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Paleoenvironmental evolution and prehistoric human environment, in the embayment of Palamari (Skyros Island, Greece) during Middle-Late Holocene

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ABSTRACT

Palamari Bay is located on the northeastern coast of Skyros Island (Sporades Islands, Aegean Sea). At the northern edge of the bay a fortified prehistoric settlement is found, dated between 2800 and 1700 BC (Early Bronze Age II–Middle Bronze Age I). Detailed geomorphological mapping of the coastal alluvial plain and paleontological, micropaleontological, palynological, sedimentological and micromorphological studies of the Holocene coastal deposits have been conducted in order to reconstruct the palaeoenvironment and the landscape evolution of the broader area of Palamari Bay.

Three main sedimentary units were recognized (A, B and C, from oldest to youngest). The lowermost sedimentary unit A, deposited between before 7500 and 3500 cal BP, consists of sediment deposited from high to moderate energy fresh water flows with some suspended load fallout in established water bodies. The microfauna indicates a shallow fresh water environment. However, a tendency to oligohaline conditions was established gradually. During the same period, the Palamari area was characterized by open mixed deciduous forests that gradually retreated as a possible consequence of the intensification of anthropic activity, associated with the settlement of Palamari. Indications of cultivating and grazing activities in the vicinity of the lagoon were identified, pointing to a strong human presence since the Neolithic. Between about 6000 and 3500 cal BP, the embayment was a lagoon southeasterly connected to the sea, therefore sheltered and protected from northeastern winds. The overlying unit B (ca. 3500–800 cal BP) is characterized by the dominance of brackish water microfauna, indicating a brackish stagnant shallow water depositional environment, which was periodically supplied with fresh water from the surrounding springs. As the result of the continuous sea-level rise during the Late Holocene, part of the northern headland was submerged. The decline of the Palamari settlement at the time of the establishment of Unit B might be related to the observed changes that rendered the embayment a restricted body of water. The uppermost sedimentary unit C corresponds to a backshore environment dominated by aeolian activity modified by fluvial processes.

1. Introduction

The embayment of Palamari is located on the northeast coast of Skyros Island (Northern Sporades, Aegean Sea: Fig. 1). The broader area of the embayment of Palamari is of great archaeological importance due to a prehistoric site located on the northern part of the bay. Preliminary excavations began in 1981 and have continued after 1985 (Parlama, 1992) until today, revealing a fortified settlement on the coast since the Early to Middle Bronze age, which was established before the middle of the third millennium BC. The continuous existence of the settlement until the middle of the 17th century BC is remarkable. After that period the location must have been abandoned, because deposits of aeolian sand covered the remains of the previous settlement. Today the impressive fortification ruins and defense structures occupy an area of 17,000 m^2 on

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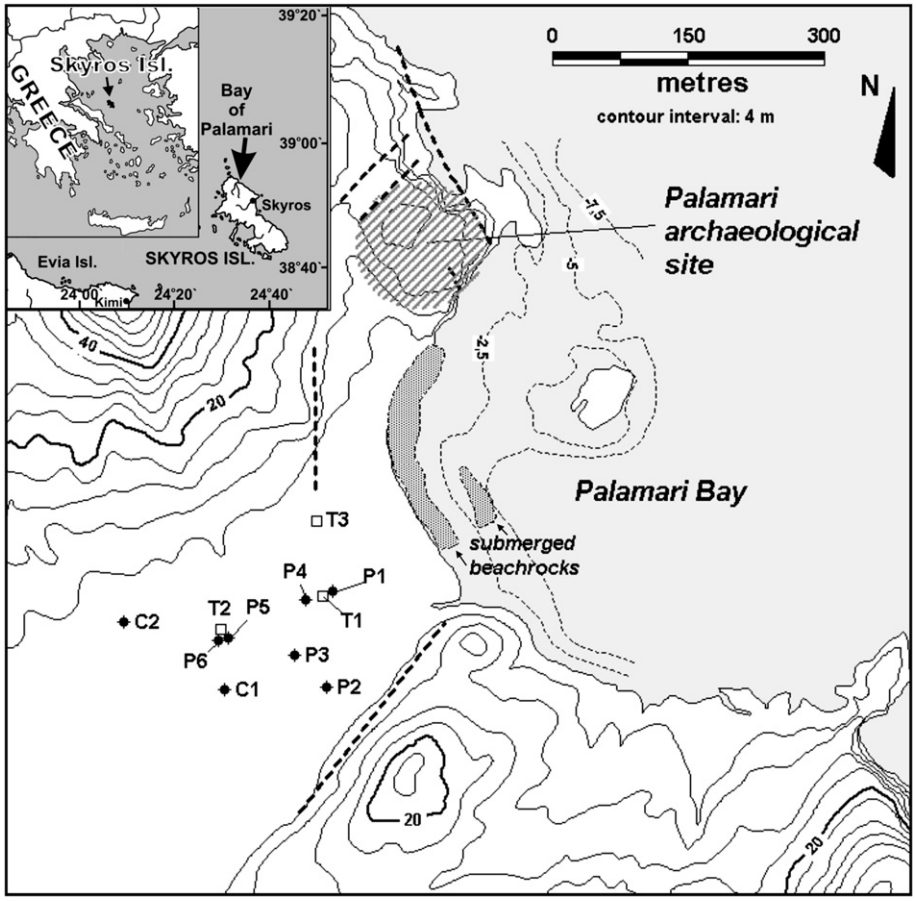

Fig. 1. Location map of Palamari area, including the location of excavated trenches (T_1, T_2 and T_3) and drilled boreholes (C1, C2, P_1, P_2, P_3, P_4, P_5 and P_6).

the top of a 19 m-high hill. Such defense structures are found in various locations along the broader Mediterranean area during the third millennium BC. The great archaeological interest of Palamari lies in the fact that the fortification is more complicated and obviously modified through time with evidence of secondary use of the site even in the Roman period. Archaeological surveys (Parlama, 1992) have shown that a well-organized skillful society occupied the site, producing and trading goods.

This study applies detailed geomorphological mapping, micropaleontological, palynological, and sediment micromorphological studies of the late Holocene coastal alluvial plain deposits, together with radiocarbon dating, in an attempt to reconstruct the paleoenvironmental and paleogeographic evolution of the Palamari embayment from the upper Holocene (last 8000 years) and since the establishment of the settlement (roughly, in the last 4500–5000 years).

2. Material and methods

Geomorphological mapping of both subaerial and subaqueous coastal parts of the bay was carried out using topographic maps at a scale of 1/5000. Landforms of the coastal alluvial plain, the shoreline and the bed of the bay down to the depth of −10 m were marked and recorded. In addition twelve detailed beach profiles were mapped across the coastline of the bay.

Eight boreholes were drilled with a portable drilling Vibracoring (Pavlopoulos et al., 2007) and two with a rotational drilling machine (C1 and C2), the deepest one at 11 m depth. In addition three trenches (Pavlopoulos et al., 2007) were excavated (Fig. 2), the deepest one reaching a depth of 4.40 m. The stratigraphy of the late Holocene sediments was recorded in detail and one hundred twenty-one samples, from selected sedimentary layers were analyzed for their micropaleontological content. For micropaleontological analysis, each sample was treated with H_2O_2 to remove the organic matter, and then washed through 63, 125, 250, and 500 μm sieves, and dried in an oven at 50 °C. The residue of 125 μm was used for benthic foraminiferal analysis and the coarser residue of 250 μm for ostracod analysis. A subset of each sample was obtained using an Otto microsplitter until aliquots of at least 200 benthic foraminifers and 300 ostracods respectively, remained. The microfauna have been identified under Leica APO S8 stereoscope. A scanning electron microscope analysis (SEM Jeol JSM 5600) was used for taxonomical purposes. The taxonomy of benthic foraminifers in this paper is based on Loeblich and Tappan (1988, 1994) and Bronnimann et al. (1992), while ostracod taxonomy is based mainly on Athersuch et al. (1989). Foraminiferal and ostracod assemblages have been expressed as number of specimens/10 g.

