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Palaeogeographic reconstruction of the Main Harbour of the ancient city of Delos (Greece)

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ABSTRACT

Delos Island, located in the Aegean region, became a major religious, cultural, and commercial hub during the Hellenistic period (323-30 BCE). From the 3rd century onwards, the island underwent significant growth, driven by the efforts of the independent city of Delos. This growth further intensified when Rome designated Delos as a free port and transferred its control to Athens in 167 BCE. The island's prosperity led to its maritime infrastructure, particularly the Main Harbour, playing a crucial role in trade. The current coastal landscape, however, bears little resemblance to the Hellenistic one. An interdisciplinary (archaeology, geomorphology, geophysics, sedimentology, micropalaeontology, and oceanography) study was conducted from 2007 to 2017 to propose a new reconstruction of the Hellenistic harbour. The study showed that the bay of the Main Harbour extended less to the north than indicated in previous studies, and that the landscape evolved considerably during Antiquity. The absence of evidence for quays suggests that access was limited to flat-bottomed boats, raising questions about the anchorage possibilities for larger boats.

1. Introduction

Located at the heart of the ancient Aegean world, Delos Island is one of the most renowned archaeological sites from Antiquity. Designated in 1990 as a UNESCO World Heritage Site, the city was a major hub for commerce in the Aegean region, connecting the Eastern and Western Mediterranean (Bruneau et al., 1996; Zarmakoupi, 2015). It saw an economic boom from the 3rd century onwards under the initiative of the independent city of Delos (Chankowski 2019). Its prosperity peaked after its declaration as a free port by the Roman authorities in 167 BCE (Hasenohr, 2012). The trading port gradually lost its importance during the 1st century BCE, but the town continued to exist until the 6th century CE.

The maritime infrastructure, particularly the Main Harbour (often defined as the Sacred Harbour) located in the northwestern part of the island (Fig. 1), played an important role in trade. Hence, reconstructing its landscape is crucial for furthering historical and archaeological knowledge. However, the current landscape bears little resemblance to the Hellenistic one, as a large volume (around 60,000 m^3 according to Mourtzas, 2012) of debris from archaeological excavations was dumped back into the Main Harbour bay in the late 19th and early 20th centuries. Therefore, previous reconstructions of the harbour's landscape during the second Athenian domination (167-69 BCE), such as those presented by Duchêne et al. (2001), were based on conflicting publications from the early 20th century. For example, according to Pâris (1916), the Grand Port was made up of basins shaped by plunging quays, whereas according to Ardaillon (1896), it consisted of a beach on which boats were pulled, bordered by a street. The first restitution is based on

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data from Cayeux (1907, 1911, 1914) which indicate that the sea level has remained stable since the Hellenistic period. The second is consistent with Négris (1903) who asserted that the sea level had risen by 3 m–3.50 m since ancient times in Delos. As several studies over the last 30 years (e.g., Desruelles et al., 2009) support this theory, the reconstruction proposed by Ardaillon (1896) seemed more coherent, raising questions about the functioning of the harbour, such as accessibility for deep-draught boats.

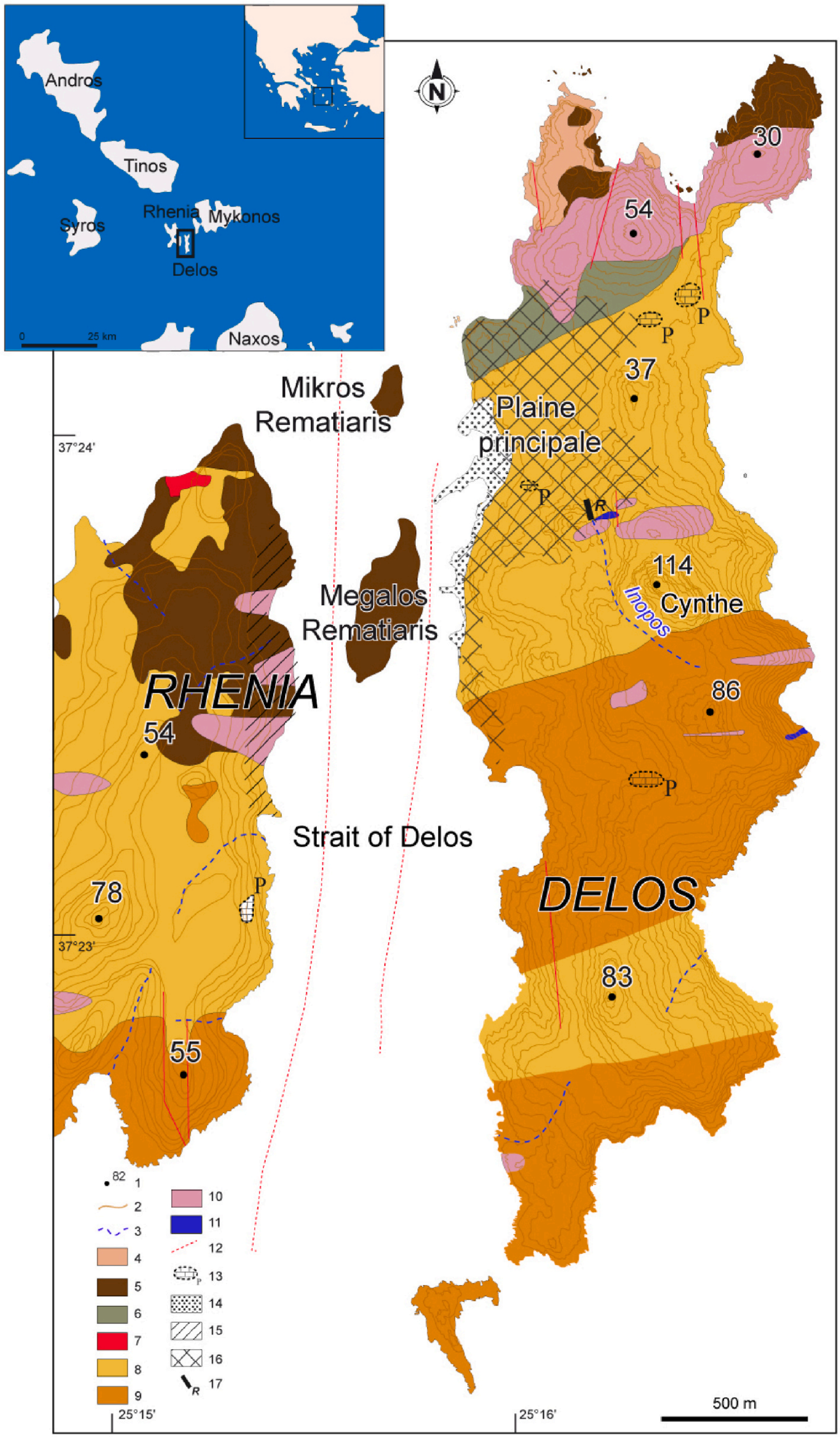

Fig. 1. Geology of Delos and Rhenia. 1: spot height (in m); 2: elevation contour (5 m); 3: ephemeral flow; 4: leucocratic gneiss; 5: biotite gneiss; 6: dykes and sills of fine-grained granite; 7: hornblende monzogranite; 8: biotite and hornblende monzogranite; 9: pyroxene monzogranite or granodiorite; 10: migmatitic gneiss; 11: marble; 12: fault or hidden fault; 13: "poros" (calcarenites); 14: necropolis; 15: antique city; 16: "Réservoir de l'Inopos". Map based on Desruelles (2004), Desruelles et al. (2007), and Jolivet et al. (2021).

In line with geoarchaeological studies based on geoscientific tools that have helped answer key archaeological questions on ancient habours (Marriner and Morhange, 2006; Marriner et al., 2005, 2010, 2017; Pourkerman et al., 2020), an interdisciplinary study was conducted from 2007 to 2017 to provide new paleoenvironmental data and, finally, to settle the debate on contradictory paleogeographic reconstructions, including issues related to the port's accessibility for deep-draught boats. This study combined cartographic archives; geomorphological, micropalaeontological, and sedimentological analyses; geophysical and submarine surveys.

2. Geomorphological and archaeological settings

2.1. Geomorphology

The island of Delos is primarily composed of Miocene granite (Fig. 1), which is part of the Mykonos-Delos-Rhenia metamorphic core complex located in the centre of the Aegean back-arc extensional basin. This area is located to the north of the subduction of the African plate under the Eurasian plate (Jolivet et al., 2021). The back-arc extension was active from the Late Oligocene to the Late Miocene (Rabillard et al., 2018), and the Cycladic plateau has likely behaved as a rigid block with no significant deformation since the Late Miocene, as indicated by the lack of major earthquakes (Tirel et al., 2004).

