Late-Middle-Holocene palaeo-environmental evolution and coastline changes of Malia (Crete)

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1. Introduction

Since 1922, the French School of Athens has been excavating the Minoan site of Malia. The Bronze Age town developed around one of the third major palaces of the Minoan period. The palace is about 1300 m inland from the Aegean coastline. Located at the bottom of the Minoan town and alongside the current coastline, a small marshy area (0.1 km^2, *Fig. 1*) has led archaeologists to formulate several questions during the last decades. Did this marsh ever open to the sea? Was it a lagoon compatible with the presence of a harbour or an anchoring place during the Minoan period? In contrast, was it always terrestrial and in this case, was it drained and under cultivation? Did it experience significant changes caused by an exceptional event such as the volcanic eruption of Thera? Numerous archaeologists have attempted to answer these questions (Hue and Pelon, 1991; Raban, 1991; Van Effenterre, 1980; Van Effenterre and Van Effenterre, 1963) but their hypotheses could not

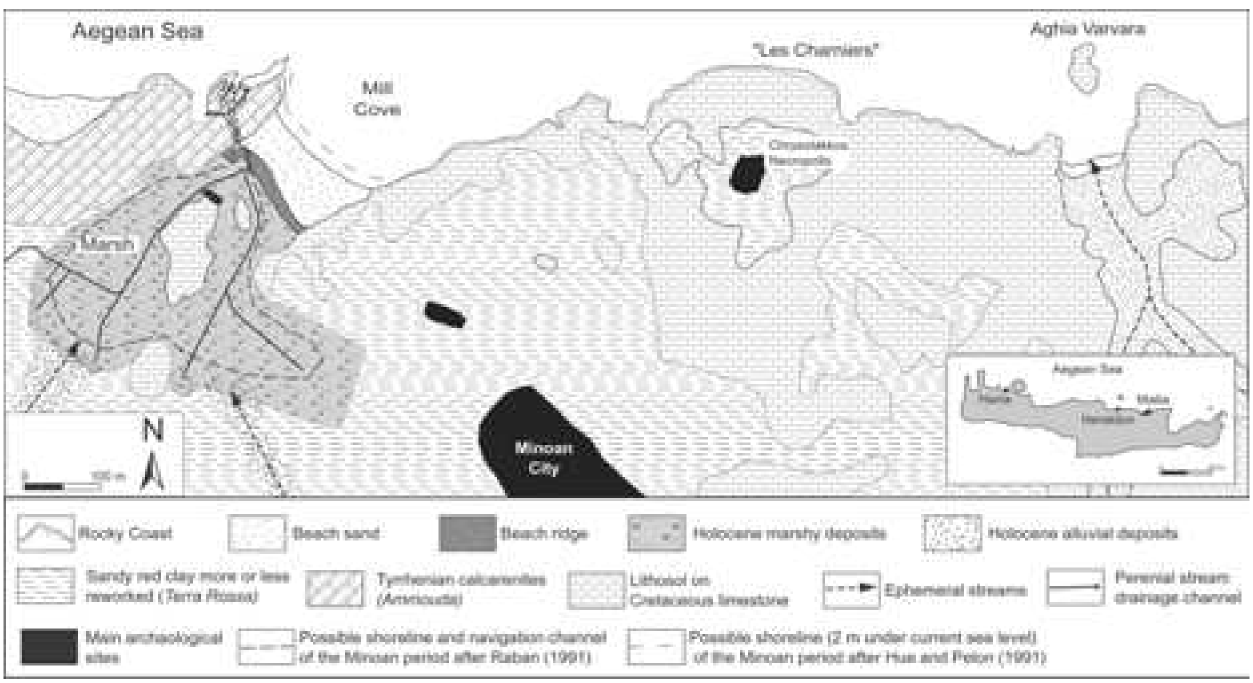


Fig. 1. Simplified morpho-pedological map of Malia area.

be supported by any palaeo-environmental data. The purpose of this study was to reconstitute the history of the marsh of Malia in connection with the coastline evolution and with the changes in land use for the last 7000 years. The investigations, based on six cores, were conducted in a research programme directed by R Dalongeville and supported by the French School of Athens and the French Ministry of Foreign Affairs (Dalongeville et al., 2001).

1.1. Study area

1.1.1. General setting

The archaeological site of Malia, inhabited from 2800 to 1200 BC (Darcque, 1996), is 40 km to the east of Heraklion, at the foot of the Selena mountain (1550 m) and alongside the northern coast of Crete (*Fig. 1*). It is situated in the eastern part of a small coastal plain.