Palynomorph analysis was performed on 42 samples from core C2 (present study) and 16 samples from trenches T1, T2 and borehole 4 (Pavlopoulos et al., 2007). Samples of known weight were processed using standard preparation methods (Faegri and Iversen, 1989) and sieved using a 10 μm sieve. Percentage pollen diagrams were constructed based on a pollen sum of regional pollen grains, excluding aquatic and hydrophylous pollen and spores. Palynomorph concentrations were calculated on the basis of comparison with the introduced Lycopodium spores and expressed as grains/g of sediment. Residues were mounted in silicon oil and microscopic analysis was performed using a Zeiss optical microscope at 500×

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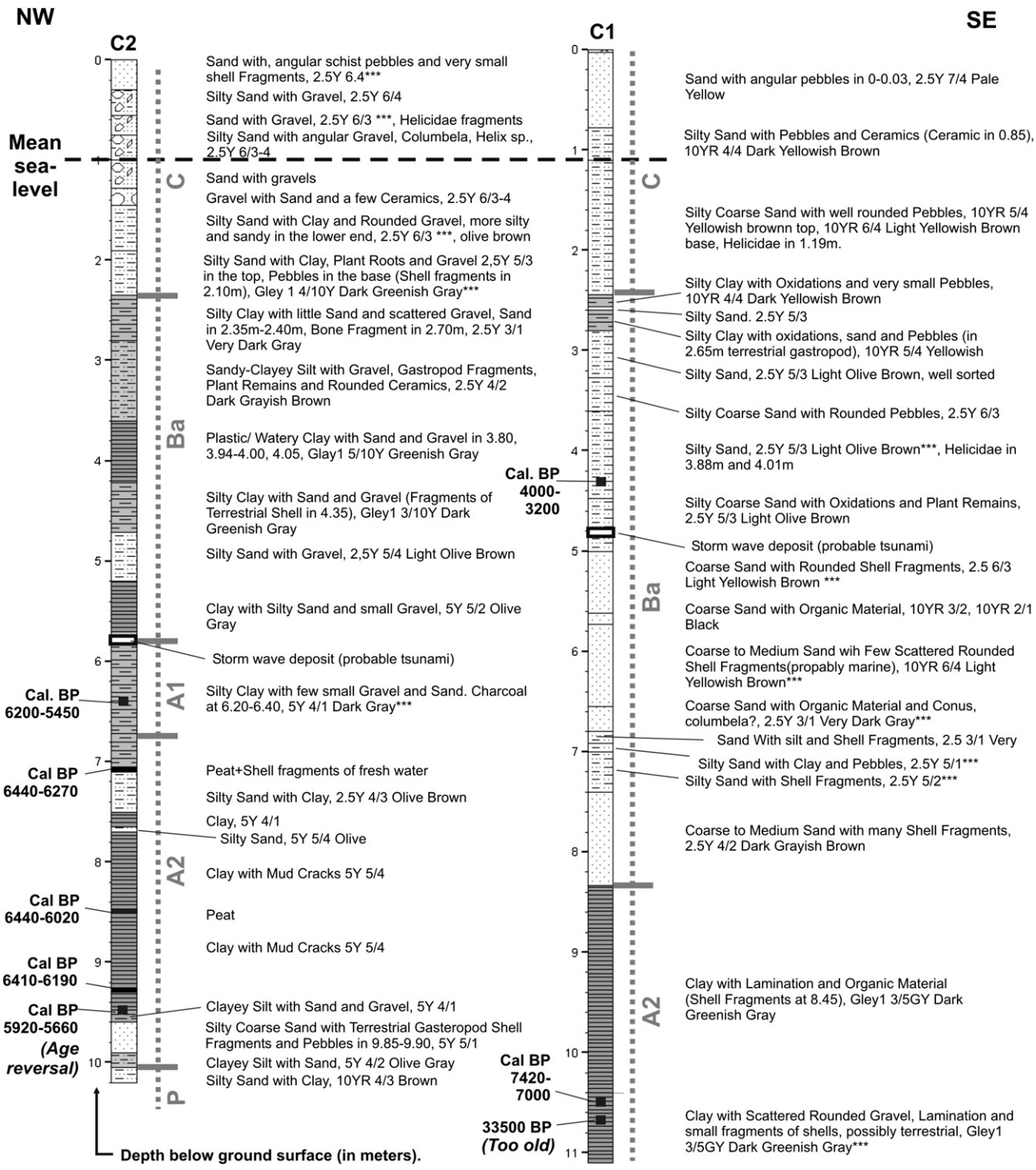

Fig. 2. Logs of boreholes C1 and C2, showing sedimentary units and ^{14}C dating results.

magnification. Pollen and spores were identified using the Moore et al. (1991) key and Reille (1992, 1995) pollen floras, while other non-pollen palynomorph identification was based on van Geel (2003) and van Geel et al. (1989). For the mollusc fossil analysis, the sample cores were split in half; one for future reference, the other for all the analysis needed. After careful inspection of the core-halves all the visible mollusc fossils were located, documented and sampled. The intact shells were hand picked and put separately in small glass vials. The fragmented shells were sampled with the surrounding sediment. Both of them were washed in 0.4 mm small wire screen to remove the dirt, air dried in room temperature and sorted in vials for further determination.

Because the visible shells were only a few, additional bulk samples (up to 518 g for C1 and up to 125 g for C2) were taken. Samples of C1 were sandy and wet sieved in a 1.0 mm screen, while the more muddy C2 samples were wet sieved in a 0.4 mm screen. The air dried residues were carefully examined under a Leitz binocular stereoscope and all the small mollusc shells and fragments as well as plant remnants, gypsum etc., were hand picked and sorted in vials and gelatin cells.

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Four undisturbed and oriented blocks of sediment were collected from trench 2, for petrographic and micromorphological studies. The samples were oven dried at 40 °C for several days and then impregnated with polyester resin under vacuum. The dried blocks of samples were cut into thin slabs and thin sections of large format (70 × 50 mm) were prepared. Thin sections were studied under a stereomicroscope at magnifications of 5–40× and under polarizing microscope at magnifications ranging from 50 to 400×.

Ten samples rich in organic material were dated using the AMS radiocarbon method, and calibrated with the Oxcal software (Bronk Ramsey, 2001), thus providing chronological constraints on the sedimentary units.

3. Results

3.1. Geomorphological setting of the coastal area

The main geological formations of the broader area of Palamari consist of calcareous schists which are overlain by micritic calcite crusts (Kissel et al., 1986a,b), and Neogene deposits of sandstones, conglomerates and marls (Melentis, 1973). These deposits are locally overlain by calcareous sandstones formed by aeolian processes (aeolianites; Fig. 1). Loose Holocene sand deposits mantle the surface of the coastal plain at the mouth of the river. Abundant sand derives probably from the weathering of the calcareous sandstones (aeolianites) and is redistributed by wind over a broader area. Coastal sand embryo-dunes are the dominant landforms, which occupy an extensive part of the coastal alluvial plain even at 30 m elevation. Calcareous schists with flint intercalations crop out in the vicinity of the study area (Melentis, 1973; Zervas and Pantziris, 1978; Baltatzis, 1988; IGME, 1989). The coastal alluvial plain southwest of the ancient settlement is the result of the infilling of the embayment by the Trichias River deposits. The main channel of this river shows an intermittent flow, being enriched by spring discharge at the apex of the alluvial plain about 500 m upstream of the coastline.

Two beachrock benches represent the dominant coastal landforms. The upper bench extends along the coastline maintaining a width of 20–35 m at a depth of −1.70 m (Pavlopoulos et al., 2007). Many archaeological remains and building stones from the adjacent archaeological site are incorporated in this beachrock bench. The lower bench (15–20 m wide) occupies the southern half of the bay lying between −1.50 m and −3.80 m in depth (Pavlopoulos et al., 2007). The detailed mapping of the beachrock benches was carried out using handheld GPS and contributed to the construction of beach profiles representing the precise position and extent of each beachrock formation. The strongly fragmented and locally displaced lower and older submarine beachrock bench corresponds to the lower sea-level of the upper Holocene. The beachrocks benches, which have formed in the intertidal zone by carbonate cementation during periods of stable relative sea-level, are good sea-level indicators (Desruelles et al., 2004) and record a general trend of relative sea-level rise in the area of the embayment.

Underwater reconnaissance of the sea-bottom revealed several remains of building structures and construction dispersed at the northern part of the embayment. Construction materials, detected at various depths between −0.5 m up and down to about −4 m, represent the ruins of the south-easternmost collapsed part of the ancient settlement (Pavlopoulos et al., 2007), indicating that the ancient settlement occupied a remarkably extensive area.

The rocky islet located in the middle of the bay (Fig. 1) represents a residual landform from a previous headland. Around the small rocky islet two abrasion platforms were observed at depths of −1.5 and −2.5 m respectively. These submerged marine-erosional surfaces were most likely formed in the same time with the first and the two benches of submarine beachrocks (0 to −1.70 m and −1.50 m to −3.80 m).

