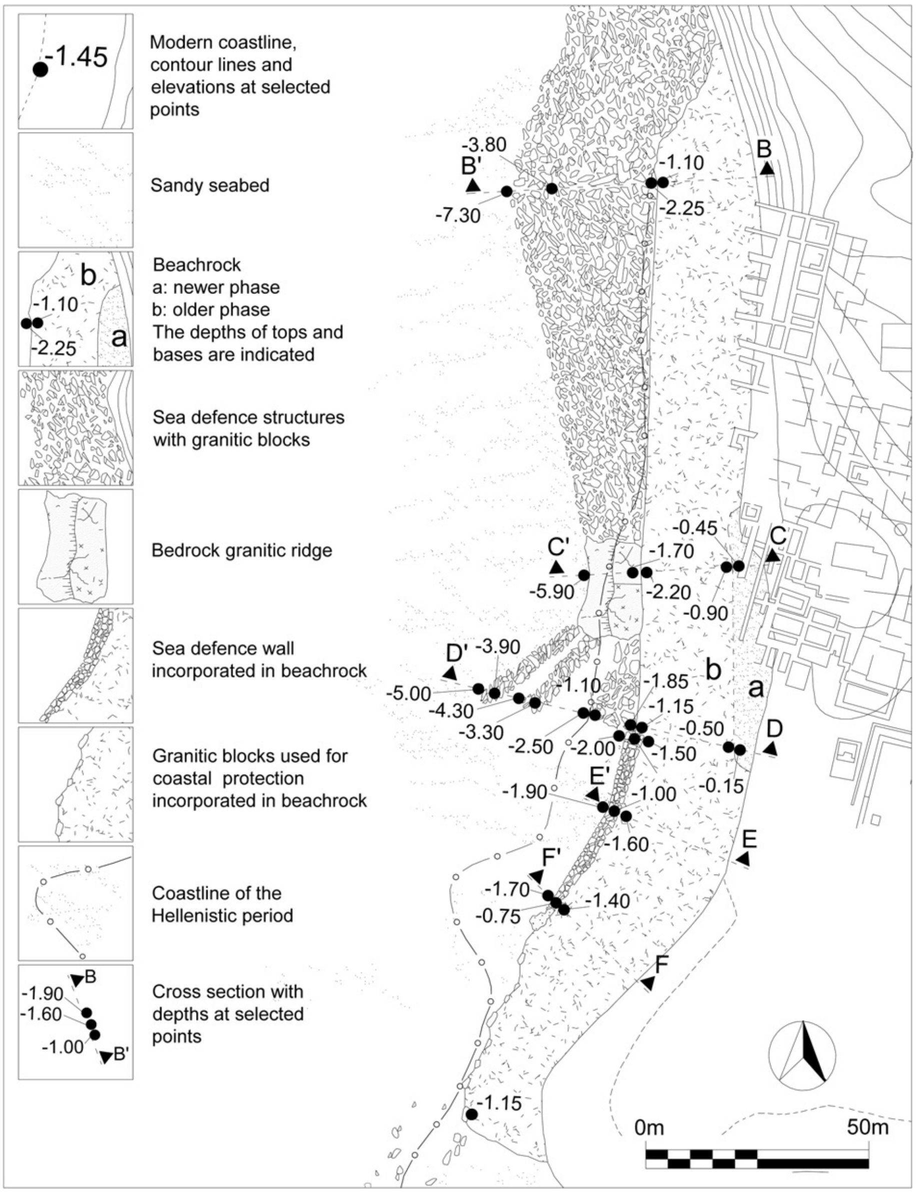

Fig. 7. The coast by the "House on the Hill" with graphic depiction of the morphology of the coastal seabed, the two submerged successive phases of beachrock formation and the foundations of ancient buildings incorporated within it, as well as the submerged ancient coastal protective works.

On the 270 m-long southern section of the coast, the beachrock formation has developed in two distinct phases. It consists of cemented coastal deposits of sands and pebbles, as well as artifacts including pottery shreds, architectural fragments and building foundations. In the northern section of the coast, the width of the beachrock is 21.50 m, in the middle section 27.0 m and in the south 16.0 m. Its younger phase with a width of 4.50 m–7.50 m appears in the middle section of the coast; the depths of its top and base vary from 0.15 m to 0.45 m and 0.50 m to 0.90 m, respectively. The width of the second, older, phase varies from 20.50 m to 22.50 m, and the depths of its top and base vary from 1.10 m to 2.20 m and 1.85 m to 2.25 m. The area of the coastal zone that was occupied in antiquity, as indicated by the archaeological remains incorporated in the beachrock, appears to have been protected from the intense waves by the construction of various coastal works.