The upper part of the Selena is composed of white Triassic marmorean limestone while its northern slope comprises blue Cretaceous limestone with Rudistids (*Sideropetra*) covered with discontinuous Mediterranean shrubs. During the Cenozoic, this slope experienced significant erosion leading to stepped erosion surfaces that have cut the Mesozoic limestone (Bonnefont, 1972). The widespread level is about 90 m high and closes the plain to the east (Arkovouno). The Minoan town is on the lowest surface, which is 15–20 m high (*Fig. 1*). This surface, bordered to the north by a cliff that dominates the Aegean Sea, shows karstic landforms with sinkholes filled by Terra Rossa. It is mainly cultivated with olive trees, like all the lower erosion surfaces.

To the west, the bedrock of the gently sloping coastal plain, with the modern village of Malia, is composed of bioclastic Messinian limestone. It is covered by red sandy loamy formations derived from Terra Rossa reworked during the Quaternary. This plain is cultivated with olive trees, bananas under glass protection, and cereals. It is bordered by a small coastal scarp often dominating sandy beaches.

1.1.2. The marsh of Malia and the sea

The marsh of Malia is situated, in between these two units, in a lowland area with an altitude corresponding to average level of standard high tide. It is mainly covered by reed (*Arundo Donax* and *Phragmites Phragmites*) and meadows with rush. It has a complex shape. To the West, contact with the plain corresponds to a gentle slope, while to the east, the slope is steeper and the likely result of a recent fault-scarp (Pareyn, 1963). Moreover, the marshy lowlands are divided in two parts by small elevations (ca. 4–5 m high) composed of Cretaceous limestone (*Sideropetra*).

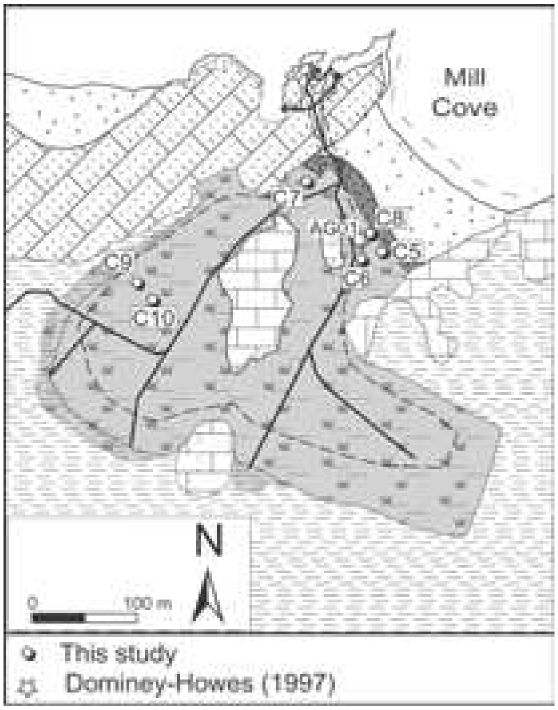
The coastline corresponds to three landforms. To the west, the marsh is closed by small hillets (ca. 5 m high) which form a low rocky coast. They are composed of Tyrrhenian coastal calcarenites (*Ammouda*) which were quarried out. Their study reveals sediments corresponding to two high sea stands during the last interglacial period with intercalations of aeolianite (Caron et al., 1998). Theses coastal formations are correlated with isotope stages 5.3, 5.2 and 5.1 (120–80 ka, Caron et al., 1998). To the east, stepped corrosion benches and vermetid coatings of the two latest transgressions of isotopic stages 5.3 and 5.1 are preserved on the cliff (Dalongeville et al., 2000). It is inferred that a small-scale swift jerky surrection of the coastal area happened during the Late Pleistocene (Dalongeville et al., 2000).

In between these two landforms, a sandy beach bordered by an embryonic shore dune constitutes the coastline at Mill Cove. The local beach drifting run east to west and tide range varies about 40 cm in amplitude. The beach and beach ridge overlie the Tyrrhenian calcarenites as indicated by the cores drilled for this study (*Fig. 2a,b*).

Today, there is no perennial stream to supply the marsh. The two streams which join in it are, most of the time, dry (*Fig. 1*). The water supply comes from aquifers hosted in the Cretaceous and Neogene limestones. They are in hydraulic communication and behave as a heterogeneous and discontinuous aquifer system (Lambrakis and Kallergis, 2001). The seasonal fluctuations of the water table never lead to a complete drying of the marsh. The three major drainage channels and the outlet of this lowland area cut in the calcarenites never dry up during the summer and prevent noticeable ingression of marine water.