3.2. Radiocarbon dating

The ^{14}C method was used for dating of the revealed peat deposits, plant remains and charcoals in layers of the sedimentary sequence. Both conventional decay counting and the AMS technique were used (Table 1).

Ten samples of organic material (peat, charcoal, plant remains) from trenches and boreholes were dated. Samples PAL 390 and M6P1 were analyzed by the BETA Analytics laboratory and all the other samples by the CEDAD AMS laboratory of the University of Salento. The type of dated organic materials is given in Table 1, as well as their depth below present sea-level and their calibrated age with the Oxcal Software (Bronk Ramsey, 2001, INTCAL04 calibration curve by Reimer et al., 2004).

Two of the samples gave ages inconsistent with stratigraphic order and the ages of the rest of the samples. Sample PALC2-945 (Table 1), although it comes from a peat, it is clearly an outlier (due to contamination or bioturbation) since it gives a younger age than the next four higher samples in the same borehole (age reversal). Sample PALC1-1067 (charcoal) gave a very old age (about 33,000 BP), something that can be attributed to reworking and redeposition.

The samples from three higher thin peat layers within unit A in borehole C2 (samples PALC2-925, 850 and 705), yielded overlapping age ranges (Table 1). Given that they are samples of in situ organic matter and that their stratigraphic order is known with certainty, OXCAL analysis (Bronk Ramsey, 2001) was performed to obtain narrower age ranges. The modelled ages thus obtained are given in a separate column in Table 1.

3.3. Sedimentary units and lithology

After grouping of sedimentary facies found in the boreholes and trenches, three main sedimentary units can be distinguished, labeled A, B and C from older to younger, overlying a brown paleosol (P) (Figs. 3 and 4).

Unit A is divided in subunits A1 and A2. A1 overlies the paleosol P and is present in boreholes PC1 and PC2. It consists of crudely bedded gray to olive clay with peat horizons. Based on the available dates, the unit was deposited between approximately 7500 and 6000 BP. The overlying Unit A2 (ca. 6000–3500 BP) is present in boreholes C1 and C2 and consists of crudely bedded silty clay to clay.

Unit B dated between 3800 and 800 BP, is also distinguished into two laterally transgressing subunits; subunit Ba and Bb. Subunit Ba consists of massive silty sand and silt. Subunit Bb consists of massive silty sand and silt. Subunit Ba is recognized at the distal parts of the coastal plain (Boreholes C1 and C2) and Bb is restricted in the inner part of the coastal plain (Trench T2, boreholes 5 and 6, see Figs. 3 and 4).

Unit C represents the uppermost part of the Palamari sequence, consisting mainly of massive sand with some minor silty sand and silt.

3.4. Sediment micromorphology

The lower part of the analyzed sequence, representing sedimentary unit A, is constituted by a sandy silt mixture of siliciclastic material and micritic calcite. Lithological composition seems to be quite limited, namely chlorite, mica, and quartz schist fragments, and their mineral components. All clasts are quite fresh. Although faint lamination is observed due to fluctuations in the coarse size content, the facies is that of a structureless sediment. Some local patches of calcite cement (nodules) in microscopic sizes also occur

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Table 1
Radiocarbon ages for dated samples from trenches and cores of Palamari, calibrated after INTCAL 04 (Reimer et al., 2004). Dating was conducted by Beta Analytic Inc. (Miami, Florida U.S.A.), and CEDAD (Univ. of Salento, Italy).

Sample code/lab. number	Depth below m.s.l. (m)	Material	$^{13}C/^{12}C$ ratio (‰)	Measured R/C age (yrs BP)	Conventional R/C age ($^{13}C/^{12}C$ corr.)	2σ calibrated age	OXCAL modelled age
M6P1 (Boreh. 6) Beta-181561	*1.05*	*Plant remains*	−27.5	850 ± 40	810 ± 40	Cal AD 1150–1280 (800–670 cal BP)	
PAL 390 (Trench 2) Beta-183746	*3.8*	*Peat*	−27.0	3480 ± 40	3450 ± 40	Cal BC 1890–1660 (3840–3610 cal BP)	
PALC1-430 LTL2196A	*2.6*	*Plant remains*	−35.5 ± 0.2		3316 ± 145	Cal BC 2050–1250 (4000–3200 cal BP)	
PALC1-1067 LTL2197A	*8.97*	*Charcoal*	−17.4 ± 0.1		33,514 ± 345	Out of calibration range	
PALC1-1048 LTL1840A	*8.78*	*Charcoal*	−36.7 ± 0.2		6293 ± 80	Cal BC 5470–5050 (7420–7000 cal BP)	
PALC2-640 LTL2198A	*4.3*	*Charcoal*	−25.5 ± 0.4		5074 ± 140	Cal BC 4250–3500 (6200–5450 cal BP)	
PALC2-705 LTL1842A	*4.95*	*Peat*	−25.9 ± 0.1		5549 ± 50	Cal BC 4490–4320 (6440–6270 cal BP)	Cal BC 4430–4250 (6380–6200 cal BP) Agreement 81.4%
PALC2-850 LTL1843A	*6.4*	*Peat*	−24.6 ± 0.6		5483 ± 70	Cal BC 4490–4070 (6440–6020 cal BP)	Cal BC 4450–4270 (6400–6220 cal BP) Agreement 99.8 %
PALC2-925 LTL1844A	*7.15*	*Peat*	−23.0 ± 0.2		5494 ± 55	Cal BC 4460–4240 (6410–6190 cal BP)	Cal BC 4490–4330 (6440–6280 cal BP) Agreement 72.6 %
PALC2-945 LTL1845A	*7.35*	*Peat*	−17.8 ± 0.1		5053 ± 50	Cal BC 3970–3710 (5920–5660 cal BP)	

around voids, which have probably been root passages. Clusters of framboidal pyrite are usually associated with organic matter.

The upper part of the analyzed sequence, representing sedimentary unit B, records a change in the depositional conditions. Between 1.50 and 1.80 m in depth the sediment consists of a stratified mixture of siliciclastic material, rounded shell fragments, and micritic calcite derived probably from calcareous charophytic algae. The lithological component, which is very diverse, encompasses several types of schist, quartzites, and metavolcanic material with no signs of weathering. Coarse-grained layers alternate with fine-grained ones, but in all cases the material is matrix-supported at a macroscopic scale while the contacts of the layers are diffuse. At about 1.50 m in depth, the deposit is mottled with oxidized and clay-enriched spots probably around root passages. At the same depth a large amount of the siliciclastic component has been weathered prior to deposition. In addition sandy layers have a silty clay matrix with vadose features that imply post-depositional infiltration of fine-grained material. Charophyte remnants were not observed. In the uppermost part of the sequence (Unit C) the content of the rounded shell fragments rises to reach almost 50% of the coarse component.

3.5. Mollusc analysis

The collected and determined mollusc fauna from Palamari boreholes include a few mollusc genera (Gastropoda: *Hydrobia*, *Planorbis*, *Gyraulus*, Helicidae, Bivalvia: *Cerastoderma glaucum*, *Abra*), that live in different environments; the common occurrence of *Hydrobia*, *C. glaucum* and *Abra* in several strata, allows an elaboration of the palaeoenvironmental conditions for these deposits.

In PC1 borehole only land snails were found (Unit C: 1.19 m, Subunit Ba: 5.63–5.79 m, 6.40–6.50 m, 6.60–6.80 m, 7.10 m, 7.70 m, 7.80 m, 7.90 m, 8.00 m, 8.10 m, 8.20 m, Unit A2: 10.95–11.00 m). They are represented by few small intact shells of Helicidae family and numerous small fragments. Preservation and immaturity of the intact shells do not allow precise determination. Some of the intact small shells preserve an open umbilicus and belong to *Helicella* sp.

At 7.80 m and 7.90 m depth (Unit Ba), two small *Hydrobia* shells were found. *Hydrobia* is abundant in most lagoons, being a fresh-brackish water gastropod. According to Guelorget et al. (1983) and Frisoni et al. (1984), this species can be found in areas more isolated than *Abra* and *C. glaucum*. Although its presence could be accidental; the sediments would indicate a small pond–marsh existence.