In the northern part of the coast, for a length of 123 m in front of the ancient sandy coast, the seabed was sloping downwards with a gentle gradient of 6° towards the west. At a distance between 24 m and 34 m from the old shoreline and in between the 5 m and 7 m isobaths its gradient increases abruptly, reaching 17°, becoming smoother again at depths exceeding 7 m. Throughout the area, granitic fragments and blocks, including fragments of ancient columns, have accumulated on the seabed. The fill has a width of 34 m, the depth of its top is 3.80 m, and that of its base 7.30 m. It is likely that during antiquity the more pronounced ridge formed by this rocky fill offered effective protection to the exposed coast (Figs. 7 and 8a).

On the following section of the coast, for about 20 m, an underwater ridge created by the morphological rise of the granitic bedrock on the seabed in front of the ancient sandy coast provided natural protection from waves without the need for additional artificial structures. This ridge has a width of ca. 11 m and its top is at a maximum depth of 1.70 m. The adjacent seabed is at a depth of 2.20 m on the landward side and 5.90 m on the seaward one (Figs. 7 and 8b).

South of the underwater ridge, large blocks were laid, and a little further out to sea, offshore breakwaters were created for the protection of the old sandy coast. Along a width of 11.50 m beyond the limit of the old sandy shore, granite blocks were placed, with their upper side at a depth of 1.10 m, and the depth of the seabed at their edge is 2.50 m. At distances of 12.50 m and 22 m from the old shoreline, two underwater ridges are formed by granitic debris, their tops at depths of 3.30 m and 3.90 m, with the adjacent seabed at 4.30 m and 5.0 m respectively. It is probable that during antiquity these ridges of rocky fill provided effective protection to the exposed coast (Figs. 7 and 8c).

The seawall that was subsequently constructed along the old shoreline has a length of 46 m. Its northern end is located 29 m offshore from the present coastline, its southern end 26 m. Its width ranges from 4 m at the northern extremity to 2 m at the southern one. The depths of its upper side vary from 0.75 m to 1.0 m, and the depth of the seabed at its landward and seaward sides varies from 1.40 m to 1.60 m and 1.70 m to 2.0 m respectively (Figs. 7, 8d and e).

On the final section of the ancient sandy coast, for a length of ~50 m and at distances of 24 m to 16 m from the modern shoreline, granitic blocks once placed here are now incorporated in beachrock, some of them protruding above the present sea level. The depth of the seabed at their landward side varies from 1.15 m to 1.40 m, and at the seaward side from 1.75 m to 2.0 m (Fig. 7).