1.2. Methods

The investigations were conducted to establish wetland stratigraphy. Detailed lithological, micro-fossil and vegetal remains analyses were used to identify shoreline and landscapes changes and



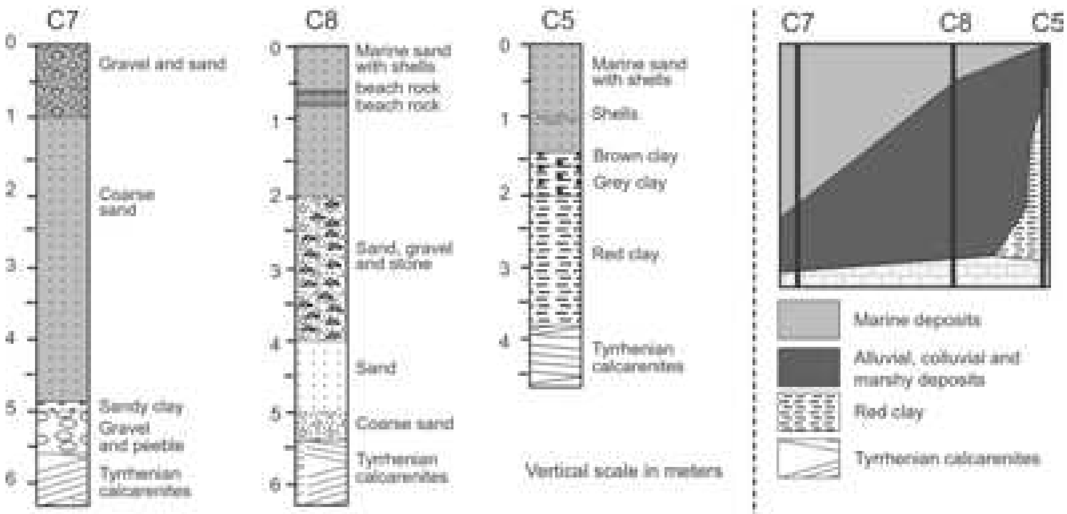


Fig. 2a. Location of coring sites (legend cf. *Fig. 1*)
Fig. 2b. Cores along the beach ridge (from west to east) and schematic transect.

terrestrial or marine transient flooding related to tectonic or hydrologic event. Six cores, 6–7 m deep were drilled out by our research team (*Fig. 2a–c*). The cores were located in the inner part of the beach ridge (C7, C8 and C5), in the marsh (C6 and C10) and on its border (C9). The sampler had a 10-cm bit diameter and could be extended by addition of a 1-m pipe segment. Each core was described in the field according to texture, grain size, colour, vegetal remains and macro-fossil content.

In the laboratory, the analyses focused on core C6 which offered the longest and most varied stratigraphy and the greatest number of organic layers significant for absolute dating. Grain size analyses were made following the techniques described by Rivière (1977) and Folk (1980). Silt and clay grain sizes were studied