In borehole C2 several mollusc genera were found. The fauna includes mainly brackish forms (*Hydrobia*, *C. glaucum*, *Abra*) between 6.95 and 9.50 m depth (Unit A2), with rare presence of fresh water snails *Planorbis* (at 7.00–7.10 m and 9.25–9.30 m), *Gyraulus* (at 9.15–920 m) and land snails Helicidae (Unit C: 2.10 m, Unit Ba: 2.42–2.45 m, 4.35 m, Unit A2: 6.94–7.00 m, 7.00–7.10 m, 9.20–9.25 m, 9.25–9.30 m). The assemblage of *Hydrobia*, *C. glaucum*, *Abra*, indicates a lagoonal mollusc association and the existence of a lagoonal palaeoenvironment between 7.00 and 9.50 m depth (Unit A2). These three mollusc species have been considered characteristic inhabitants of "euryhaline and eurythermal biocoenosis in brackish waters" according to Picard (1965), or of "paralic realm" according to Guelorget et al. (1983) and Frisoni et al. (1984). They also reported as a common association from the present lagoons around the Mediterranean (Marazanof, 1969; Zaouali, 1975; Vatova, 1981; Nicolaidou et al., 1988; Kevrekidis et al., 1996).

C. glaucum (a Mediterranean species, while former synonym = *Cerastoderma edule*, is considered as an Atlantic species) is abundant in many lagoons and especially those with the best contact with the sea (Kevrekidis et al., 1996), it also prefers relatively sheltered areas because it is unable to tolerate even a small amount of wave action (Boyden and Russel, 1972). It lives on all types of soft substrate, but it is more abundant in very well sorted fine sand and in low energy environments (Poluzzi et al., 1981; Kevrekidis et al., 1996). *Abra* is a very common species in Mediterranean lagoons and

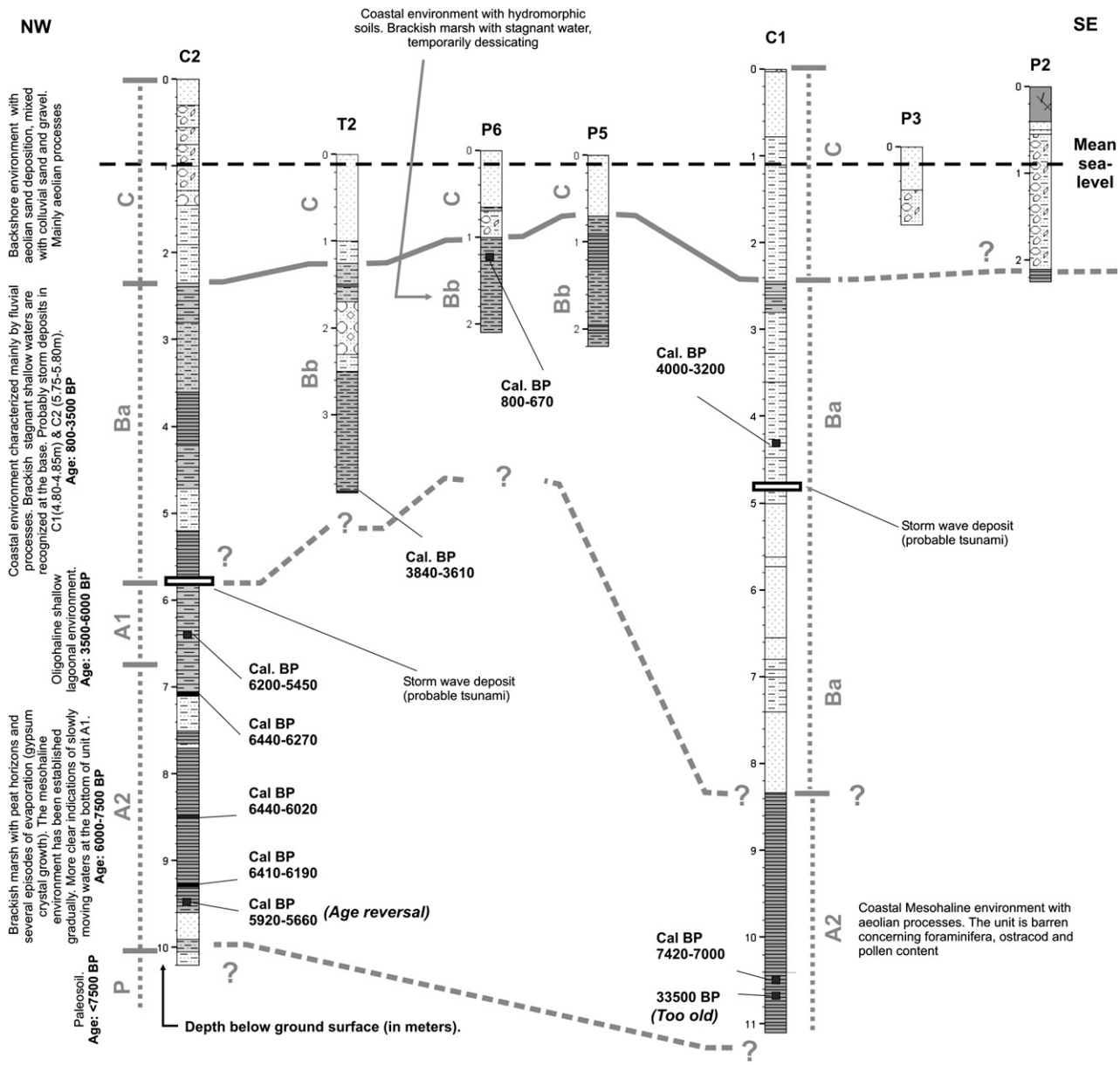

Fig. 3. NW–SE longitudinal section showing Upper Holocene stratigraphy and sedimentary units between boreholes C1 and C2 . Borehole locations are projected to the section line. The distance of the projected locations of boreholes P5 and C1 has been slightly shortened for in order to fit the figure in portrait view without decreasing its legibility.

estuaries, and has been found in muddy, silty to sandy–silty substrates (Vatova, 1981; Bourgoutzani and Zenetos, 1983; Nikolaidou and Karlou, 1983).

All the above genera can survive large salinity fluctuations e.g. 3–41% for *Abra*, 3–60% for *C. glaucum*, and 2–43% for *Hydrobia* (Marazanof, 1969; Zaouali, 1975; Vatova, 1981; Nicolaidou et al., 1988). In the Evros Delta, Kevrekidis et al. (1996) indicated salinities: for *C. glaucum* 11.5–35% (optimum 30.5%), for *Abra* >25‰ (optimum 32.5%) and for *Hydrobia* 2.5–>40% (optimum 33%). Although they coexist in the same environment, it seems that small salinity fluctuations can favour one or the other. *Hydrobia* prefers areas with no or restricted contact with the sea and with higher salinity values than *Abra* and *C. glaucum*, while *C. glaucum* is favoured in lagoons with established contact with the sea (Kevrekidis et al., 1996).

In addition numerous plant residues (at 7.00 m and 9.25–9.40 m; PC2, Unit A2) indicate existence of stagnant water. Gypsum crystals (numerous at 9.20–9.40 m; C2, Unit A2) support the presence of evaporitic-desiccation conditions.

3.6. Micropaleontological analysis

Altogether, twenty-one foraminiferal and five ostracod taxa have been recognized in the studied samples. Microfauna in sedimentary unit A (Subunit A1) is represented by ostracod assemblages mainly consisting 99% of *Cyprideis torosa* accompanied by rare *Cyprinotus salinus*. *Ammonia beccarii*, and rare specimens of *Elphidium crispum*, *Cibicides refulgens*, *Neoconorbina* sp. represent the foraminiferal content. Some episodes of stronger fresh water influence (presence of oligohaline ostracods *Candona* spp., *C. torosa*, *Ilyocypris* spp., *Limnocythere* sp. together with probably transported marine species *Xestoleberis* spp., *Calystocythere* spp., *Aurila* spp., *Semicytherura* sp. and coastal benthic foraminifera) are recorded in distinct depth levels (e.g. 7.55–8.20 m).