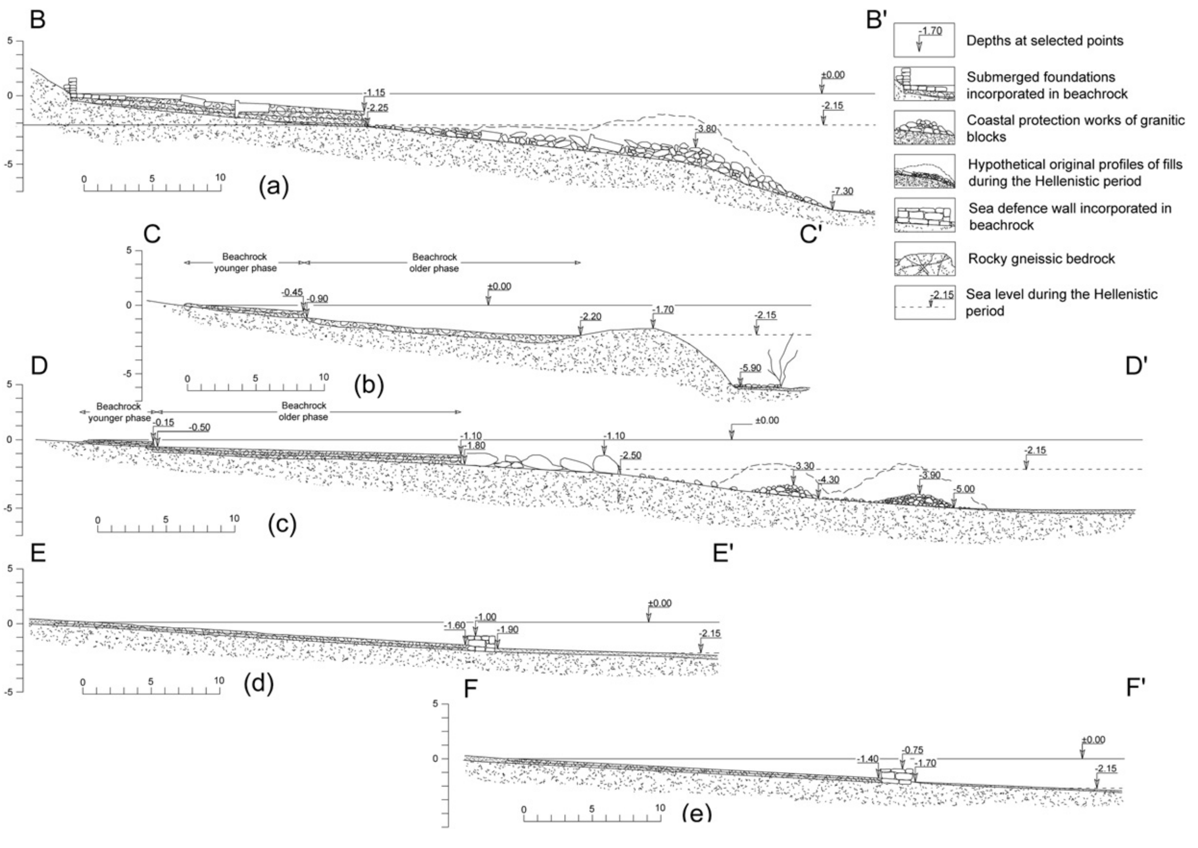

Fig. 8. Characteristic profiles of the underwater area of the coast by the "House on the Hill".

9.3. Coast of the "Sacred Harbour"

The shallow engulfment in the area of the "Sacred Harbour", with an NW–SE orientation, has a length of 110 m, a width of 75 m, and an area of 7,000 m^2, its opening to the sea is 85 m wide, and its coastline measures 219 m in length. The depths of the seabed vary from 0.10 m to 1.50 m (Fig. 9). The deepest areas are located at the SE side, where they do not exceed 0.95 m, as well as at the area of its entrance, where they reach 1.50 m. The seabed upward from the engulfment presents a wide convex shape, with an upper sub-horizontal part approximately 60 m wide, on a slight gradient towards the south, its depth increasing gradually towards the south from 0.10 m up to 0.90 m. The gradients of the seabed subsequently increase towards the west. On this steeper part of the seabed, following its convex shape, remains of rock fill probably indicate the existence of two breakwaters for the protection of the coast, one offshore and another littoral, constructed during antiquity by accumulation of granitic pieces and blocks. These protective works, at a distance of 17 m and 24 m from the coast at their northern edge and 123 m and 155 m at the southern limit, begin directly beyond the south edge of the beachrock formation on the shore by the "House on the Hill" with its protective blocks. They initially follow an SW direction for lengths of 65 m and 85 m, respectively, turning towards the SE for 44 m and 15 m (Fig. 9). The morphology of the southern part of the area of the "Sacred Harbour" was altered mainly during the first decade of the archaeological excavations at Delos in the late 19th century AD, when some 60,000 m^3 of excavation debris was dumped here. This deposit has formed an elongated ledge oriented NE–SW, with a total length of 310 m and width of 90 m. The depth at its top varies between 1.50 m and 3.15 m, at the base from 5.80 m to 6.30 m. A small part of this fill protrudes above the modern sea level to a height of up to 1 m, on a length of 270 m and a width of 40 m. Today it is used as a dock for the disembarkation and embarkation of sightseers (Fig. 9).

9.4. Coast of the "Commercial Quarter"

This section of coast, with a general NE–SW orientation and a length of about 420 m, is bounded to the north by the contemporary breakwater and to the south by an artificial ledge, 90° to the coast in an E–W direction. Beachrock formation was only observed at the southernmost part of this coast. Its length is 10 m and the depth of its top is 0.75 m. The extent of human activity here could be determined on the basis of submerged building foundations, collapsed walls, and numerous pottery shreds and cut blocks. In the northern part, the width of this area varies from 20 m to 32 m, while at the southern end