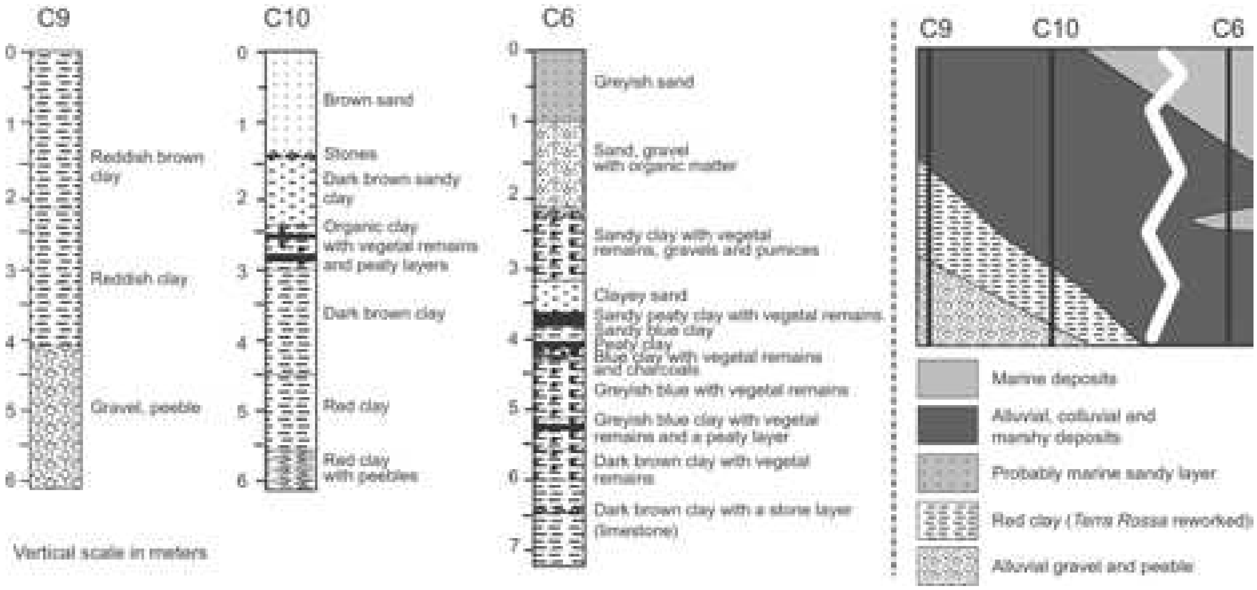


Fig. 2c. Cores in the marsh on its borders (from west to east) and schematic transect.

using a Sedigraph Micromeritics 5100. The sand fraction (between 50 µm and 2 mm) was sieved and examined under a binocular microscope (Lespez et al., 2002). Micro-fossils of Foraminifera, wood remains and pollen were removed and identified. The pollen analyses, because of the abundance of worthwhile materials, will mainly be published in a separate and detailed article (Noirel-Schutz, in press). Eleven samples were analysed for radiocarbon dating on plant remains, charcoal and total organic matter (*Table 1*). This was performed at the Radiocarbon Centre of the University of Lyon 1; the conventional result being expressed at ±1 S.D. Dates were then calibrated according to Stuiver and Braziunas (1993) and expressed at ±2 S.D.

2. Analyses of Core C6

2.1. The rate of sedimentation

The eleven radiocarbon dating lead to establish an age/depth diagram which shows a rate of sedimentation since the 7th millennium BP (*Fig. 3*). All dates are lined up a straight line. A large part of the information brought accounted for a linear regression with a high correlation coefficient (R^2 = 0.97). This infers regularity in the filling of the marsh of Malia during the last seven millennia (0.74 mm/year). Two dates step back a little from the model. They also seem questionable because their reverse stratigraphic positions are compared to the following (Ly-7121) or the previous dates (Ly-7113). Due to the regularity of the sedimentation as a whole indicated by the nine other dates, we think these two dates give evidence of contamination by more recent organic matter (Ly-7121) or reworking of old deposits (Ly-7113), which is also inferred by the significance of the S.D., particularly for Ly-7121. In detail, the rate of sedimentation was higher at the beginning, between 7440 ± 80 and 5080 ± 65 BP (0.93 mm/year), than later (0.65 mm/year) except for a short period (2020 ± 70 to 1770 ± 55 BP, 0.94 mm/year).

2.2. The sedimentary facies

The grain size analyses and the sand examination have concerned 20 samples regularly disposed along the core and representative of the different sedimentary facies. Six facies have been identified and described (*Figs. 4 and 5*).

2.2.1. The fine sediments of the lower part of the core (type 1)

Six samples of dark brown colour (S78, S80, S81, S83, S87, S89) taken in the lowest part of the core have clay texture (clay > 30%) with an average grain diameter between 100 and 140 µm. Sorting (13–35) indicates

Table 1. Radiocarbone dates. Evin and Oberlin, Centre de datation par le radiocarbone de Lyon.

Labo code	*Depth (m)*	*Material*	*Dates BP (1σ)*	*Calibrated dates (2σ)*
Ly-7112	1.83–2.04	Organic clay	536 ± 75	1297–1480 AD.
Ly-7113	2.16–2.20	Organic clay	1910 ± 70	40 av.–315 AD.
Ly-7114	2.70–2.77	Organic clay	1770 ± 55	128–315 AD
Ly-7115	2.95–2.99	Organic clay	2020 ± 70	190–414 AD
Ly-7116	3.74–3.77	Peat	3340 ± 50	1739–1513 BC
Ly-7117	3.99–4.09	Plant remains	3790 ± 45	2395–2040 BC
Ly-7118	4.15–4.20	Charcoal	3955 ± 50	2576–2287 BC
Ly-7119	4.82–4.84	Organic clay	5080 ± 65	3979–3713 BC
Ly-7120	4.97–5.01	Organic clay	5210 ± 55	4221–3829 B.
Ly-7121	5.30–5.34	Plant remain	4765 ± 165	3944–3042 BC
Ly-7122	6.92–7.14	Organic clay	7440 ± 80	6420–6050 BC