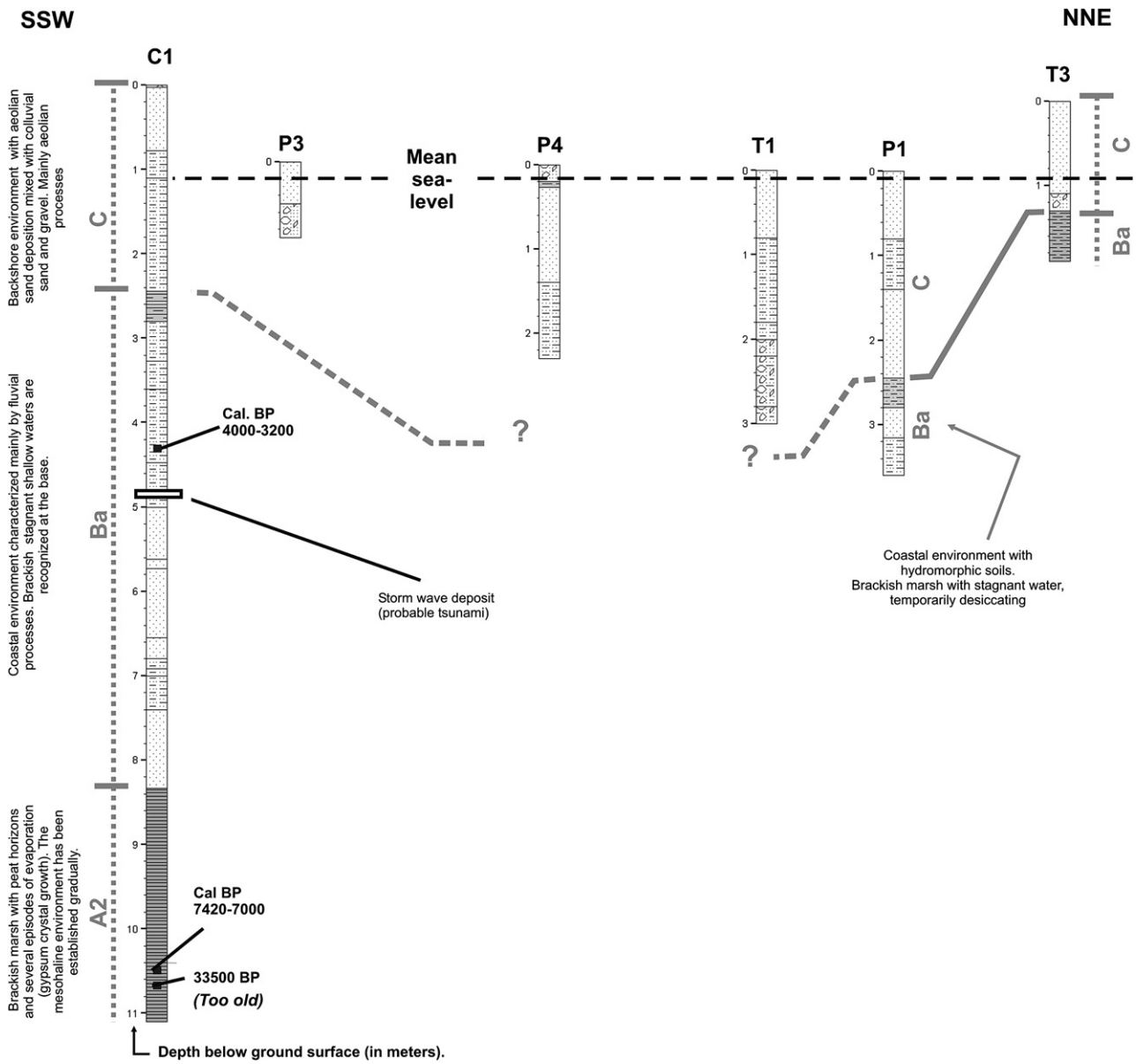

Fig. 4. NNE–SSW longitudinal section showing Upper Holocene stratigraphy and sedimentary units between boreholes C1 and T3. Borehole locations are projected to the section line.

Subunit A2 contains abundant ostracod assemblages consisting of *Candona neglecta* accompanied by *Ilyocypris gibba*, *Limnocythere* sp. and rare *C. torosa* and *C. salinus*, which indicate a shallow fresh water environment (Sokac, 1978; Carbonel, 1980; Calderini et al., 1998; Mazzini et al., 1999; Clavé et al., 2001). The foraminiferal species *E. crispum*, *Cibicides lobatulus*, *C. refulgens*, *Quinqueloculina* sp. are rare, broken, commonly rounded and poorly preserved, indicating reworking from coastal marine environments. However, the rare presence of *Trichohyalus aguayoi*, *C. torosa* and *C. salinus* supports the oligohaline character of Subunit A2. *T. aguayoi* is generally considered as a brackish foraminiferal species, which dominates in oligohaline conditions under an influence of fresh water input (salinity less than 15%; Bronnimann et al., 1992; Triantaphyllou et al., 2003; Pavlopoulos et al., 2007).

Unit B is distinguished into two laterally transgressing subunits, Ba and Bb. Subunit Ba is recognized at the distal parts of Palamari coastal plain (boreholes C1 and C2). In particular, subunit Ba in borehole C2 is characterized at its upper part by the common presence of the coastal species *E. crispum*, *Peneroplis pertusus*, *Quinqueloculina triangularis*, combined with few specimens of miliolids, *Rosalina bradyii*, *Rosalina* sp., *C. lobatulus*, *C. refulgens*, *Neoconorbina* sp. (Levy et al., 1993, 1995, 1996). However, most foraminiferal specimens bear rounded tests. Brackish stagnant shallow waters are indicated by the rare presence of the ostracod *C. torosa*, at the base of subunit Ba. A distinct event is recognized at a certain level in both C1 (4.80–4.85 m) and C2 (5.75–5.80 m) boreholes. This level shows a substantial increase of marine foraminifera (*E. crispum*, *Quinqueloculina* sp., *R. bradyi*, *A. beccarii*, *C. lobatulus*, *C. refulgens*, *Planulina* sp.) and ostracods (mainly the brackish *C. torosa* accompanied by *Candona* sp., *Ilyocypris* sp., *Limnocythere* sp. and the marine species *Loxoconcha* sp., *Callistocythere* sp., *Aurila convexa*, *Caudites* sp.). In addition, several specimens of planktonic foraminifera have been detected, implying transport from an environment far from the coast.

Subunit Bb is restricted in the inner part of the coastal plain (trench T2, boreholes 5 and 6; Pavlopoulos et al., 2007) and is characterized by the dominance of the brackish water ostracod species *C. torosa*, *C. salinus* and the fresh water to oligohaline species

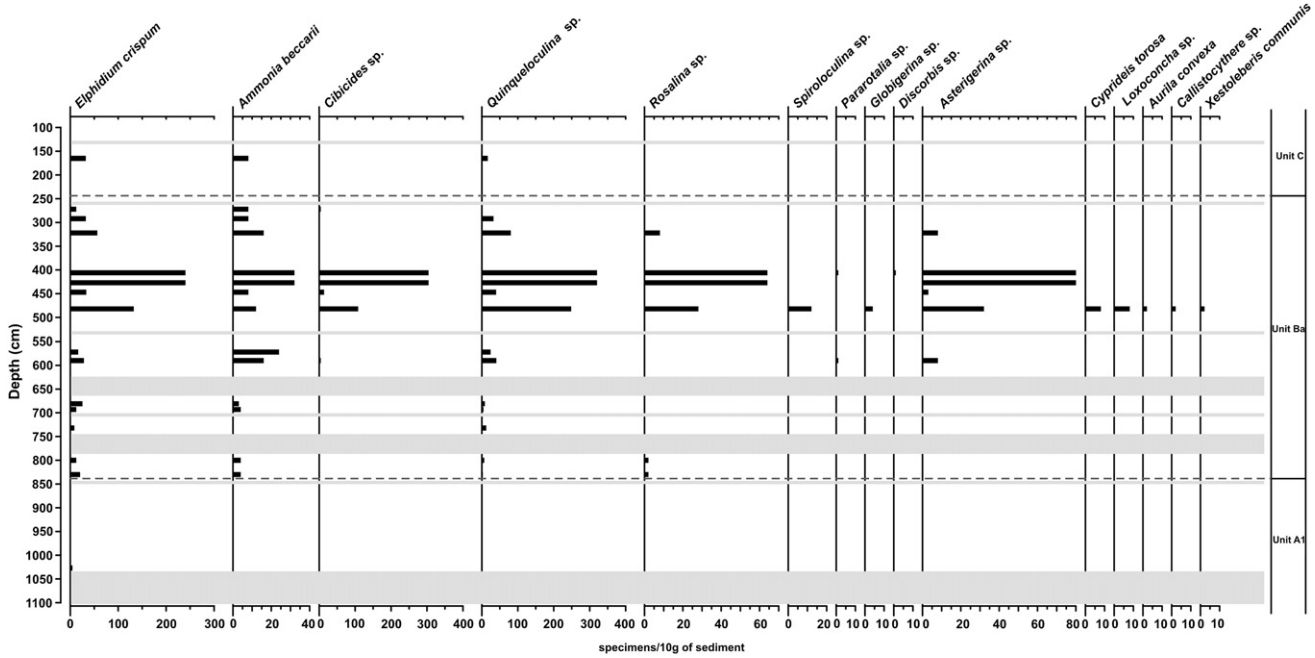

Fig. 5. Abundance (specimens/10 g of sediment) of selected foraminifera and ostracod species in borehole C1. Gray intervals correspond to barren samples.