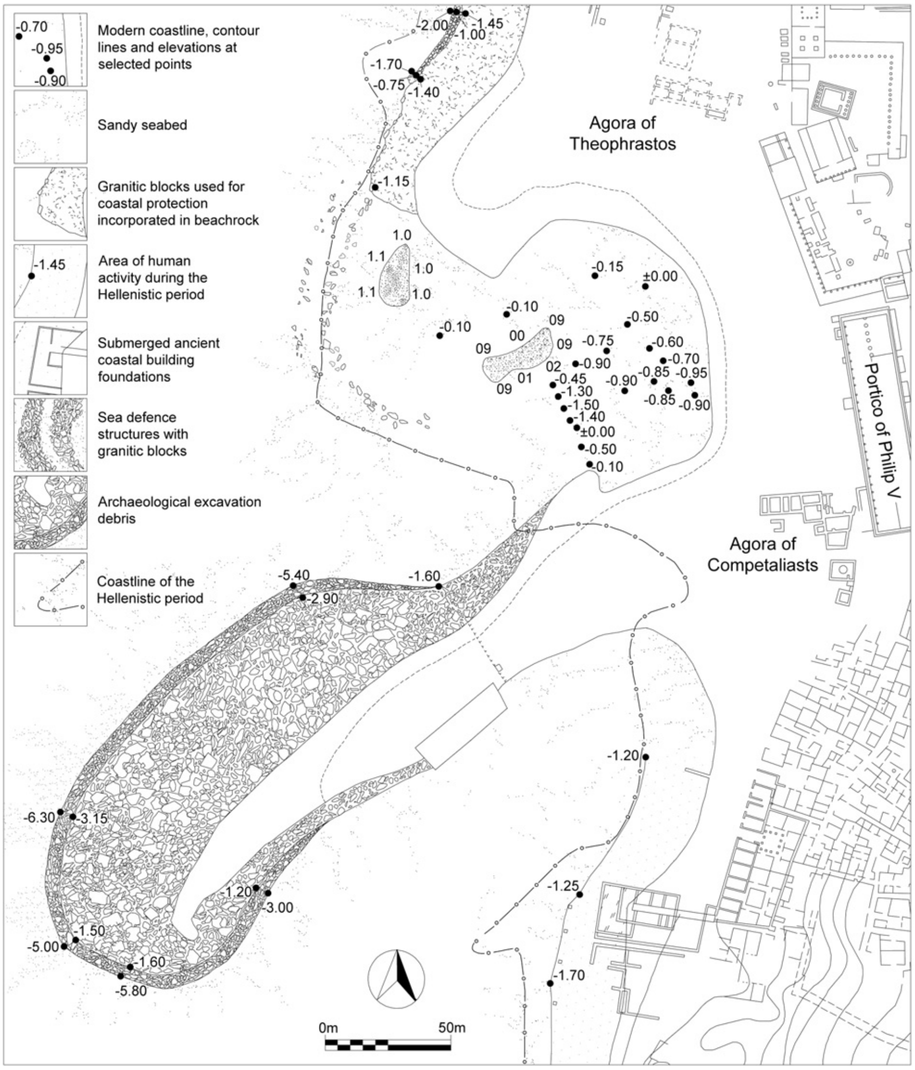

Fig. 9. The coast at the "Sacred Harbour" with graphic depiction of the coastal seabed and the submerged ancient coastal protective works.

it decreases to between 9.50 m and 13 m. The maximum depth of the area varies between 1.40 m and 1.70 m (Fig. 10).

10. Palaeogeographic reconstruction of the seafront of the ancient city of Delos

All archaeological hypotheses regarding the palaeogeomorphology of the coast and the relation between the city of Delos and its coast are based on opinions about sea level stability during historical antiquity (Cayeux, 1907; Paris, 1916). According to these opinions, the shoreline of the 8th century BC was at a distance of approximately 70 m east of the present one, while the younger shoreline, dated to the 2nd century BC, was about 60 m from the present one (Fig. 3). In antiquity, this section of the coast received artificial fills, with the purpose of expanding vital space for human activity. According to the aforementioned opinions, breakwaters and docks protected the complex harbour installations and facilitated the loading/unloading of merchandise and the disembarkation and embarkation of visitors. The schematic representations of the ancient harbour zone include extensive artificial structures along the coast, based on coastal geomorphology contemporary to that witnessed by the researchers.