According to Desruelles et al. (2009), the mean sea level in Mykonos-Delos-Rhenia was approximately 2.50 (±0.50) meters below the present sea level (b.s.l.) around 400 BCE. This evolution over time is due to eustatism and glacio-hydro-isostasy, whose effects are enhanced by the subsidence trend (Lambeck and Purcell, 2005; Pavlopoulos, 2010; Pavlopoulos et al., 2011; Sakellariou and Galanidou, 2016; Benjamin et al., 2017; Roy and Peltier, 2018).

The Main Harbour is located in a shallow bay surrounded by rocky bluffs to the north and south. The bay borders a flat low-lying area called the "Main Plain" ("Plaine Principale"; Fig. 1) where the Apollo Sanctuary was located. The current shape of the bay is a result of the accumulation of debris from excavation sites, leading to the construction of a jetty at the beginning of the 20th century. This jetty retains the sediments brought in by the longshore drift, resulting in silting over much of the bay. To the west is the Strait of Delos (Fig. 1), which separates Delos from Rhenia. Despite a low tidal range (up to 0.30 m), access to the harbour by boat can be difficult due to the shallowness of the strait and the presence of two islets (known as "mikros" and "megalos" Rematiaris; Fig. 1), as well as the influence of the north swell, which can be strong in summer because of the wind.

2.2. Archaeology

The earliest identified harbour constructions date from 314 BCE to

Fig. 2. Archaeological remains (constructions, rip-rap …) drawn from the plans published by Ardaillon (1896) and Holleaux (1909). 1: elements on the plan published by Ardaillon; 2: elements on the plan published by Holleaux; 3: elements on the plans published by Ardaillon and Holleaux. Basemap: https://sig-delos.efa.gr.

167 BCE, when trade began to prosper. The harbour was later expanded when the city became a free port in 167 BCE. An extensive backfill of the harbour area was funded by the city of Delos during at least the period between 217 and 180 BCE and before 125 BCE by the Athenian *epimeletes* Theophrastos (Duchêne and Fraisse, 2001; Karvonis, 2008; Zarmakoupi, 2015; Malmary and Karvonis, 2016; Chankowski, 2019). Many commercial buildings were then built south of the harbour (Hasenohr, 2002; 2012). Previous reconstructions of the harbour's landscape during the second Athenian domination (167-69 BCE), such as those presented by Duchêne et al. (2001), were based on conflicting publications from the early 20th century.

- According to Ardaillon (1896), the harbour was located in a shallow bay bordered by a wetland and protected by a natural barrier that had been artificially reinforced (Fig. 2). This barrier, referred to as a "jetty" ("jetée"; Supplementary material 1), would have shielded the harbour basin from swell, and its sandy beach was used to pull the boats ashore. Ardaillon estimated that the basin was originally between 1 m- and 3 m-deep, allowing ships to anchor there. He reconstructs an 8 m-wide paved street along the Apollo Sanctuary and a beach of the same width. He also located two 13.50 m-by-8.50 m rectangular structures, referred as "X1" and "X2" on Fig. 2 in the vicinity of the West Portico and to the south of the "jetty". He believed these to be monumental bases marking the entrance to the Main Harbour. No remains of quays were identified during his excavations.
- In 1916, Pâris published an alternative reconstruction of the Main Harbour, based on the surveys directed and published by Holleaux (1909). According to Pâris, the harbour consisted of quays, rip-raps, and moles (Fig. 2). The jetty mentioned by Ardaillon (1896) is referred to the "Great Mole" ("Grand Môle"; Supplementary material 2), which would have been an artificial structure, at least in part, and probably covered by a quay. To the northwest of the Main Harbour's basin, Pâris suggests the existence of a small secondary basin. The main basin would have been bordered by rip-raps on the southern edge of the Agora of Theophrastos. He also posits that quays would have bordered the Apollo Sanctuary and the West Portico (Fig. 2). Finally, the southern part of the basin would have been delimited by a quay on the edge of the Agora of the Competaliasts, extended by a supposed "Small Mole" ("Petit môle"). This quay and the eastern wall of the "Small Mole" match the southern and eastern sides of building "X1", as identified by Ardaillon (1896). However, no accurate records support the Pâris (1916) reconstruction.

These two contrasting reconstructions of the ancient harbour landscape were each influenced by two conflicting theories about sea level variations. The first was influenced by Négris (1903), who asserted that the sea level had risen by 3–3.50 m since ancient times, based on the observation of submerged Hellenistic remains. In contrast, Cayeux (1907, 1911, 1914), who has influenced Pâris (1916), argued that submersion does not necessarily indicate a rise in sea level, as the structures could have very well been built in the water from the start. According to him, because of their composition (including many intact mollusc shells), these backfills would have been deposited underwater to extend the port into the sea (Cayeux, 1907). However, the fossil marine organisms that Cayeux claimed to have found to support his reconstruction have not been recovered (Duchêne and Fraisse, 2001).

Archaeological excavations conducted in the Agora of the Competaliasts have revealed that the paved esplanade was constructed on a backfill deposited in the 2nd century BCE to cover a coastal marsh that had formed at the mouth of the Inopos river (Hasenohr, 1996; Desruelles, 2004), prior to the construction of a dam upstream ("le Réservoir de l'Inopos"; Fincker and Moretti, 2007). The western edge of this esplanade probably marked the boundary between the marsh and a sandbar. The Inopos is the sole watercourse on Delos (Desruelles, 2004). While its flow is intermittent, it surely has played a significant role in the infilling of the bay as well as in the shaping of the coastline. Like many watercourses in the Cyclades, its valley was more extensive during the Last Glacial Period. Studies relying solely on bathymetric surveys from the early 20th century suggest that prior to being submerged during the Holocene due to Post-Glacial Sea-Level Rise, the palaeo-valley of Inopos flowed westward towards the island of Rhenia, passing between the islets of Mikro and Megalo Rhematiaris (Nakas, 2022).

Considering the uncertainties present in the early 20th century reconstructions and the recent findings regarding the relative sea level changes since the Antiquity, a new study leveraging updated materials and methods was initiated.

3. Material and methods

3.1. Analysis of historical maps

In order to understand the topography and underwater landscape of the Main Harbour bay before its disruption because of archaeological debris, maps from the late 19th and early 20th centuries were gathered, georeferenced, and integrated into a Geographic Information System using the Greek HGRS87 (Hellenic Geodetic Reference System) or EGSA ("ΕΓΣΑ'87" in modern Greek) system (Delikaraoglou, 2008). The map drawn by Ardaillon in 1896 (Supplementary material 1) proved to be particularly useful in this effort.

3.2. Geophysical surveys

Two types of geophysical surveys were conducted in order to assess the geometry and thickness of surface deposits and determine the depth of the bedrock, as well as identify buried archaeological structures.

- Six terrestrial and two marine electrical resistivity tomography (ERT) campaigns were carried out in September 2007 (Fig. 3). The 2D subsurface profiles were created using the ABEM Lund Imaging System (Terrameter LS/4 channel) with a 64-electrode array and a Schlumberger-Wenner reciprocal layout protocol. A computer inversion program (Res2Dinv; Loke, 2003) generated images of the resistivity distribution on a cross-section beneath the survey line.
- An electromagnetic survey was conducted in August 2008 in the Apollo Sanctuary (Fig. 3) using EM31 and EM38 conductivity meters (Geonics Ltd). These instruments consist in two coils spaced 3.66 m (EM31) and 1 m (EM38) apart and operated at a frequency of 9.8 kHz (EM31) and 14.6 kHz (EM38), respectively. The measurements were taken along profiles spaced 5–10 m (EM31) and 1–2 m (EM38) apart.

3.3. Submarine survey

Bathymetry and seafloor imagery between Delos and Rhenia were acquired by sonar systems in November 2016 (Fig. 6). The shallow-water bathymetry was obtained using a single-beam echo sounder (Humminbird 998c SI Combo GPS Chartplotter), while the deep-water bathymetry was measured using a multi-beam echo sounder (Reson SeaBat 7125). Additionally, 10 km of high-resolution seismic profiles were acquired from the Strait of Delos using a Chirp Profiler from GeoAcoustics. However, seismic profiling was not possible in the shallow depths between Delos and the "megalos" and "mikros" Rematiaris islets, which means that the thickness of the alluvial and anthropogenic sediments in front of the modern harbour could not be determined through this method. The data was processed using the SB-Interpreter (Triton Imaging Inc) and SonarWiz (ChesaPeake Technology) softwares and subsequently integrated into a Geographic Information System.