I. gibba, *Ilyocypris bradyi* (Figs. 5 and 6). This assemblage indicates an oligohaline to low mesohaline environment (Gliozzi and Mazzini, 1998; Mazzini et al., 1999; Clavé et al., 2001). Hence, the persistence of a restricted temporary communication with the sea is inferred. This is reinforced by the presence of the benthic foraminifer *T. aguayoi*. The remaining foraminiferal species, *C. refulgens*, *E. crispum*, *P. pertusus*, *Rosalina* sp., *R. bradyii*, *Q. triangularis* indicate an influence from coastal marine environments.

Unit C is featured in the inner part of the coastal plain (trench T2, boreholes 5 and 6; Pavlopoulos et al., 2007) by the common presence of the species *E. crispum*, *P. pertusus*, *Q. triangularis*, combined with few specimens of miliolids, *R. bradyii*, *Rosalina* sp., *C. lobatulus*, *C. refulgens*. This assemblage indicates a coastal marine environment that occurs on the inner shelf (Levy et al., 1993, 1995, 1996). However most foraminiferal specimens are not considered *in situ* assemblages in sand, as they have rounded tests, suggesting reworking from aeolian coastal deposits. Ostracod specimens are missing except for a certain level in trench T2 in which specimens of *I. gibba* and *I. bradyi* are accompanied by very rare specimens of *C. salinus* (Fig. 6). This ostracod fauna indicates a shallow fresh water environment, as both *I. gibba* and *I. bradyi* can be found in springs, rivers, or stagnant water, which dry up periodically (Sokac, 1978; Calderini et al., 1998).

3.7. Palynological analysis

The sandy character of the majority of the Palamari deposits and preservation of palynomorphs were the limiting factors of the palynological analysis. Several palynomorph-barren intervals were discovered within deposits of core C2 (Fig. 7), as a result of the unfavourable preservation conditions, especially in the first 6 m of the core.

Palynoflora of sedimentary subunit A1 is dominated by herb vegetation mainly Poaceae and Compositae (Fig. 7). *Ranunculus acris* type, *Sanguisorba minor* and *Plantago lanceolata* type contribute significantly to the pollen spectra, while cereal pollen (*Cerealia*-type) is constantly present. *Pinus*, *Quercus* and *Carpinus/Ostrya* type are the more abundant arboreal pollen. Coprophilous fungi *Sordaria*-type 55A: Van Geel, 2003) are recorded at the top of subunit (C2: 6.70–7.10 m).

In addition, the distribution of juvenile foraminiferal linings (Bakker and van Smeerdijk, 1982) and the presence of the green algae *Spirogyra* (van Geel et al., 1989) mark the pollen spectra (Fig. 7) further supporting the marine influence. Moreover the numerous *Gloeotrichia*-type (type 146) palynomorph suggests open-water phases with slowly flowing waters (van der Wiel, 1982).

In subunit A2, pollen spectra are characterized by low arboreal pollen percentages and the expansion of Compositae. The presence of the green algae *Spirogyra* (Fig. 7) is indicative of shallow, stagnant waters (van Geel et al., 1989).

The depositional environment of subunit Ba results in poor preservation of pollen and other palynomorphs in C2 at the distal part of the coastal plain. However, spectra from levels with preserved pollen are dominated by *Compositae liguliflorae*, Poaceae, and pteridophyte spores.

Pollen flora of the analyzed samples from the inner part of the plain, i.e. subunit Bb, (trenches T1 and T2, and borehole 4; Pavlopoulos et al., 2007) is characterized by the presence of Mediterranean taxa such as *Olea*, *Pistacia* and Cistaceae. Herb vegetation dominates the spectra while taxa with minor soil requirements being the most abundant (*C. liguliflorae* and tubuliflorae, *S. minor*, *Plantago* species and *Ophioglossum*).

The palynoflora of unit C appears very poor in all investigated profiles from the coastal plain (C2 present study; trenches T1 and T2, borehole 4; Pavlopoulos et al., 2007). All spectra are characterized by very high values of the erosion-resistant *C. liguliflorae* (reaching 60% of the pollen sum) and by the absence of algal remains. Numerous coprophilous fungi (*Sordaria*-type 55A; *Sporomiella* like-type 112: Van Geel, 2003) are present in spectra of trench T1 and borehole 4 (Pavlopoulos et al., 2007).

4. Discussion and synthesis

4.1. Paleoenvironmental changes

The fortified settlement on the coast, which was established before the middle of the third millennium BC, has continuous

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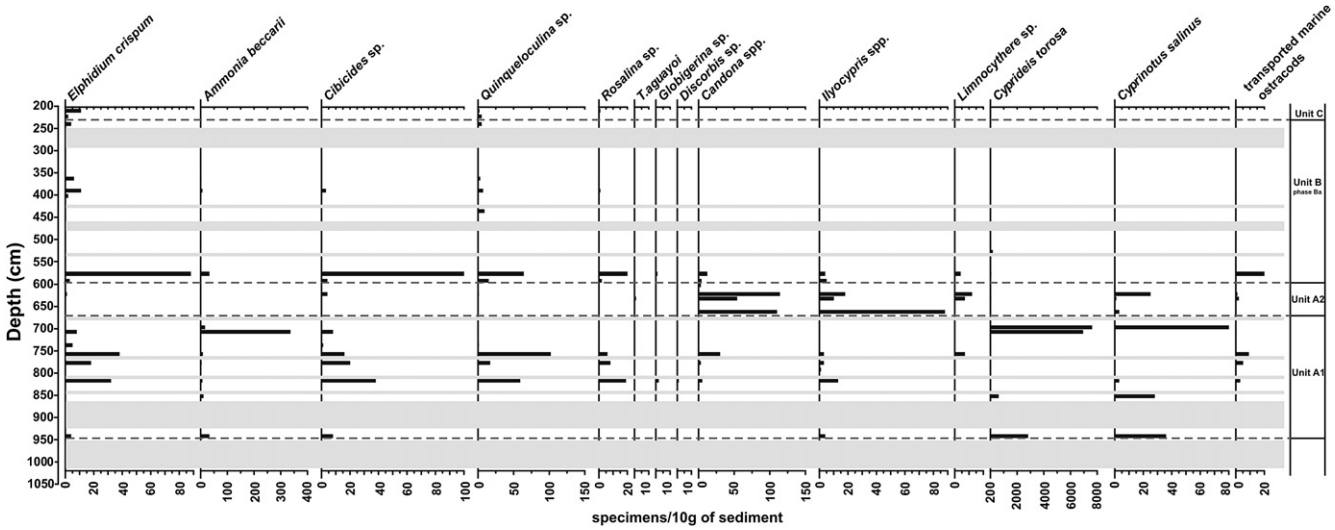

Fig. 6. Abundance (specimens/10 g of sediment) of selected foraminifera and ostracod species in borehole C2. Gray intervals correspond to barren samples.

existence until the middle of the 17th century BC. This period corresponds to Unit A (approximately between 7500 and 3500 cal BP). Unit A is probably the result of ephemeral high to moderate energy flows with some suspended load fallout in water bodies. Gray colours and the presence of framboidal pyrite imply reducing conditions in the water bodies.

In particular, subunit A1 (ca. 7500–6000 cal BP), which is the lower one, generally represents a shallow fresh water environment with some brackish marsh intervals. However a tendency to oligohaline conditions was established gradually in this subunit. This environment must have had temporal-ephemeral connections with the sea.