The results of the present palaeogeographical reconstruction of the coast based on the recording and interpretation of all indicators for sea level change reaches radically different conclusions. The sea level during the Hellenistic period was 2.15 m lower than at present, and the coast at least 30 m wider on average. The coastline of the archaeological site of Delos suffered important interventions, mostly due to the dumping of large quantities of debris from the excavations. The main bulk of these fills was deposited during the

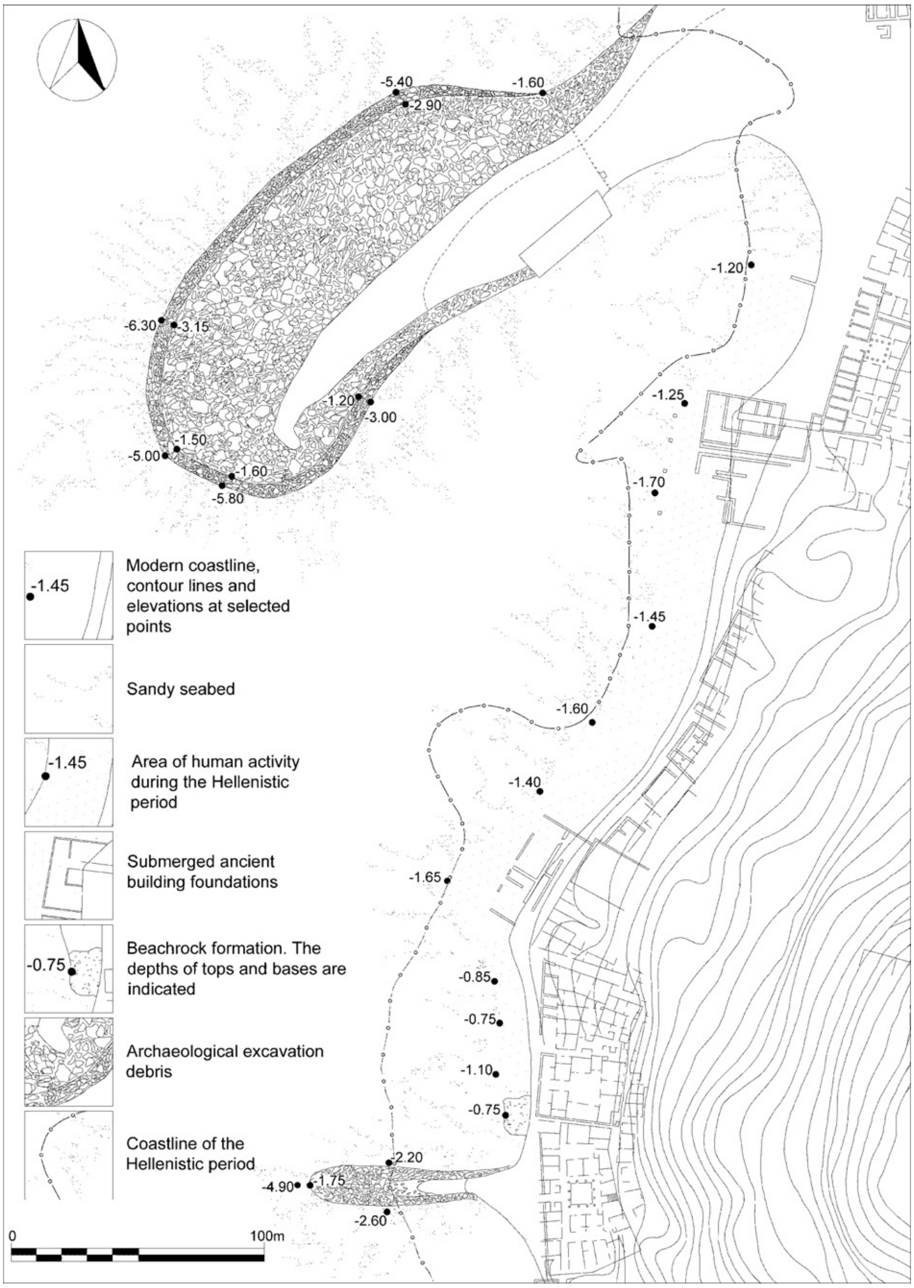

Fig. 10. The coast of the "Commercial Quarter" with graphic depiction of the coastal seabed, the submerged beachrock formation, the limits of the area of human activity during antiquity and the submerged foundations of ancient buildings.