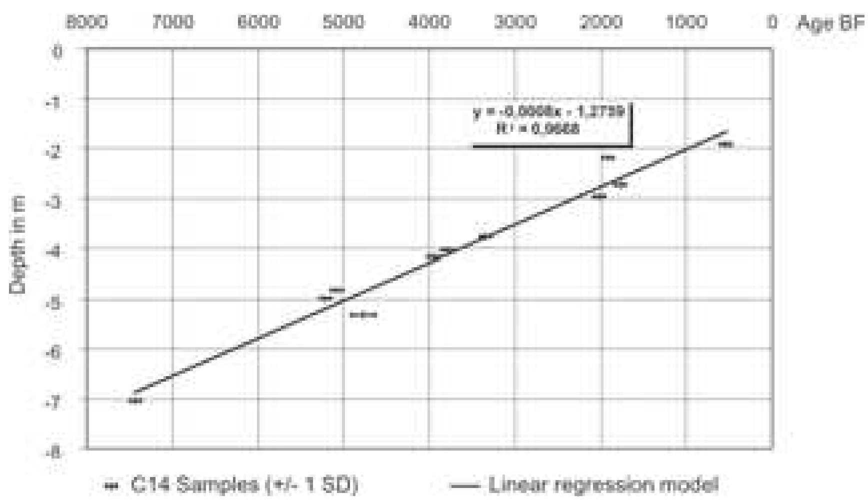


Fig. 3. Age/depth diagram (core C6).

very poorly sorted sediment. The cumulative curves are sub-logarithmic with a hyperbolic fine fraction (*N* = 0.07; Rivière, 1977). It indicates a mixing between two sedimentary fractions. The sand comprises several angular to sub-angular quartz and feldspar grains. This is proof of a calm environment with fine detritic deposits in a marshy area. The presence of a significant clayey fraction probably reveals a pedogenic alteration after deposition.

2.2.2. The marshy sediment of the middle part of the core (type 2)

These samples, of a grey-blue colour (S27, S40, S58, S61, S66, S73) taken in the middle part of the core, have a loamy sandy clayey to loamy clayey texture. Sorting (10–25) indicates very poorly sorted sediment. The cumulative curves are sub-logarithmic (*N* = 0.07; Rivière, 1977) but it is necessary to