During the same time, the Palamari coastal plain was characterized by open herbaceous vegetation with typical Mediterranean characters such as *Pistacia* and *Juniperus*, and scarce pine trees. Open deciduous forests prevailed in the broader area of Palamari, mainly consisting of deciduous oaks accompanied by *Carpinus/Ostrya*, *Corylus*, *Tilia* and other broadleaved trees. Cereal pollen constantly recorded from the base of unit A clearly indicates agricultural activities in the area from the Neolithic. Human presence is also supported by the abundance of other anthropic indicator species such as *S. minor* and *P. lanceolata* (Bottema, 1982; Bottema and Woldring, 1990; Jahns, 1993). The presence of coprophilous fungi at the top of subunit A1 points to pastoral activities in the area.

Subunit A2 (6000–3500 cal BP) represents an oligohaline shallow lagoonal environment with intense fresh water input. The deposition of Subunit A2 reflects possibly an intense humid episode, more or less corresponding to the 5200–4200 cal BP humid phase recorded in marine core sediments from the SE Aegean Sea, (Triantaphyllou et al., 2009). The observed retreat of open mixed forest observed in pollen spectra of this period may be attributed to the intensification of anthropic activity in the area (associated to the settlement of Palamari).

After 3700 cal BP, the location must have been abandoned and deposits of aeolian sand covered the remains of the Palamari settlement. Unit B (approximately 3500–800 cal BP) corresponds to this period. This phase is characterized by high to moderate energy fresh water flows. In addition the enrichment of this part of the sequence with weathered clastic material implies high erosion of

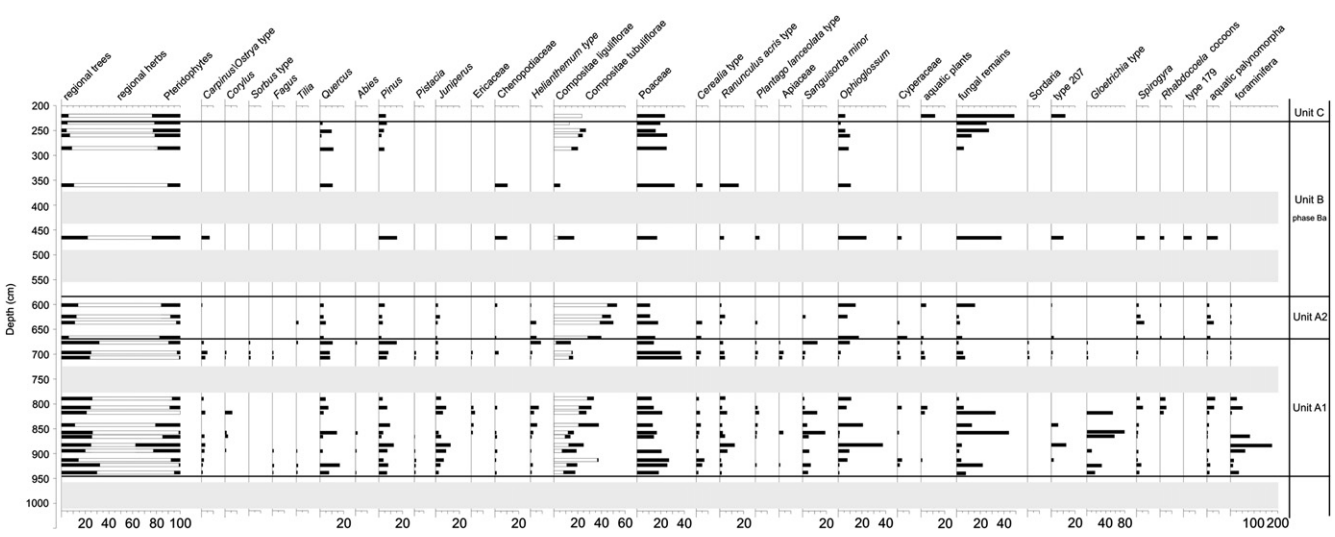

Fig. 7. Percentage diagram of selected palynomorphs in borehole C2. Gray intervals correspond to barren samples.

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the soil cover of the hillslopes around the area. This is most likely attributed to a decrease in the density of plant cover protecting soil from erosion. The palynological analysis show that during the deposition of Unit B the area was covered by herbaceous vegetation with sparse pine and oak trees, and characteristic Mediterranean taxa such as *Olea*, *Pistacia* and Cistaceae (Pavlopoulos et al., 2007). The presence of cereal pollen (*Cerealia*-type), *Puccinia* teleutospores (Carrion and van Geel, 1999), and secondary indicator species (*Polygonum aviculare*, *Centaurea cyanus*, Poaceae; Bottema, 1982) reflect cultivation activities in the area (Pavlopoulos et al., 2007). Pastoral activities are represented by the numerous coprophilous fungi (*Sordaria*-type 55A; *Sporomiella* like-type 112: Van Geel, 2003), and secondary indicator species (*P. lanceolata* type, *S. minor* type; Bottema, 1982; Bottema and Woldring, 1990; Jahns, 1993).

The compilation of the microplaeontological findings including the prominent presence of planktonic foraminiferal specimens in the coastal deposits, evidences the backshore trace of a mega-storm event recognized at the same level in both C1 and C2 boreholes, dated probably around 3500 cal BP. The recognized event in the deposits of Palamari coastal plain could be the imprint of a tsunami related with the Santorini volcano activity, as its age is in good accordance with the Minoan eruption dated at 3581 cal BP (Ramsey et al., 2004). Similar traces of tsunami deposits related to the Thera eruption have been also reported from the coasts of western Turkey and northern Crete (Minoura et al., 2000). A more prominent record has been described from northwestern Crete by Bruins et al. (2008).

The sedimentary Unit C (800 cal BP to present) represents the uppermost part of the Palamari sequence consisting of sand, silty sand and silt and characterized as a backshore environment with aeolian sand deposition mixed with colluvial sand and gravel. Only land snails were found and numerous well worked marine shell fragments. All the shells are actually "sedimentary grains" because are rounded and filled with sandstone. This indicates that this sediment possibly represent coastal sand deposited on the land along the seashore (backshore environment). Indications of pastoral activities in the area are supported by the presence of numerous coprophilous fungi in the pollen spectra.

4.2. Relative sea-level changes and Paleocoastline reconstruction

The radiocarbon dated materials from different stratigraphic units, as well as one shore platform whose age is constrained indirectly by archaeological evidence, can be used to provide first constraints on the history of relative sea-level (RSL) changes in the bay of Palamari. The RSL graph in Fig. 8 contains RSL points and their associated error ranges, based on the reasoning described below. Transported samples (charcoal, and archaeological sherds in beachrock that we correlate to the −1.5 m shore platform) provide maximum-limiting ages (terminus post quem) for the sea-level at the time of their deposition. Thus, in these samples horizontal error bars are open on the right hand side. Only in situ samples (peat and plant remains) have closed horizontal error bars on both sides. Vertical error bars depict the error in the measurement of sample elevation above present m.s.l. and, the more important uncertainty associated to the determination of past sea-level elevations, given that dated samples do not come from sedimentary units deposited exactly at sea-level. Peats may have been deposited several tens of centimeters above sea-level (e.g. Vella and Provensal, 2000). Therefore, their elevation provides only maximum-limiting values for sea-level at the time of their formation. Vertical error bars for peats in Fig. 8 are closed only at the top side, and are open at the bottom because it is not known just how much lower than the peat was the respective past sea-level. Charcoal and plant remains samples were treated in the same manner, considering that they come from sedimentary units that were deposited up to 50 cm above sea-level or, below sea-level. The vertical error bar for the −1.5 m shore platform is closed on both sides, because it depicts the error in the determination of the depth of the platform inner edge (the inner edge is the past sea-level marker in this case).

The RSL dataset obtained at Palamari generally compares well to the RSL model of Lambeck and Purcell (2005) for the area of Skyros (dashed line in Fig. 8). This model depicts RSL changes caused by eustatic sea-level change as well as glacio- and hydro-isostatic adjustment of the earth's crust. Assuming that the model is accurate in the area of the Aegean, the agreement with the field data suggests that vertical tectonic movements at Palamari have been small during the last 7000 years, although Skyros is located within a broader area that is tectonically quite active (e.g. Ganas et al., 2005). Palamari in specific, is located on a NW–SE stretch of coast that is conspicuously straight at a broad-scale, that is, in all probability tectonically controlled. This coast parallels the adjacent offshore strike-slip fault (just NW of Skyros) that gave the Mw 6.4 Skyros 2001 earthquake (e.g. Ganas et al., 2005). The strike-slip kinematics (left-lateral) of this fault may offer an explanation the absence of appreciable vertical tectonic movements during the Holocene.