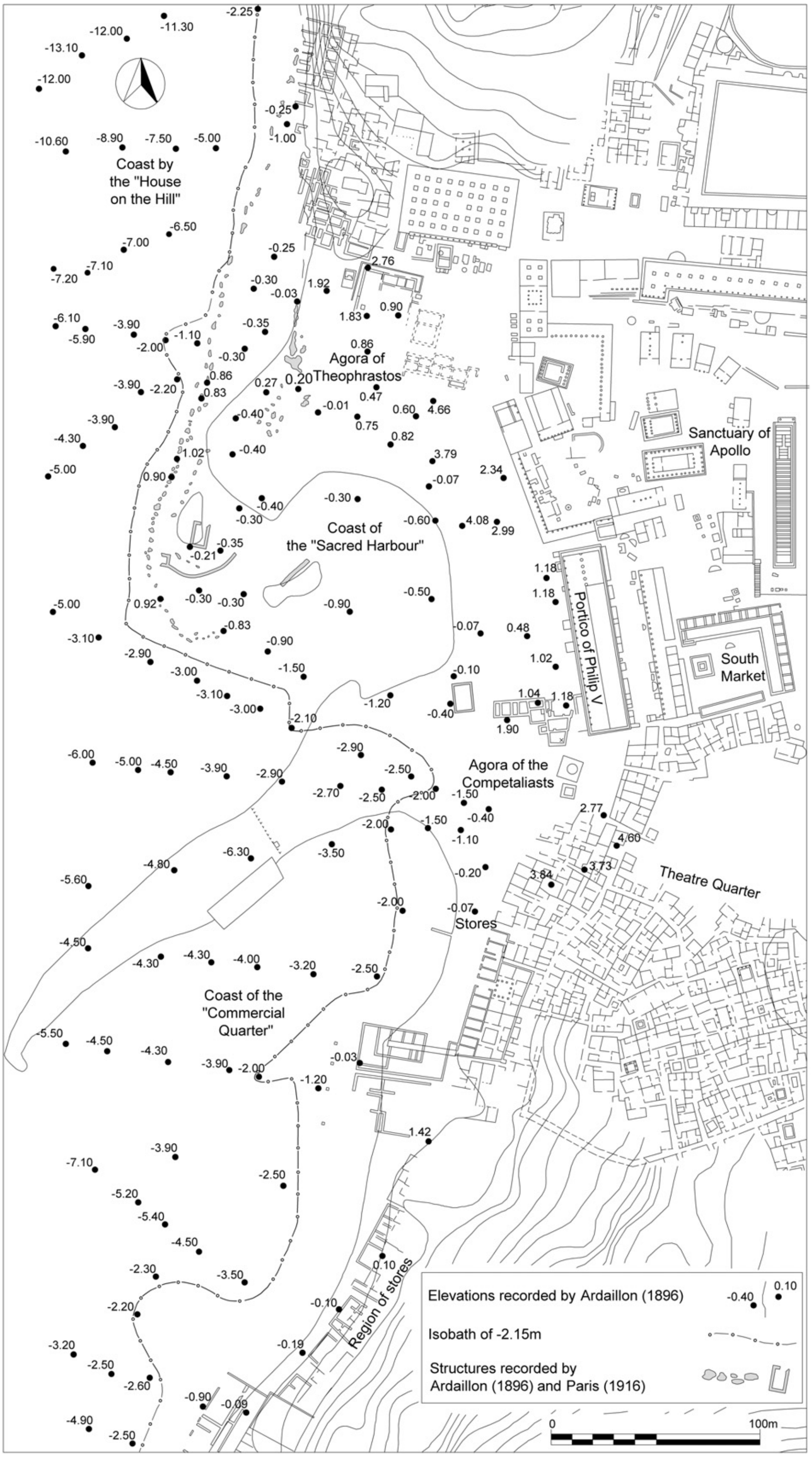

Fig. 11. The coastline during the historical period was 2.15 m lower than today, based on depth measurements and altitudes recorded by Ardaillon (1896), before any later human interventions altered the morphology of the coast.