3.4. Sediment core sampling and analysis

Eleven cores (C1 to C11) were drilled with a Cobra TT vibrocorer in

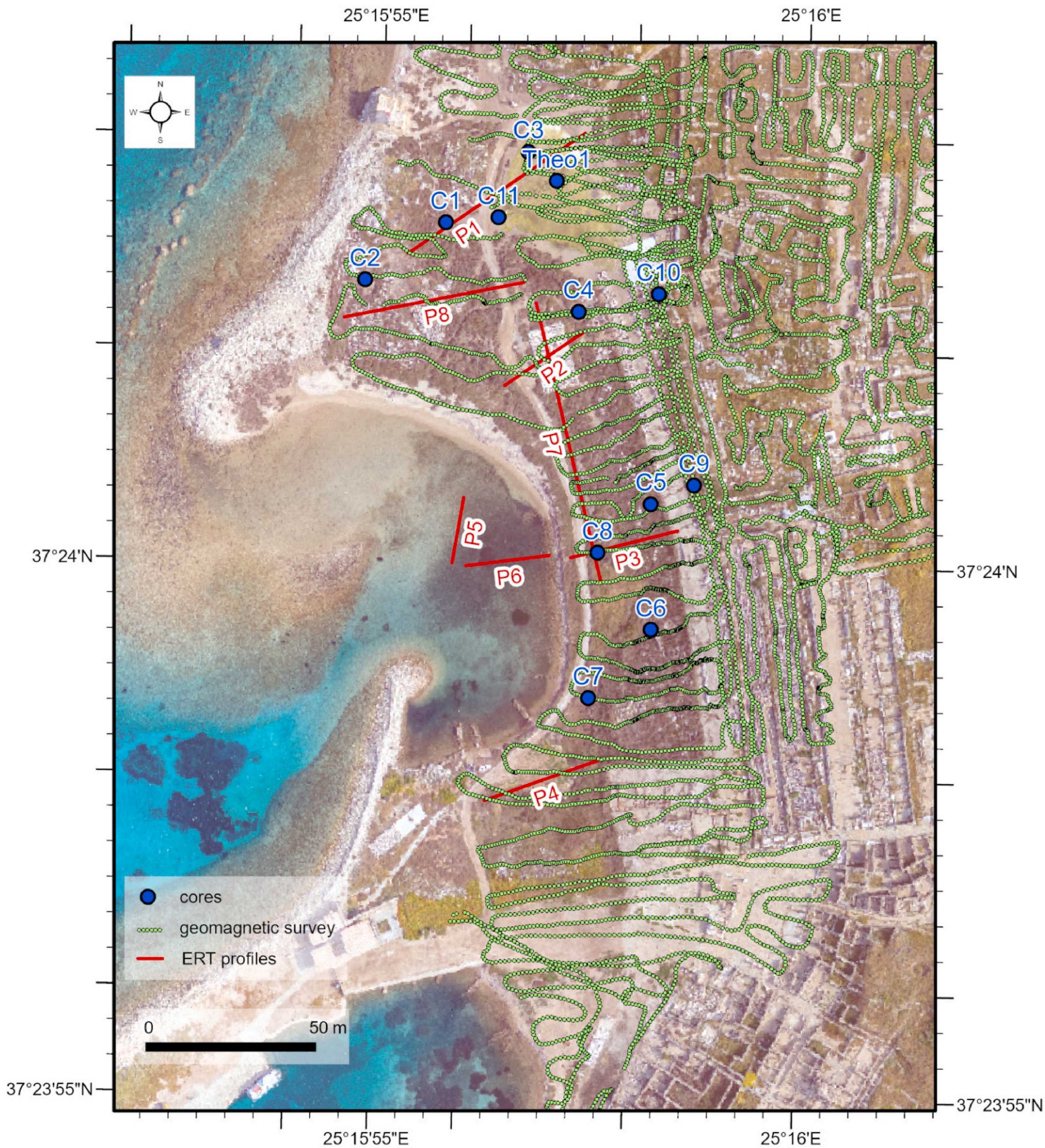

Fig. 3. ERT profiles, electromagnetic survey, and drill core locations. Coordinate system: WGS 1984 UTM Zone 35 N. Basemap: https://sig-delos.efa.gr.

October 2007 (Fig. 3), with a diameter of 50 mm and to a maximum depth of 5.20 m below ground surface. They were positioned according to the results of the geophysical survey. They were precisely levelled in the HGRS87/EGSA system (whose altitudes are 0.86 m higher than the Dellinger system used by the archaeologists of the French School at Athens; Moretti et al., 2015). In 2016, an additional vibrocore (Theo1) was extracted from the Agora of Theophrastos as a control sample for this study (Fig. 3).

3.5. Micropalaeontological analyses

A stratigraphical description of the sediment's texture and colour was conducted in the field. Micropalaeontological analyses (benthic foraminiferal assemblages) were performed on 41 samples collected from cores C3, C6, C7, and C11 (Supplementary material 4). Each sample (dry weight: 10 g) was treated with H2O2 to remove the organic matter, wet-sieved through a 63 μm mesh, and dried at 60 °C. Whenever possible, a total of 200–300 foraminiferal specimens were manually selected from each sample for analysis. The microfauna has been identified using a Leica S6E stereomicroscope and the applied taxonomy on benthic foraminifera assemblages is based on Loeblich and Tappan (1987), Cimerman and Langer (1991), Hottinger et al. (1993), and Dimiza et al. (2016). The benthic foraminiferal relative abundances and density (Number of foraminifera specimens/g) were estimated, and the BR-ratio has been calculated.

3.6. Radiocarbon dating

Twenty-four marine shells (based on the results from the analyses mentioned in §3.6 above), pieces of charcoal, bones, plant remains, and wood samples were dated using AMS at the "Centre de datation par le Radiocarbone" in Lyon, France (Fig. 4). The ^{14}C dates were calibrated using the IntCal20 and IntCalMarine20 calibration curves as well as the CALIB 8.2 program (Reimer et al., 2020; Stuiver et al., 2022). Marine calibration was applied based on δ^{13}C values and the marine reservoir effects were considered based on Reimer and McCormac (2002) and Heaton et al. (2020).

4. Results

4.1. Borehole chronostratigraphy

The lowermost substratum is found to be weathered for every core, with a surface that varies between ~4.80 m below the mean sea level (b.s.l.; core C7) and ~0.20 m above the mean sea level (a.s.l.; core C9). Six main morphosedimentary units overlie the bedrock (Fig. 5).

- Unit A covers the bedrock in cores C3 and C11, between 2.35 m b.s.l. and 1.85 m b.s.l. It primarily consists of silty coarse sand with an abundance of clay but no shells or pottery remains. The microfauna is dominated by marine species (Fig. 6): small rotaliids (mainly *Rosalina bradyi*, *Discorbis williamsoni*, *Cibicides refulgens*, *Lobatula lobatula* and *Conorbella imperatoria*; 9 % in core C3, 33 % in C11), *Elphidium crispum* and *Elphidium complanatum* (20 % in core C3, 33 % in C11), *Ammonia beccarii* (17 % in core C11), and miliolids (mainly *Quinqueloculina seminula*; 18 % in core C3). However, this unit also includes species adapted to low-salinity environments: *Ammonia tepida* (associated with rare *Aubignyna perlucida* and *Haynesina germanica)* particularly in core C3 (52 %). According to the dating for core C3 (565-402 BCE), these sediments were deposited before the Hellenistic period (323-30 BCE).
- Unit B overlies the bedrock in core C7, between 4.65 m b.s.l. and 3.55 m b.s.l. It primarily consists of coarse sand including shell debris, as well as pebbles, cobbles, and a few fragments of pottery. Its top layer is composed of sand, pebbles, and charcoal. The microfauna is dominated by marine species such as *Peneroplis pertusus* (~25 %), miliolids (22–38 %), and small rotaliids (~15 %), but also includes a high concentration of *A. tepida* (15 % at 4.325 m and 35 % at 4.625 m). This layer is dated as ranging from 212 to 92 cal. BCE (core C7).
- Unit C covers the bedrock in cores C1, C4, C5, and Theo 1. It overlies Unit A in cores C3 and C11. Its top elevation ranges from ~1.35 m b.s.l. (C4) To ~0.35 m b.s.l. (C3). It primarily consists of coarse sand, including pebbles, and sometimes debris of shells. It is characterised by its abundance of cobbles and pottery fragments. The microfauna is dominated by marine species such as small rotaliids (15–50 %), miliolids (~20 %), and *Elphidium* spp. (15–30 %). This unit has been dated as ranging from 571 to 404 BCE (core C5) to 371-175 BCE (core C3).
- Unit D1 covers Unit C in cores C1, C2, C3, C4, C5, C11, and Theo 1. Its thickness varies greatly, ranging from 0.12 m (core C3) to 1.20 m (core C1). It is mainly composed of sand of different textures (silty to coarse) and pebbles. It is characterised by its abundance of shell fragments and the scarcity of pottery fragments. The microfauna of core C11 consists mainly of typical infralittoral marine species, such as small rotaliids (R. *bradyi*, D. *williamsoni*, C. *refulgens*, and C. *imperatoria*; 30–50 %) and miliolids (Q. *seminula*, Q. *irregularis*, Q.