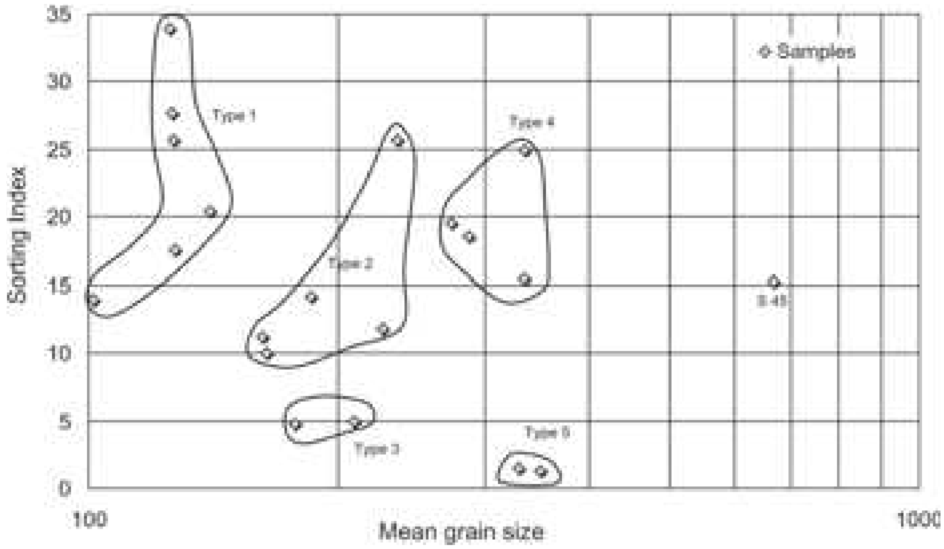
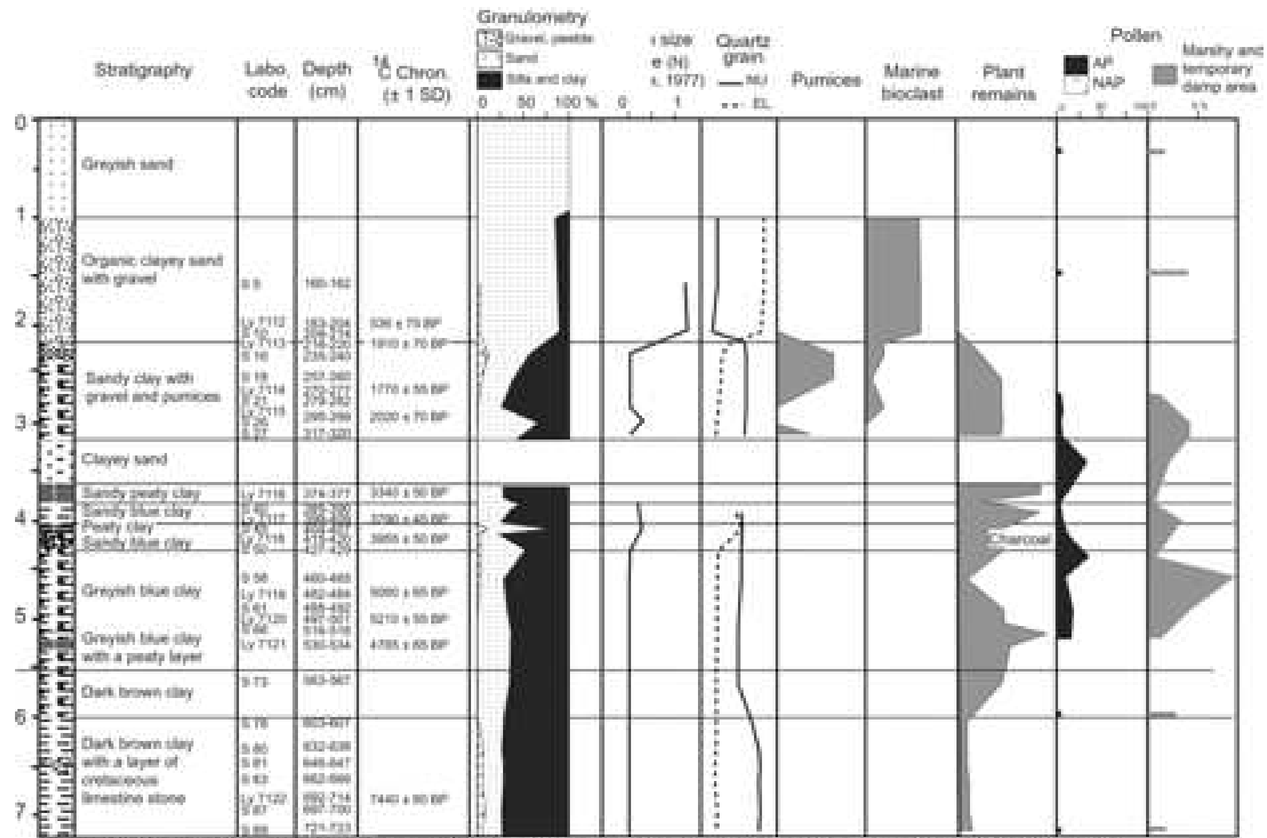


Fig. 4. Sedimentological facies according to sorting and mean grain size.



Radiocarbone dating: C. Oberlin and J. Evin; Granulometry: L. Lespez; Sand grain examination: J.-F. Pastre; Foraminifera: R. Matthieu; Pollen analyses, C. Noirel-Schutz (in press).

Fig. 5. Core C6 results of analyses, Malia, Crete.

distinguish two sub-types with respect to texture and average grain diameter. The first sub-type corresponds to fine sediment (average grain diameter <200 μm) with a relatively better sorting index (10–15). The second (S27, S61) indicates coarser deposits (mean grain diameter >250 μm) with a worse sorting index (>15). In both the cases, the sand fraction comprises selenite and sub-angular to sub-rounded quartz and feldspar grains. This indicates calm environment with fluviatile deposits (sand and loam) in a marshy area. The selenite probably reveals wind-brought additions.

2.2.3. Fluvial-type sediment (type 3)

Two samples (S26 and S50) coming from the middle part of the core indicates relatively well-sorted sediment in comparison with the rest of the sedimentation (So ~ 5). They correspond to more or less loamy or clayey sandy deposits with a mean grain diameter (170–210 μm) significantly lower compared to the marine sand. The sand comprises mainly sub-angular quartz and feldspar grains. These sediments reveal significant alluvial sand in the marshy area.