Defining the exact magnitude of Holocene vertical tectonic movements that may have in part influenced the RSL changes

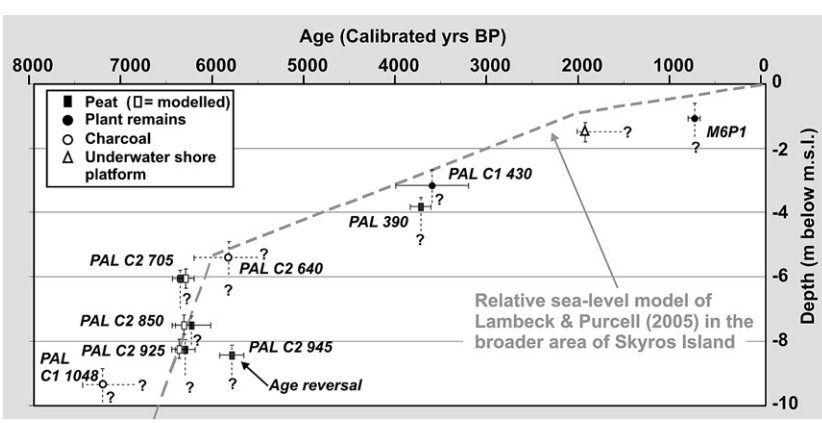

Fig. 8. Constraints on the relative sea-level change history at Palamari Bay. Sea-level data points are based on ^{14}C datings of sedimentary units and archaeological dating of beachrock that correlates to a submerged shore platform (see text for explanations). The relative sea-level model of Lambeck and Purcell (2005) for the area of Skyros Island is also plotted for comparison (see text for further commentary).

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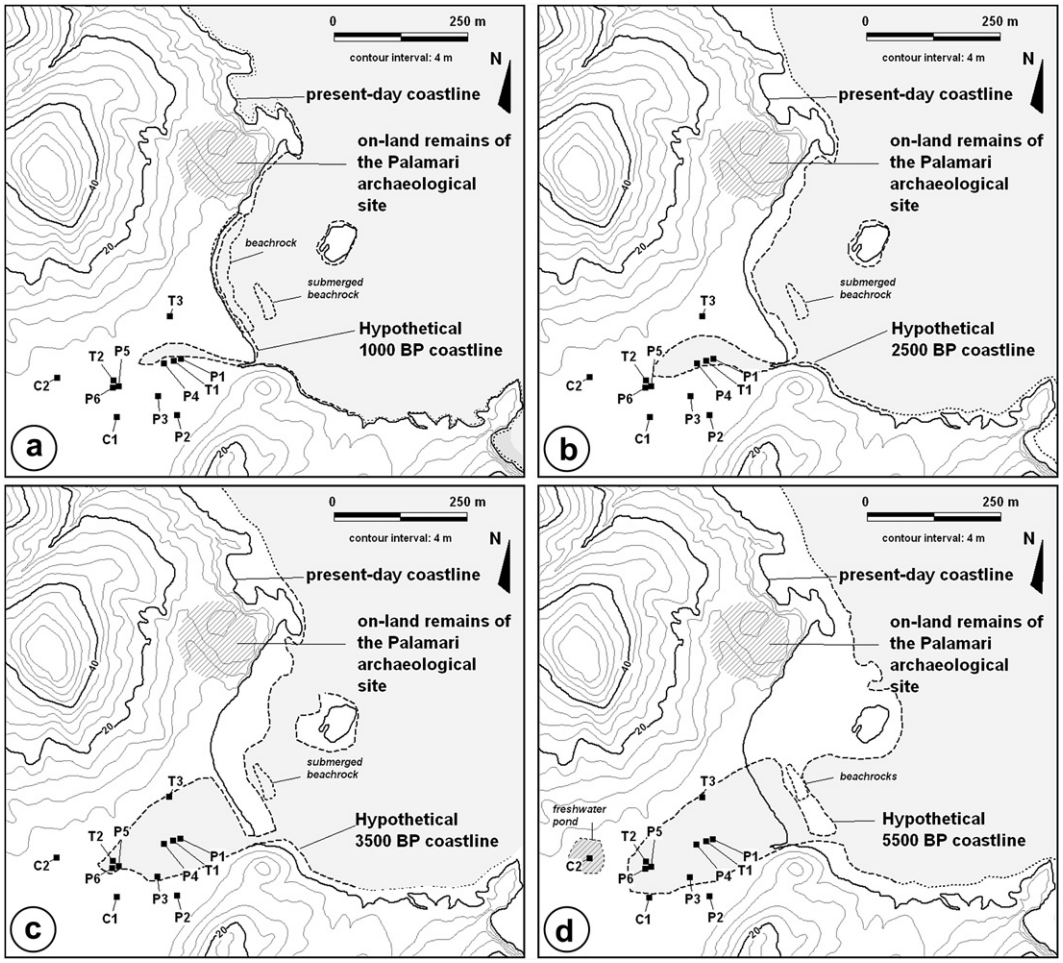

Fig. 9. Paleogeographical reconstruction of the coastline in Palamari Bay at 1000 cal BP (a), 2500 cal BP (b), 3500 cal BP (c) and 5500 cal BP (d), based on stratigraphic data from trenches and boreholes, bathymetric data in the embayment, and the relative sea-level changes predicted by the model of Lambeck and Purcell (2005) for the Skyros area.

(and the settlement history) at Palamari, requires more data than those presently available. In a more detailed comparison with the Lambeck and Purcell model, the RSL dataset obtained at Palamari indicates lower sea-levels in the period 4000–500 cal BP, and a faster RSL rise rate between 7500 and 6000 cal BP. These differences could be taken as indications of tectonic movements (subsidence), but, they could also be (a) the result of fluctuations of the rate of eustatic sea-level rise (which are not depicted in the Lambeck and Purcell model) or, (b) the result of (small) inaccuracy in the Lambeck and Purcell RSL model in the specific area.

Based on the above, the RSL curve obtained from the Lambeck and Purcell (2005) model is adequate for the purpose of obtaining a first approximation of paleocoastline positions. This is done in Fig. 9, based on detailed bathymetric data for the Palamari bay (provided by the local Ephorate of Antiquities) and the stratigraphic data in the boreholes and trenches, for 1000, 2500, 3500 and 5500 cal BP.

Between 6000 and 3500 cal BP (1500 BC), the paleo-shoreline of the retreated Palamari coastal area must have been located about 75 m to the east from the present mouth of the Trichias River and about 150 m to the south of the excavation area (Fig. 9). At the same time the small rocky island was probably connected to the mainland. In fact, this island represents the southeastern extent of the headland. During this period the embayment was southeasterly connected to the sea, therefore sheltered and protected from northeastern winds. The configuration of the embayment at that time could have supported the use of a port by the Palamari settlement. After this time the whole embayment was changed. The headland was submerged and the lagoon became a rather shallow stagnant water body. The front coastal area was vulnerable to the northeastern wind. It is thus probable that the decline of the Palamari settlement might be partially attributed to the observed coastal changes.

5. Conclusions

The sedimentary sequence of the Middle-Late Holocene of the Palamari coastal plain consists of lagoonal deposits. Both agricultural and grazing indications are recorded since the Neolithic period and bear strong influence on the paleovegetation of the area.

Three main sedimentary units were recognized named A, B and C respectively.

The sedimentary sequence of Unit A (7500–3500 cal BP) is probably the result of ephemeral fresh water flows. Initially a fresh water shallow environment was established (subunit A1) that gradually gave way to a shallow lagoon with intense fresh water input (Subunit A2). At that time the embayment was southeasterly connected to the sea and might have been well used by the Palamari settlement as a port.

Unit B (3700–800 cal BP) represents a coastal environment characterized mainly by high to moderate energy fluvial processes. Brackish stagnant shallow waters have been documented (subunit

Ba) with backshore traces of a mega-storm event at around 3500 cal BP. This event might be attributed to a tsunami associated with the Minoan Santorini eruption. In the inner part of the plane a brackish marsh is evident (subunit Bb). The paleoenvironment reflects the dominance of stagnant waters with temporal desiccating periods and prominent imprints of human activity. The geomorphic setting of the embayment was totally different from that corresponding to the previous unit. Part of the northern headland was submerged and the lagoon became a very shallow and rather stagnant body of water. This period corresponds more or less to the abandonment of Palamari settlement, something that might be related to the environmental changes observed in the embayment.

Unit C (800 cal BP to present) is characterized as a backshore environment with aeolian sand deposition mixed with colluvial sand and gravel.

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