Core	Code sample	Depth (in cm)	Material	Δ^{13}C	Conventional ^{14}C age BP	Error	2 σ calibrated results	Median probable age
C1	Lyon-7100	190	Marine shell	0,59	2410	30	248 BCE- 149 CE	198 BCE
C3	Lyon-7084	84	Charcoal		2205	30	371-175 BCE	273 BCE
C3	Lyon-7085	155	Organic matter		2245	30	390-204 BCE	297 BCE
C3	Lyon-7086	250	Charcoal		2205	30	371-175 BCE	273 BCE
C3	Lyon-7087	258	Charcoal		2420	30	565-402 BCE	483 BCE
C4	Lyon-7101	147	Shell	2,23	1870	30	417-725 CE	571 CE
C4	Lyon-7420	156	Coral/vermetid	2,15	1410	25	602-659 CE	630 CE
C5	Lyon-7088	85	Wood		135	30	1672-1942 CE	1807 CE
C5	Lyon-7089	112	Bone		2430	30	571-404 BCE	487 BCE
C6	Lyon-7090	42	Plant	-28,06	180	30	1656-1950 CE	1803 CE
C6	Lyon-7091	52	Plant	-29,47	/	/	>1950 CE	/
C6	Lyon-7092	66	Plant	-28,7	260	30	1620-1672 CE	1646 CE
C6	Lyon-7093	190	Charcoal		2150	30	212-92 BCE	152 BCE
C6	Lyon-7102	230	Marine shell	2,41	1245	30	1046-1346 CE	1196 CE
C6	Lyon-7094	258	Charcoal		1855	30	120-245 CE	182 CE
C6	Lyon-7095	260	Charcoal		1485	30	548-642 CE	595 CE
C6	Lyon-7103	268	Marine shell	3,05	1525	30	759-1100 CE	929 CE
C6	Lyon-7096	273	Charcoal		1420	30	592-660 CE	626 CE
C6	Lyon-7104	370	Marine shell	2,67	2090	30	164-526 CE	345 CE
C7	Lyon-7097	12	Plant	-29,76	/	/	>1950 CE	/
C7	Lyon-7098	26	Plant	-31,11	/	/	> 1950 CE	/
C7	Lyon-7105	367	Marine shell	2,52	1645	30	662-974 CE	818 CE
C7	Lyon-7099	395	Charcoal		2150	30	212-92 BCE	152 BCE
C8	Lyon-7106	356	Shell	0,14	2155	30	82-437 CE	259 CE

Fig. 4. Radiocarbon dating results. The ^{14}C dates were calibrated using the IntCal20 and IntCalMarine20 calibration curves, as well as the CALIB 8.2 program (Reimer et al., 2020; Stuiver et al., 2022).

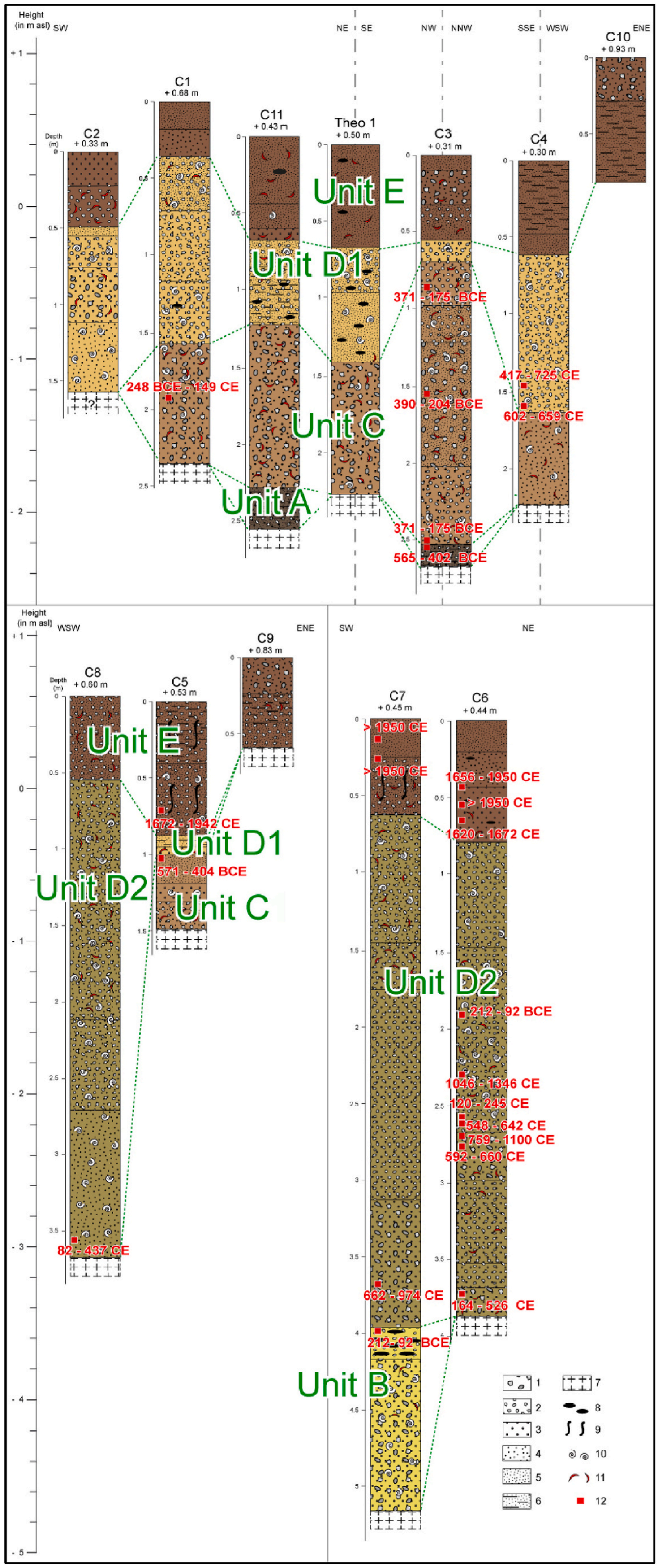

Fig. 5. Chronostratigraphic cross-section based on drilled cores. 1: cobbles; 2: pebbles; 3: coarse to very coarse sand; 4: "medium" sand; 5: fine or silty sand; 6: clay; 7: weathered substratum; 8: charcoal; 9: roots; 10: shells; 11: pottery remains; 12: AMS radiocarbon dating.