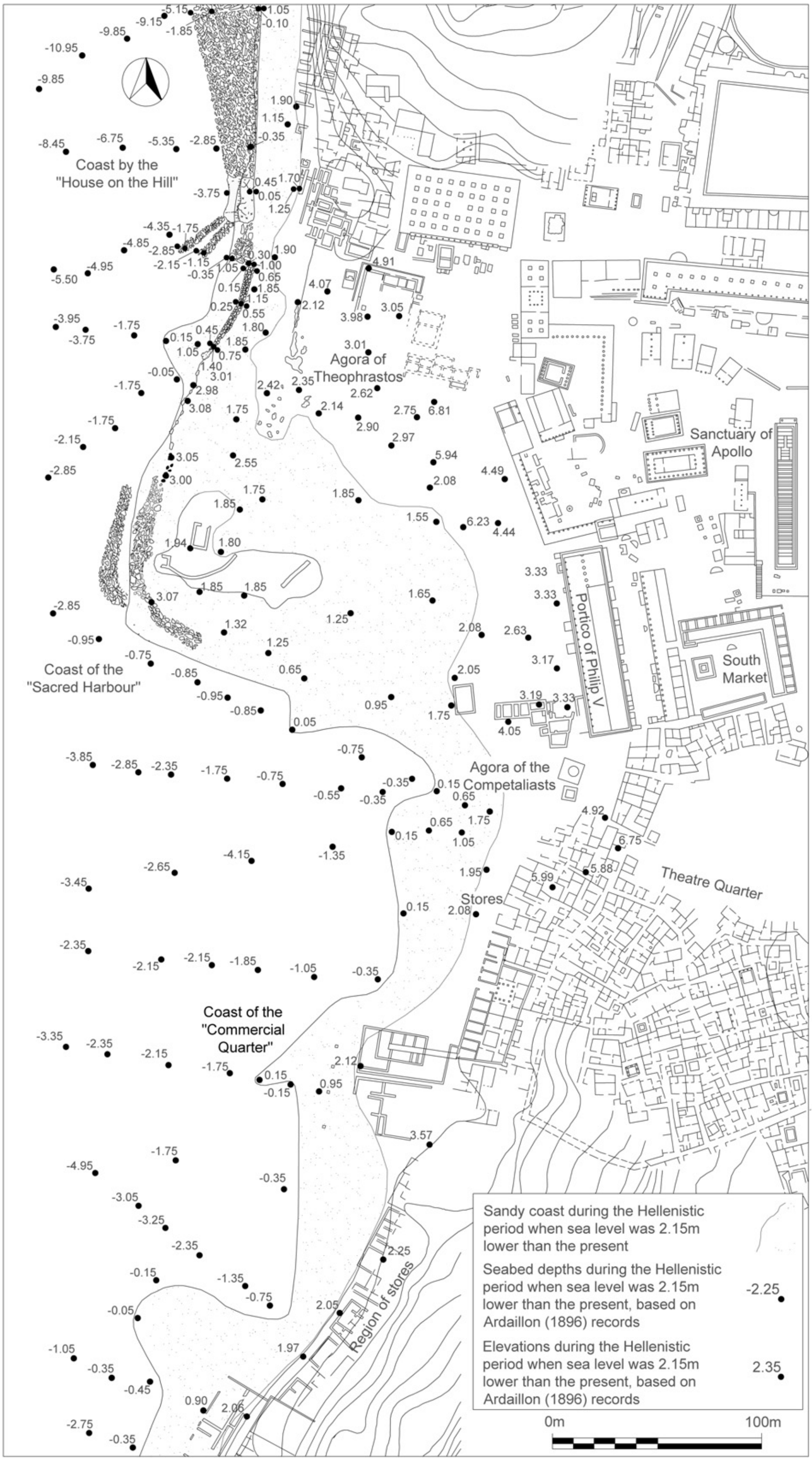

Fig. 12. Palaeogeographic reconstruction of the coast during the historical period, when sea level was 2.15 m lower than at present. Elevations of seabed and land are indicated, based on Ardaillon (1896). The position of ancient constructions for coastal protection is indicative, as recorded by this research, in relation to the coastline.

first decade of excavations, between 1894 and 1904. Ardaillon (1896) published a map of the coastal zone of Delos, recording the morphology of the coast, the altitudes of the land and the depths of the seabed before any such interventions took place. On corresponding maps of the coast created later by Bringuier and Dardinier, published by Paris (1916), substantial human interventions are obvious in the area of the "Sacred Harbour" as well as the southern section of the coast by the "Commercial Quarter".

Thus, the present effort of tracing the older shoreline necessarily made use of the altitudes and depths published by Ardaillon (1896), complemented by measurements resulting from a new survey. The measurements were made in locations considered to have remained unaltered since Ardaillon's study, as they appear to have been affected neither by the extensive deposition of excavation debris, nor by the accumulation of deposits and the coastal erosion which followed that dumping and the disturbance of the coastal environment that resulted from it.

In the period after the end of Macedonian rule, when the destruction of Corinth and the decline of Rhodes led to Delos becoming the most important commercial center of the (then) known world, the city's coastline bore no resemblance to the present one. The ancient sandy coast, the locale of various activities that took place along it, was by far wider than its present successor, and was furthermore protected by various artificial works along it, mainly in its most exposed sections (Figs. 11 and 12).