2.2.4. 2.2.4. Sediment with a marine influence (type 4)

Three samples (S16, S18, S21), taken from the middle part of the core just under the upper marine sand, have a more or less sandy clayey texture. The average grain diameter is large (270–340 μm) and they are very poorly sorted (15 < So < 44). This indicates a mixing between fine to middle sand and clay with fine loam. The cumulative curves are sub-logarithmic (0.05 < N < 0.07; Rivière, 1977). The sand fraction comprises pumice (S16, S18), automorphic feldspars (S18), marine bioclasts (S16), Foraminifera (S16, S21) and sub-rounded, smooth, shinning quartz grains. This is indicative of a mixing between marine sand and fine palustral sediment. It bears evidence of a breaching of the beach ridge or of significant wind-brought inputs. Even if pumice could be reworked by the sea and wind, automorphic feldspars indicate direct or little reworked volcanic inputs.

2.2.5. Marine sediment (type 5)

Two samples (S5 and S10) from the upper part of the core correspond to more or less clayey sandy deposits. They are very well sorted compared with the rest of the sedimentation (So < 1.5) and have an average grain diameter of medium sand (330–350 μm). Their cumulative curves are parabolic and indicate deposition along a sandy coast characterised by normal roughness (N > 1; Rivière, 1977). The sand comprises mainly fragments of rolled shell, sea-urchin and Foraminifera while the quartz grains are sub-rounded, smooth and shiny. This asserts of the marine nature of the deposits. Nevertheless, the percentage of clay, particularly for S5, indicates a mixing with marshy deposits. This infers probably reworking of marine deposits in the inner part of the marsh by a marine ingression or the wind.

2.2.6. A specific sample (S45)

Sample S45 taken in the middle part of the core (4.04–4.07 m) is very poorly sorted (So = 15.8) and possesses a high average grain diameter (667 μm). Its cumulative curve is slightly parabolic (N = 0.2; Rivière, 1977) and the sand comprises sub-angular to sub-rounded quartz and feldspar grains and selenite. It is a mixing of coarse to medium sand with marshy deposits the source of which is difficult to establish. There is no shell fragment, Foraminifera or other marine element and the surface texture of the sediment is equivocal. Nevertheless, based on the high value of average grain diameter and the parabolic curve, it seems possible to infer a marine source for this sediment relative to an alluvial one.

2.3. Palaoebiological analyses

2.3.1. Foraminifera

The 23 samples used for the micro-fauna analysis are overall sterile and attest of a terrestrial evolution of the marshy area during the Holocene. Only two samples (S16 and S21) contain Foraminifera (*Table 2*). The benthonic Foraminifera identified indicate coastal micro-fauna of warm temperate marine water, typical of the Aegean Sea. But even in these samples, micro-fauna are scarce and comprise just few individuals (20 and 21) and few taxa (2 and 10). This probably reveals a reworking of marine sediment by a short time marine ingression or by wind.

Table 2. Foramineferals analyses of C6 (Mathieu).

No. of sample	*Depth (cm)*	*Ammonia parkinsoniana*	*Amphistegina lessonii*	*Cibicides lobalutus*	*Elphidium crispum*	*G. aspera*	*Peneroplis pertusus*	*Quinqueloculina sp.*	*Quinqueloculina trigonula*	*Sorites orbiculus*	*Trinoculina gibba*	*Triloculina plicata*	*No. of Foraminifera*	*Environment*
S16	235–240	*	*	*	*	*	*	*	*	*	*	*	20	
S21	279–282	*						*					21	Marine influences
S32	369–372													
S41	394–396							*						
S47 à S89*	410–412 à 721–723													Terrestrial deposits

* Twenty-three samples were analysed. In between 410 and 723 cm, the 19th samples analysed are sterile.

2.3.2. Vegetal remains, charcoal and pollen

The vegetal remains characterise the middle part of the core between 2 and 6 m depth (*Fig. 4*). They give evidence of a marshy area covered by hydrophilic vegetation between 6500–6000 and 2000 BP. The weakness of riparian wood remains assessed by the xylologic analysis (*Table 3*) and consistent with palynological data (Noirel-Schutz, in press) indicates that the marsh was never covered by wooded or shrubby vegetation. On the other hand, the numerous remains in vertical position of *Arundo donax* and *Phragmites phragmites* attest the marsh was covered by reed from the Neolithic to the Roman period.