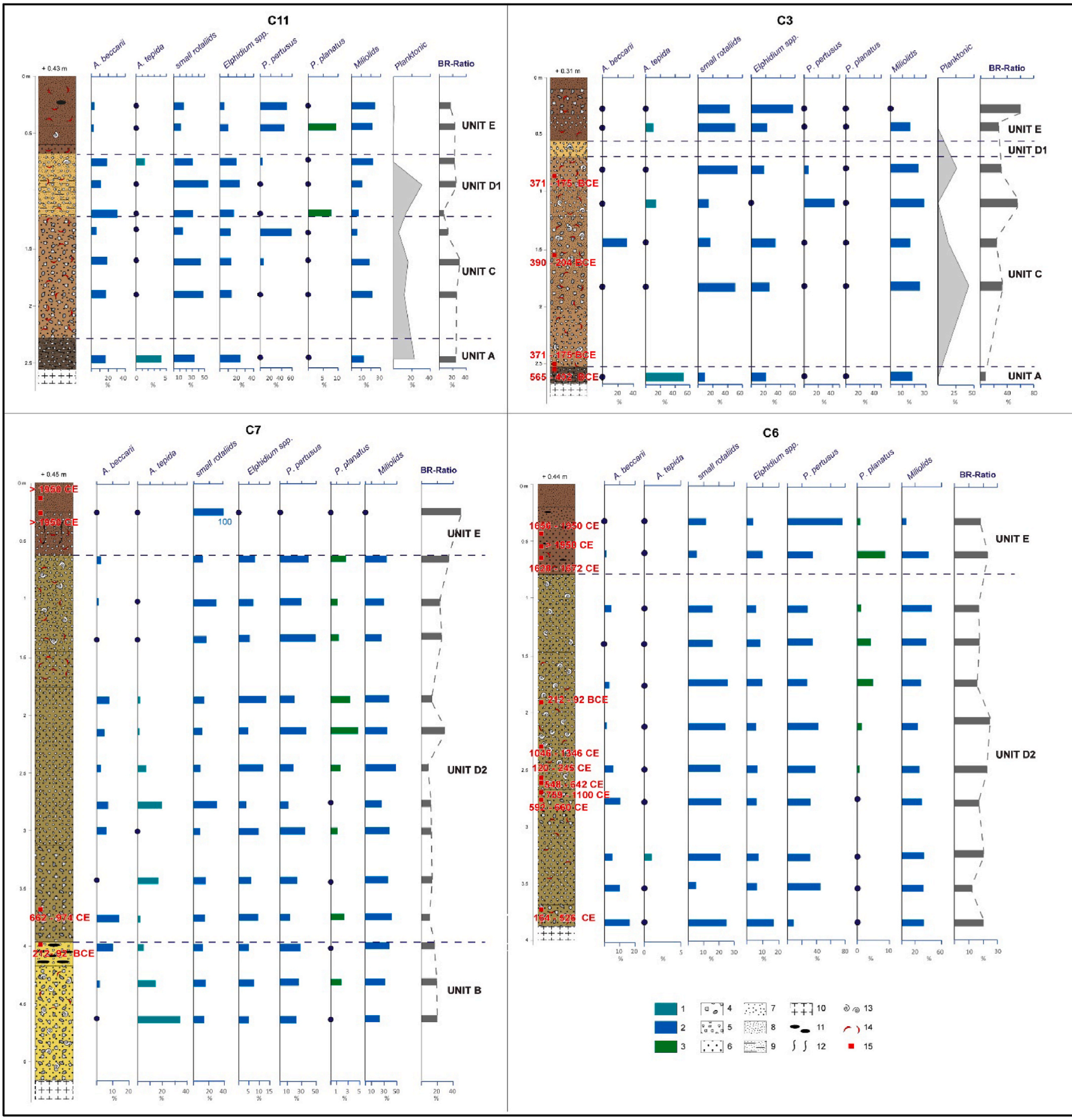

Fig. 6. Benthic foraminiferal relative abundance in cores C3, C6, C7, and C11.1: brackish water species; 2: rich algal vegetation species; 3: marine, infralittoral species; 4: cobbles; 5: pebbles; 6: coarse to very coarse sand; 7: "medium" sand; 8: fine or silty sand; 9: clay; 10: weathered substratum; 11: charcoal; 12: roots; 13: shells; 14: pottery remains; 15: AMS radiocarbon dating.

bicarinata; e.g., Sgarrella and Moncharmont Zei, 1993; 10–20 %), associated with planktonic foraminifera (up to 30 %). This assemblage suggests relatively shallow palaeoenvironmental conditions with a direct connection to the open sea (e.g., Triantaphyllou et al., 2021). In addition, the presence of P. *planatus* (8 %) at the bottom of the unit implies the presence of rich algal vegetation in the palaeoenvironment (e.g., Faber and Lee, 1991). According to the dating for core C4 (602–659 CE and 417–725 CE), these sediments deposited during the medieval period.

- Unit D2 overlies either the bedrock (core C6) or Unit B (cores C7 and C8). Its thickness varies between 2.20 m (core C8) and 3.35 m (core C7). It is mainly composed of sand or coarse sand, including pebbles, cobbles, and shell debris. Unlike Unit D1, it contains many fragments of pottery. The microfauna consists mainly of marine species such as small rotaliids (10–30 %), *Elphidium* spp. (5–15 %), *A. beccarii* (<18 %), miliolids (20–50 %), *P. planatus* (5 %), *P. pertusus* (10–50 %), and *A. tepida* (up to 20 % in core C7 but negligible in core C6). These deposits (ranging from 120 to 245 CE to 1046–1346 CE in core C6)

are posterior to the Hellenistic period (323-30 BCE), but also include an earlier piece of charcoal (212-92 BCE) in core C6.
- Unit E, found in all cores, is comprised of sand, pebbles, pottery remains, and, at times, marine shell fragments. It is posterior to 1518 CE.

4.2. Submarine survey

4.2.1. Bathymetry and seafloor imagery

The underwater terrain in the vicinity of the current port as well as the "mikros" and "megalos" Rematiaris islets is quite uniform, with depths ranging from 3 to 4 m. The depth increases between the two islets, reaching almost 25 m to the west of the strait. Sonar data reveals a succession of fine-grained sediments, ripple-marked sands, rocks, and patches of seagrass in front of the current harbour (Fig. 7b). The strong hydrodynamics (longshore drift along the North/South axis) make it challenging to differentiate the sediments deposited by the Inopos river from those reworked by currents and waves from the archaeological excavations.

4.2.2. High-resolution seismic profiles

Seismic profiling was not possible in the shallow depths between Delos and the Rematiaris islets, which means that the thickness of the alluvial and anthropogenic sediments right in front of the modern harbour cannot be determined through this method. However, the survey revealed a submerged palaeo-valley to the southwest of Delos (Fig. 7c), with a depth of 25 m and a width of 100 m approximately. This valley is filled with late-Quaternary/early-Holocene alluvial sediments with an apparent thickness of up to 10 m at the bottom. This palaeo-valley could match the prehistoric course of the Inopos river and provide valuable insight into the prehistoric palaeogeography of the island (Kapsimalis et al., 2009; Sakellariou and Galanidou, 2016). The upper sedimentary unit is believed to consist of Holocene, fine-grained material such as sand and mud. These results demonstrate that the palaeo-valley of Inopos did not extend between the Rematiaris islets (Fig. 7a).

4.3. Geophysical survey

No evidence of the rip-rap and quays mentioned by Pâris (1916) was found at the western boundary of the Apollo Sanctuary based on the results of the ERT and electromagnetic surveys. Nonetheless, three ERT profiles (Fig. 8) detected resistive anomalies.

- To the south of the Agora of Theophrastos, the high resistivity values in the middle of P8 are likely due to recent underground pipework.
- In the centre of the Main Harbour bay (P5 and P6), the resistivity values at depths of 2–4 m are higher compared to those at 4–6 m, indicating the presence of submerged constructions from an unknown period.