Sea level changes submerged the ancient sandy coast along with the remains of human activities upon it, as well as the protection works. The prevailing opinion that the sea level had not changed from antiquity to the present led scholars to identify multiple and complicated port facilities adjusted to the later morphology of the coast, which was formed by a sea level rise of ca. 2.15 m. Thus, the protection works were interpreted as an extensive breakwater of the "Sacred Harbour", and the traces of buildings in the supposed ancient harbor basin were seen as remains of the foundations of lighthouses, monuments, and docks.

More specifically, at Skardana Bay the sandy coast was 29 m wider in antiquity, and a building was placed along its entire width up to the limits of the ancient sandy coast, part of its foundations now incorporated in the beachrock formation. The rocky fill covering the steeply sloped seabed at the entire front of the ancient sandy coast is an artificial structure protecting the coast, constructed for more effective absorption of wave energy and control of coastal erosion (Figs. 5 and 12).

On the coastal section by the "House on the Hill", the sandy coast was between 27 m and 16 m wider, and intense human activity took place along it, as indicated by building foundations, columns, as well as numerous pottery shreds, now cemented within the beachrock formation. This section of the coast, which is also exposed to the strong winds and the NW sea currents that prevail in the Straits of Delos, faced problems of intense erosion and demanded works to protect these human activities. Thus, protective works, such as littoral and offshore breakwaters built of granitic blocks, fills of rocky blocks and stones, as well as quays were constructed along this section of the coast (Figs. 7 and 12).

Taking into account that during the period when the "Sanctuary" was functioning, the sea level was 2.15 m lower than at present, the coastal morphology in the area of the "Sacred Harbour" was entirely different from today's situation. The engulfment that characterizes the modern coastline here had not formed, and the area was part of the old sandy coast, located at 0.75 m to 2.0 m above the sea level of that period (Figs. 9 and 12).

The area of the "Agora of Theophrastos", today located at the same elevation as the sea and notably swampy as a result, lay 2.50 m to 7 m above sea level during its period of operation. For the protection of the northern parts of the sandy coast in the "Sacred Harbour" area, two lines of littoral and offshore breakwaters were probably constructed through the artificial accumulation of rocky blocks and pieces (Figs. 9 and 12).

The sandy coast by the "Commercial Quarter" was wider by 18 m to 72 m, allowing intense human activity, with a width reaching 32 m west of the present shoreline. The buildings that were constructed along the seafront stood on foundations placed 0.90 m to 2.10 m above the sea level of that period. Along this section of the coast, no protection works were found, a fact that should be attributed to the morphology of the coast in the area of the "Sacred Harbour", which protected the coast of the "Commercial Quarter" from strong waves (Figs. 10 and 12).

11. Conclusions

After the end of the Hellenistic period, the coasts of Delos submerged initially by 1.35 m, and then, during a second phase of submersion, by a further 0.80 m. These two distinct phases of submersion recorded in this survey, together with an older sea level at 3.60 m lower than at present, seem to have affected the centre of the Cyclades during the Upper Holocene (Desruelles et al., 2009).

There is, however, a differentiation regarding the dating of the intermediate phase of submersion. Desruelles et al. (2009) estimate a date of ca. 400 BC for this phase. Based on the archaeological dating of ancient structures (Paris, 1916; Bruneau, 1972) now incorporated within the beachrocks that have developed along the coast by the "House on the Hill", it appears, however, that the subsidence ought to be dated after the destruction of Delos by Mithridates in 69 BC. It is clear that these ruins were incorporated into the beachrock formation after the abandonment of the site and the collapse of the buildings, during a period of sea level stability.

The sea level change radically altered the palaeogeomorphology of the coasts and resulted in the transgression of the sea to varying extent throughout the island's shores: on the sandy coast of Skardana by 29 m; in the southern part of the coast by the "House on the Hill" by 16 m to 27 m; in the area of the "Sacred Harbour" by 165 m; and on the coast of the "Commercial Quarter" by 18 m to 72 m.

Along the shoreline of Delos, a complex system of coastal protective works, such as breakwaters and seawalls, was constructed to shelter the coast from wave action. Previously, the interpretation of these harbour works, described and schematically reconstructed by Ardaillon (1896), Cayeux (1907), Paris (1916), and Papageorgiou-Venetas (1981), has been largely conjectural, based on scant archaeological evidence as well as on the view that both the sea level and the morphology of the coast remained constant over time. The palaeogeographic reconstruction of the coasts presented in this study reveals that the positioning of harbor basins, breakwaters and docks as interpreted by Paris (1916), all located east of the old shoreline on what was dry land in antiquity, would have been functionally impossible.

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