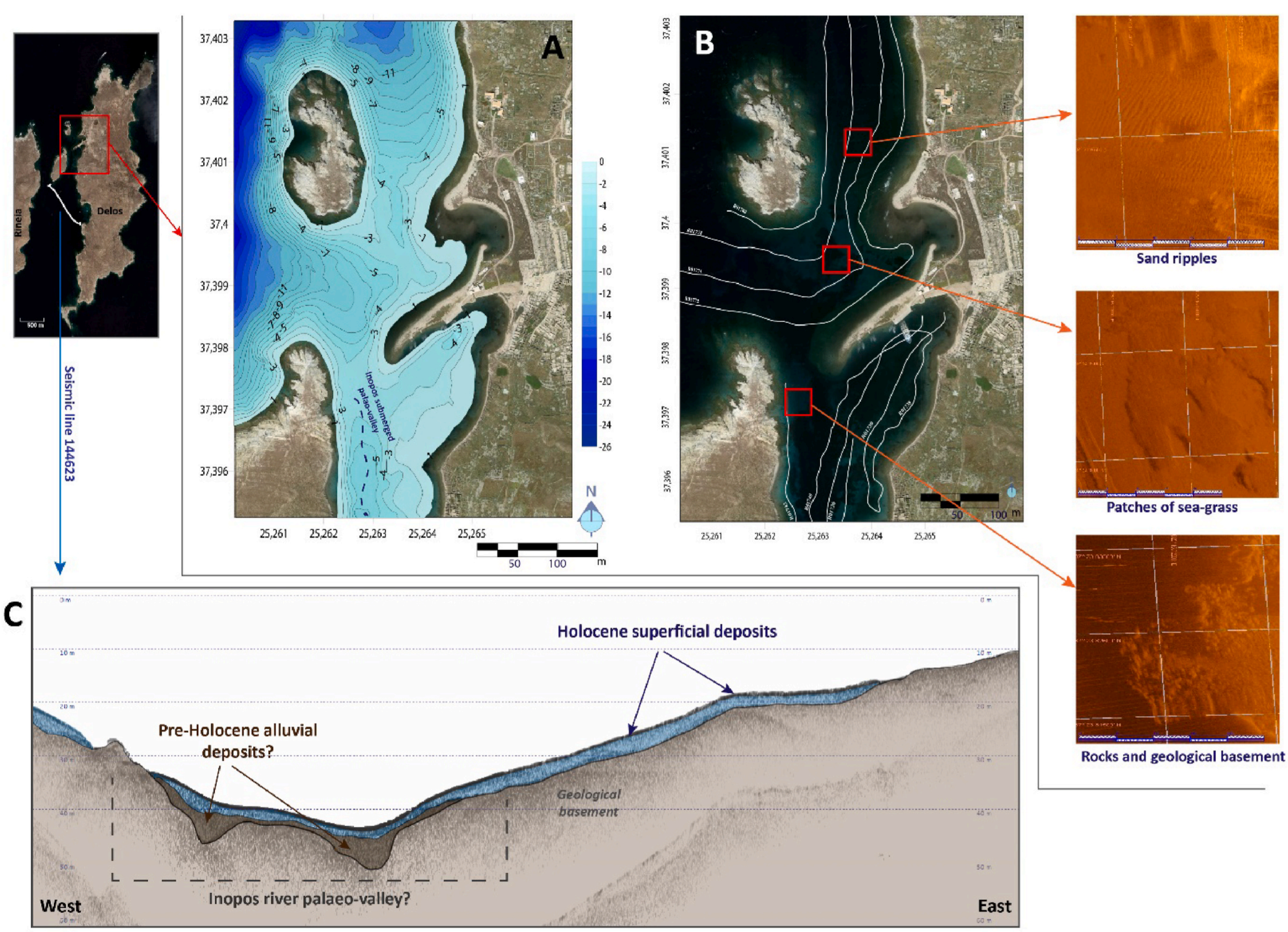

Fig. 7. Oceanographic survey results. A: Bathymetric contours in front of the Main Harbour (contour lines: 1 m); B: Submarine sonar morphological features; C: Seismic line and stratigraphic interpretation of the submerged Inopos palaeo-valley.

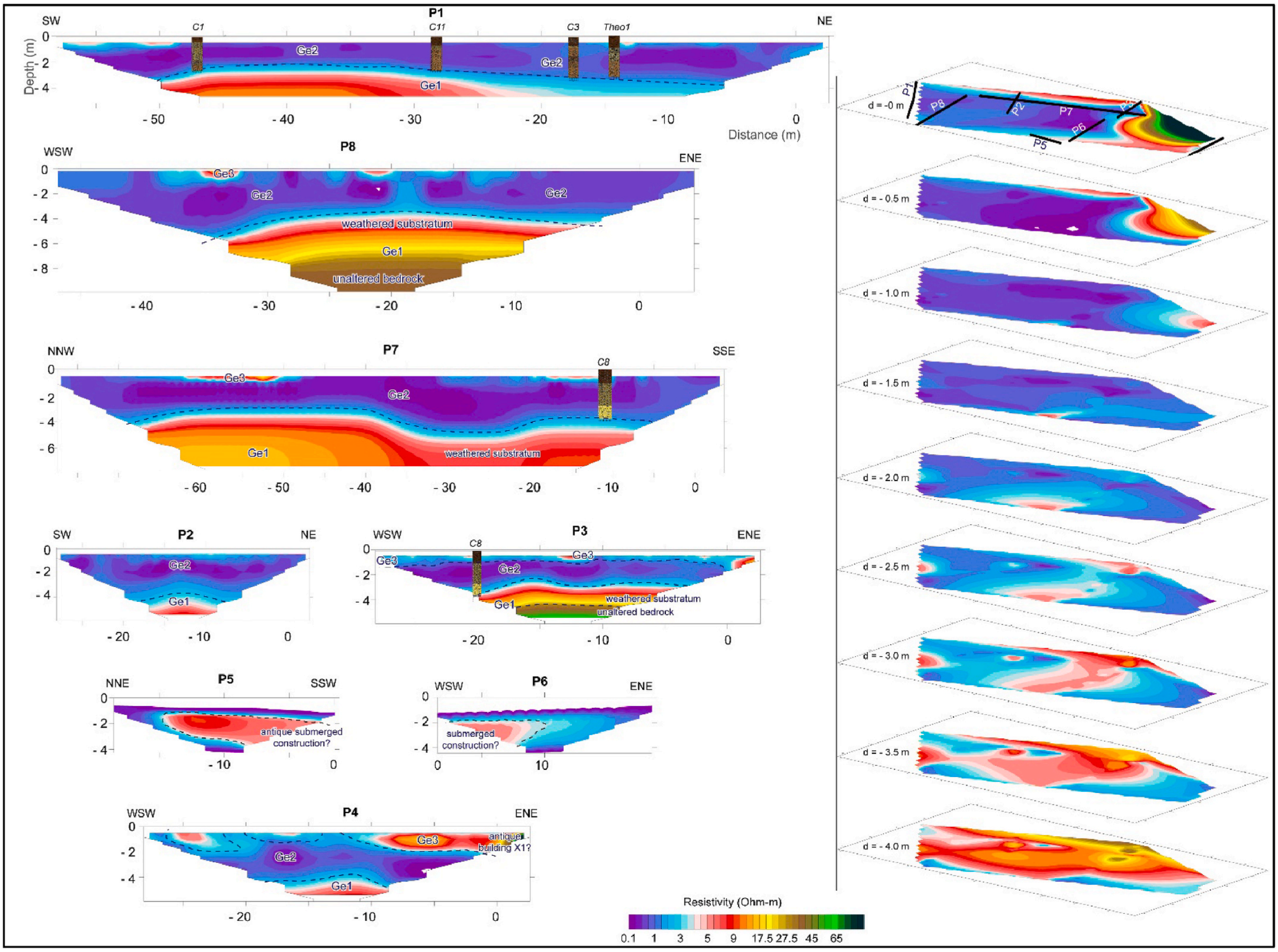

Fig. 8. ERT profiles, identified geoelectric units (Ge), and comparison with drilled cores.

- In the southern part of the bay, the higher resistivity values in the eastern part of P4 above a depth of 2 m are likely caused by the ancient structure referred by Ardaillon (1896) as "X1" (Fig. 2).

Overall, the resistivity values indicate that the bedrock slopes towards the west and south. The correlation of the ERT profiles and the stratigraphy found in boreholes (e.g., P3 and P7 with core C8), allowed us to identify three geophysical units (Fig. 8).

- Unit Ge1 is characterised by highly-variable resistivity values. The resistivity values of the weathered substratum are found to be between 2 and 30 Ωm, while those for the unaltered bedrock are higher than 30 Ωm.
- Unit Ge2, with low resistivity readings (<2 Ωm), corresponds to primarily sandy layers filled with salt water (Units B, C, D1, and D2 identified in the boreholes).
- Unit Ge3, with resistivity values lower than 10 Ωm, corresponds to coarse material (Unit E).

The electromagnetic survey shows a weighted average of conductivity values up to 3–6 m (EM31) and up to 1–2 m (EM38) in depth. This reveals two distinct areas (A and B) in terms of conductivity values (Fig. 9). Area A, with conductivity values higher than 100 mS/m, is characterised by an abundance of salt sediment fillings, which enhance the transmission of the magnetic field. This interpretation is supported by most of the cores and ERT profiles. By contrast, the low conductivity values (<30 mS/m) in area B can be attributed to the presence of crystalline outcrops and a very thin sedimentary cover, as demonstrated by cores C9 and C10, which reveal that the bedrock surface is only 0.60–0.80 m deep. The boundary between these two areas is a line pointing North located at the western limit of the Apollo Sanctuary.

5. Interpretation and discussion

5.1. Palaeogeographic evolution of the Main Harbour bay since the 3rd century BCE

The reconstruction of the palaeogeographic evolution of the Main Harbour bay since the Hellenistic period is challenging due to post-Antique sedimentation and the absence of archaeological reports detailing the excavations carried out in the area during the late 19th and early 20th centuries. Some of the boreholes may have crossed backfills from these excavations.

The analysis of the sediment's characteristics and chronology, as revealed in the cores, led to the following interpretation of the stratigraphic units (Fig. 5).

- The lack of shell and pottery remains combined with the abundance of foraminiferal species (significant quantities of *A. tepida* associated with a scarcity of *A. perlucida* and *H. germanica*; Fig. 6) in Unit A suggests freshwater inputs into the palaeoenvironment. *A. tepida* is associated with a wide range of salinity in near-shore environments

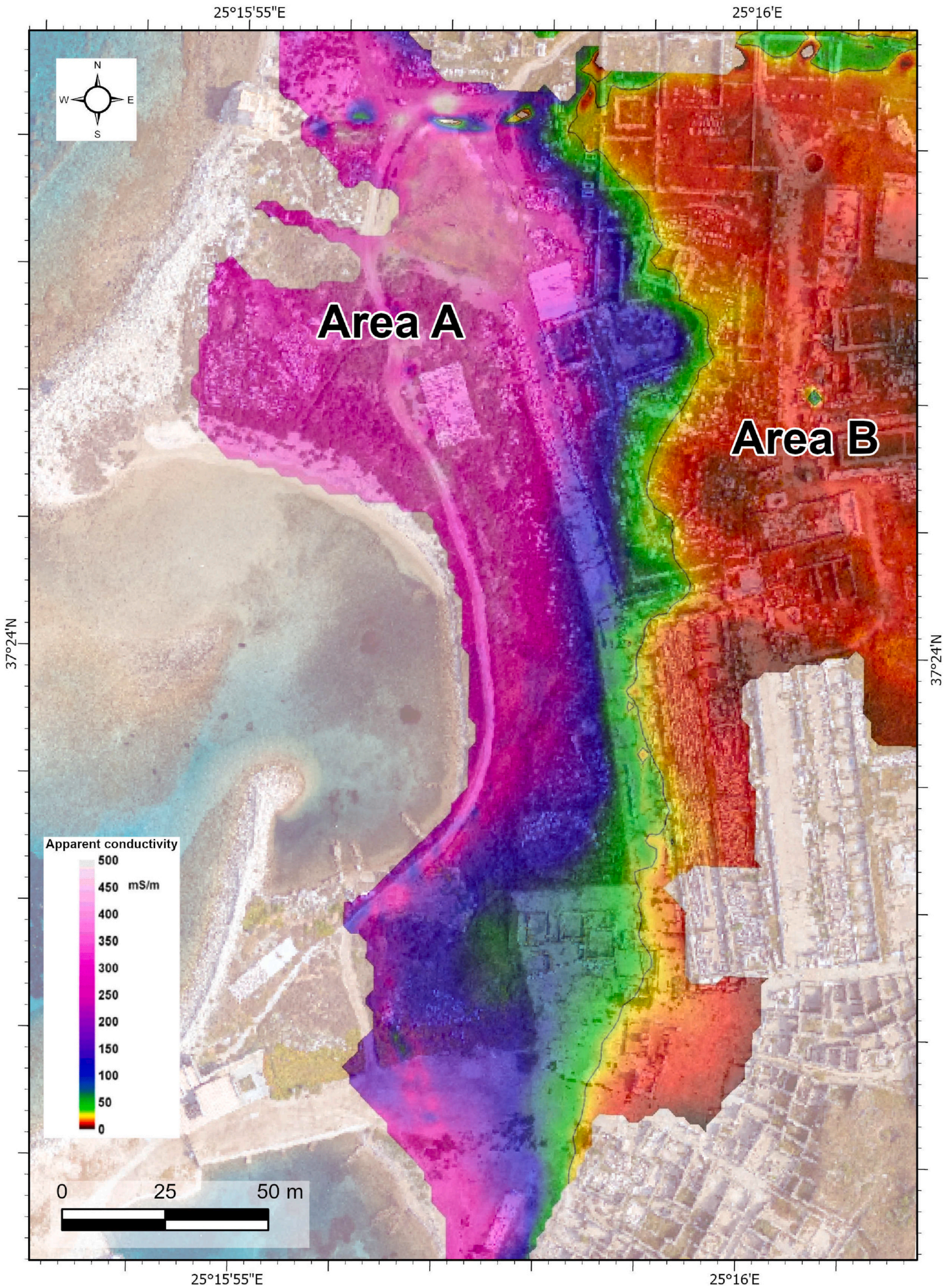

Fig. 9. Electromagnetic survey results (EM31) and identified units.

(e.g., Frontalini et al., 2009), while *H. germanica* and *A. perlucida* are typical species of estuarine and shallow marine environments (e.g., Carboni et al., 2010; Koukousioura et al., 2012), featuring mesohaline to oligohaline biofacies in modern closed lagoons of the Aegean area (e.g., Koukousioura et al., 2012; Dimiza et al., 2016) and meso-oligohaline conditions in several Aegean coastal plains (e.g. Triantaphyllou et al., 2003; 2010; Evelpidou et al., 2010; Goiran et al., 2011). Based on these results, Unit A can be interpreted as pre-harbour deposits (according to the Ancient Harbour Parasequence (AHP) model defined by Marriner and Morhange, 2006) in a very quiet environment. We reconstruct a lagoon, shaped in an alveolus (resulting from the bedrock weathering).

- Unit B, rich in shell debris and relatively poor in pottery remains, can be interpreted as the sedimentary floor of the Main Harbour bay during Antiquity. Its foraminiferal assemblage, dominated by *P. pertusus*, miliolids, small rotaliids, and a relatively high content of *A. tepida* (Fig. 6), indicates shallow marine sediments with freshwater input (probably linked to the underflow of the Inopos river. The top of this unit, rich in charcoal probably of human origin, can be considered as the foundation surface of the harbour according to the AHP model (Marriner and Morhange, 2006).
- Unit C, characterised by its richness in cobbles and pottery fragments, can be interpreted as the backfill installed by the city of Delos or Athens from the end of the 3rd to the end of the 2nd century BCE, as per epigraphic sources (Hasenohr, 2002). Its absence from core C2 is probably due to post-Antique marine erosion. At the end of the 19th century, the area where core C1 was drilled was covered by the beach, and the shoreline was at the location of core C2 (Ardaillon, 1896, Fig. 10c).
- Due to its chronology, sedimentary characteristics (sand rich in shell fragments and relatively poor in pottery remains), and foraminifera composition (typical infralittoral marine species), Unit D1 is interpreted as post-Hellenistic marine deposits corresponding to harbour abandonment facies, according to the AHP model (Marriner and Morhange, 2006), in a relatively shallow palaeoenvironmental conditions with a direct connection to the open sea.
- The chronology and sedimentary characteristics of Unit D2, which differs from D1 by its abundance of pottery debris, lead to its being interpreted as the natural or anthropogenic deposition of sediments in the Main Harbour bay after the Hellenistic period. The early dating (212-92 BCE) of the sample “Lyon-7093” collected 190 cm depth from C6 (Figs. 4 and 5) may be due to dredging to maintain sufficient draught (see 5.2). However, its stratigraphic position above the others (Fig. 5) does not exclude the possibility of reworked sediments.

The foraminifera identified in this unit suggest shallow palaeoenvironmental conditions with a direct connection to the open sea. A relatively higher rate of *A. tepida* at a depth of ~2.80 m and 3.50 m (Fig. 6) indicates past freshwater influence. However, given the very likely human influence on these deposits, palaeoenvironmental interpretation is uncertain.

- Unit E corresponds to recent soils and fills.

The cores did not cross fine-grained harbour silts and clays, as usually found in the stratigraphy of abandoned ancient harbours (Marriner and Morhange, 2006; Marriner et al., 2005, 2010, 2017; Pourkerman et al., 2020), This sedimentation gap may be due to deposits from the major excavation of the late 19th/early 20th century or to dredging (see 5.2).

North of the Main Harbour bay, cores C1, C2, C3, C11, and Theo 1, as well as profiles P1 and P8, reveal that the Agora of Theophrastos was created by filling in a lagoon (Unit A) with a backfill (Unit C) dating from 390 to 175 BCE (Figs. 5, 10a and 10b). The size and shape of this former wetland, located in an alveolus resulting from bedrock weathering, cannot be accurately determined. According to core C3, the bottom of this oligohaline environment was slightly above sea level around 400 BCE (2.35 m below present sea level corresponding to 0.15 m a.s.l. around 400 BCE, according to Desruelles et al., 2009), which explains the mixture of fresh and salt water. Based on the current bathymetry, which is likely similar to that of the Hellenistic period (323-31 BCE) due to the absence of sediment covering the substrate in this area, the Hellenistic shoreline corresponded to the “Great Mole” (Figs. 2 & 10b). The huge blocks that form it are believed to be remnants of a rip-rap built before the Hellenistic period (maybe during the Archaic period, 776-480 BCE) according to Duchêne and Fraisse (2001). Around 400 BCE, this wall, located along the extension of the western limit of a submerged abrasion platform (west of the “House on the Hill”; Mourtzas, 2012), protected an emerged area filled with buildings from the north swell.

The western buildings of the Apollo Sanctuary, located further south, are primarily built on a granitic platform, referred to as the “Terrasse du Temenos” by Cayeux (1907), which was identified through the electromagnetic survey (conductivity values < 30 mS/m; area B in Fig. 9). Results from cores C9 and C10 indicate that the bedrock surface was at ~2.70 m a.s.l. around 400 BCE (i.e., currently 0.20 m a.s.l.). According to the plan published by Holleaux (1909; Supplementary material 3) and Maar (drawn from 1901 to 1910–1911; Etienne, 2018), a paved street with a width of 6–8 m ran alongside the sanctuary (Fig. 10b). Profile P7, as well as cores C4, C5, C6, C7, C8, and C9, suggest that the bedrock sloped towards the west and south, from a height of ~1.50 m a.s.l. around 400 BCE near core C5 to ~2.25 m b.s.l. in the vicinity of core C7. This paved street was built on top of a sedimentary layer, which was likely filled with a backfill (Unit C) to level the ground surface on the

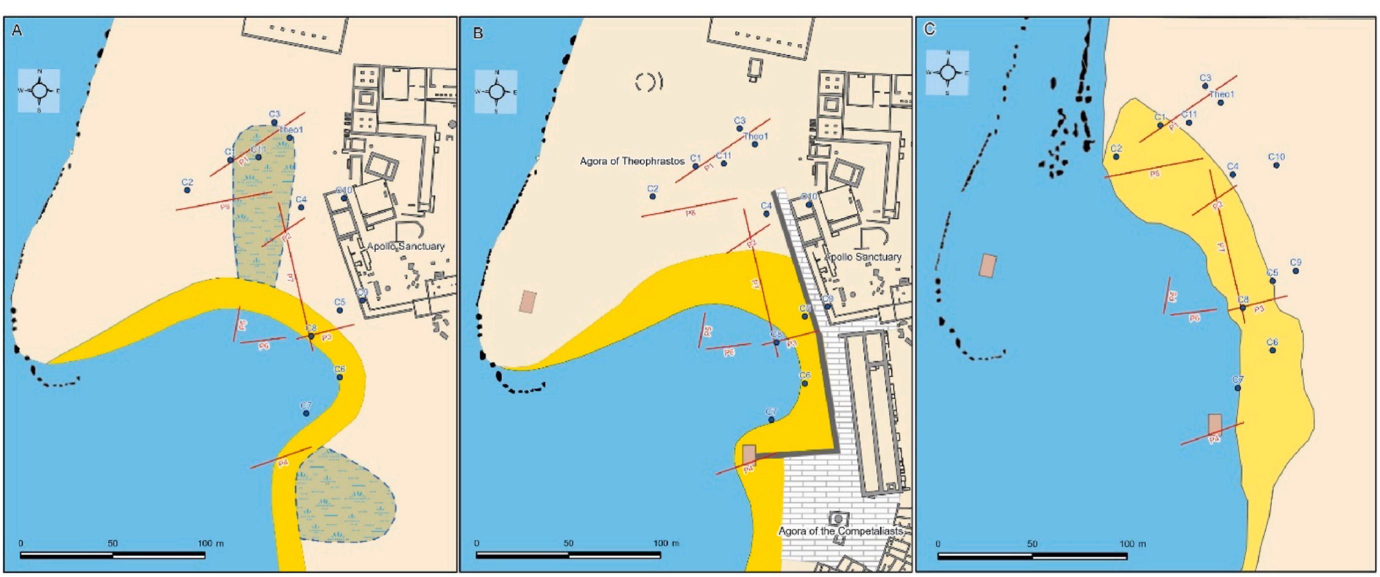

Fig. 10. Palaeogeographic reconstruction of the Main Harbour bay of Delos at the end of the 3rd century BCE prior to the backfill (A); in 100 BCE (B); and at the end of the 19th century (C; according to Ardaillon, 1896).

sloping bedrock. It borders a beach whose bottom was ~0.60 m b.s.l. around 400 BCE (currently 3.10 m b.s.l.) at the location of core C8. Considering a 1 m-thick sedimentary body on the bedrock (since there was 1.20 m 40 m to the south, according to core C7), the shoreline was in the vicinity of core C8, to the southwest. 25 m to the southeast, the bedrock surface around core C6 was at 1 m b.s.l. around 400 BCE (currently 3.50 m b.s.l.), which means that given the thickness of the beach, the shoreline was very close to the location of this core (Fig. 10a).

In the southeastern area of the harbour, the Agora of the Competaliasts was built on a backfill that filled a marsh (Desruelles et al., 2007, Fig. 10a). West of the agora, P4 reveals that building "X1" was erected on sedimentary deposits whose top was at ~0.50 m a.s.l. around 400 BCE (currently 2 m b.s.l.). This data shows that the shoreline was located to the west of this building in the 3rd century BCE (Fig. 10b).

Inside the Main Harbour bay, the shoreline remained relatively unchanged after the Antiquity despite the rise of the sea level (Fig. 10c). The "Great Mole" to the north provided sufficient protection from erosion. In contrast, after the harbour was abandoned, sediments began to accumulate, enriched by debris from archaeological excavations. North of the bay, the abrasion platform and some archaeological remains west of the "House on the Hill" were submerged due to the rise of the sea level (Desruelles et al., 2007).

5.2. A shallow depth harbour

During the Second Athenian domination (167-69 BCE), the beach was used to haul boats. However, the depth of the draught in the Main Harbour bay is difficult to determine due to post-Antique sedimentation. Currently, there is a sediment body up to 4.50 m-thick, mainly posterior to the Second Athenian domination (Unit D2 in core C7; Fig. 5), overlying the bedrock. Considering the bathymetric data provided by Ardaillon (1896) and the thickness of these post-Antique deposits, we estimate that the draught was between 1 and 2 m inside the Main Harbour bay. This hypothesis tends to be confirmed by core C7 (Fig. 5), whose stratigraphy shows that, around 400 BCE, a sedimentary layer about 1 m-thick covered the bedrock and that the sedimentary floor (Unit B) was at ~1.05 m b.s.l. (currently 3.55 m b.s.l.). In addition, 25 m southeast of this core, P4 (Figs. 3 and 8) shows that a sedimentary layer about 2 m-thick covered the bedrock when building "X1" (Fig. 2) was constructed during the Antiquity. Recent research conducted in the Roman ports of Ostia and Portus has shown that the minimum navigational depth required for the circulation of Roman ships was 1.40 m (Salomon et al., 2016; 2017).

To sustain this shallow draught, it is highly likely that the Main Harbour was dredged during the Hellenistic period. Many ancient ports (e.g. Marseille, Sidon, Tyre, Naples) were dredged to avoid silting up (Morhange and Marriner, 2010). However, there is no archaeological evidence that this was done in Delos.

The southern part of the bay was more accessible to boats due to the shape of the bedrock. During the last glacial maximum (17,000 to 21,000 years ago), when the sea level was about 120 m lower than today (Lambeck et al., 2014; Benjamin et al., 2017), the Inopos stream carved a riverbed in the extension of its emerged valley, heading south (Fig. 7a). The part of the strait, located west of the two Rematiaris islets, was relatively deep and more suitable for navigation. According to bathymetric maps (Gallois, 1910; Service hydrographique et océanographique de la Marine, 1986), the sea was shallower between the "Great Mole" and the "mikros Rematiaris", which meant only shallow-draught boats could reach the beach, while larger merchant or round ships would have remained anchored in the bay (Nakas, 2022). However, dredging activities could have potentially deepened the bay. Evidence of harbour dredging in Greece during the Roman period has for example been highlighted in the port of Lechaion (Morhange et al., 2012).

6. Synthesis and conclusion

Our study suggests a revised reconstruction of the Delian coastline on the outskirts of the Apollo Sanctuary. It indicates that the Main Harbour bay extended less to the north than previously suggested by Ardaillon (1896) and Pâris (1916). During the second Athenian domination, the "Great Mole" served as a barrier, protecting an area that was probably covered with buildings now lost to the sea due to rising sea levels. The esplanades of the Agora of Theophrastos and the Agora of the Competaliasts were created by filling in wetland areas with a backfill from the end of the 3rd to the end of the 2nd century BCE. These enhancements, which accompanied the growth of transit trade, could also have been a result of either the rising sea level or the gradual silting up of the port behind the "Great Mole". The landscape underwent significant changes during Antiquity: the submerged structures found in the bay, whose purpose remains unknown, may have been associated with different phases in the port's development. The Main Harbour seems to have lacked, and only flat-bottomed boats could access the beach. It raises several questions: how did larger ships approach the island to get to its commercial facilities; which way did they actually sail in order to come closer; where indeed did they drop anchor; and then, how were they unloaded/loaded (if they even were unloaded).

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2023.105857.

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