The xylologic analysis of samples S17 and S22 indicates arboreal vegetation with species specific of dry environment *Pinus*, *Quercus*, *Cupressus* and *Juniperus*. It is impossible to understand their growing in a marshy area and the fragments observed must indicate local reworking. This infers a wooded cover in the vicinity of the drilling site. We formulate the hypothesis of a beach ridge partially covered by a xerophylous and psammophylous vegetation (*Pinus*) and/or xerophylous wooded cover (*Pinus*, *Quercus*, *Cupressus* and *Juniperus*) on the small calcareous elevation located in the midst or around the marshy area during the Roman period at least.

Between 4.3 and 4.1 m deep, the sedimentary layer is very rich in charcoal. The density of charcoal, its deposition in a marshy area without significant wooded cover gives evidence of a source located outside the marsh. It also corresponds to a significant decrease of arborean pollen (Noirel-Schutz, in press; *Fig. 5*) and probably indicates important fire, around the marshy area, in the forest of limited extension at that time (ca. 4000 BP). Their deposition in the lowland area probably derived from transportation by ephemeral streams.

3. Interpretation

Sediment and palaeo-biological analyses lead to establish a synthetic chronostratigraphy of core C6. Results are summarized in *Figs. 4 and 5* and account for five different periods in the sedimentological record of core C6.

Table 3. Wood remains analyses of C6 (Darmon).

	S13	S17	S22	S24	S34	S39	S42	S46	S48	S53	S55	S57	S68	S69	S86
Depth (cm)	220–225	256–266	276–290	290–320	374–378	365–385	390–410	407–408	410–414	434–438	445–450	422–458	525–528	512–520	658–692
Alnus											*				
Cupressus		*													
Juniperus		*													
Pinus		*	*		*	*			*		*				
Quercus		*	*										*		

3.1. Unit 1: marshy sedimentation (ca. 6500–5200 cal. BC)

The lowest part of the core (7.2–6 m) is characterised by a relatively high sedimentation rate (0.93 mm/year) in a hydromorphic lowland area. This rate of sedimentation is explained by the rapid Holocene sea-level rise, slowing down from about 6000 BP onwards, and by the natural barrier constituted downstream by Tyrrhenian calcarenites. The filling of a previous hydrographic pattern incised in the bedrock and divided in two parts by a small calcareous hill lead to an expansion of the marshy environment.

3.2. Unit 2: a complex marshy sedimentation (ca. 5200–1500 cal. BC, Neolithic–Late Minoan period IA or IB)

The lowest part of the middle portion of core C6 (6–3.6 m) corresponds to a marshy sedimentation characterised by clayey settling deposits and influx of loamy to sandy alluvial material. This indicates an expansion of the marshy environment and an increase of alluvial dynamics probably in connection with the triggering of soil erosion around the marshy area. The marsh was covered by hydrophilic vegetation mainly composed of reed as it is inferred by peaty layers, the density and type of vegetal remains in organic clay.

The organic clayey layers probably indicate at least seasonal free water areas of limited extent into the marsh. On the contrary, the peaty layers (1739–1513, 2395–2040 and ca. 4300–4100 cal. BC.) within the organic clayey sedimentation indicate temporary lower water table level. This short-time lowering of the water table level at the level of the marshy area is also suggested by the connection with the decrease of pollen of marshy and hydromorphic origin (*Fig. 5*; Noirel-Schutz, in press).

Between 4.3 and 4.1 m deep, a sedimentary layer, very rich in charcoal, probably indicates important fire, around the marshy area, in a forest cover of limited extent. This layer is dated from ca. 2600–2250 cal. BC (Early Minoan II–III) which is consistent with the first known period of inhabitation of the site of Malia (2800–2000 BC). In this period, the plain of Malia probably experienced a significant land fire-clearing by farmers living in the neighbouring marshy area.

3.3. Unit 3: a specific sedimentary event (ca. 1739–1513 cal. BC to 190–414 cal. AD, Late Minoan IA or IB–Hellenistic period)

A clayey sand layer (3.2–3.6 m) is interbedded within the marshy sedimentation. Its significant sandy fraction indicates a clear hiatus in palustral sedimentation and a more energetic hydrodynamic environment. Unfortunately, this influx of coarser deposits cannot be studied because it was not preserved in the core tube. This hiatus can be explained by fluvial-type or marine deposits. It is dated between 1739–1513 cal. BP and 190–414 cal. AD. The following layers comprise pumices and automorphic feldspars. These observations lead to make a connection with the consequences of the Thera eruption. Indeed, the Thera eruption is dated from 1628 cal. BC according to Manning (1999) or 1550–1530 cal. BC according to Warren and Hankey (1989) and Driessen and MacDonald (1999) and the

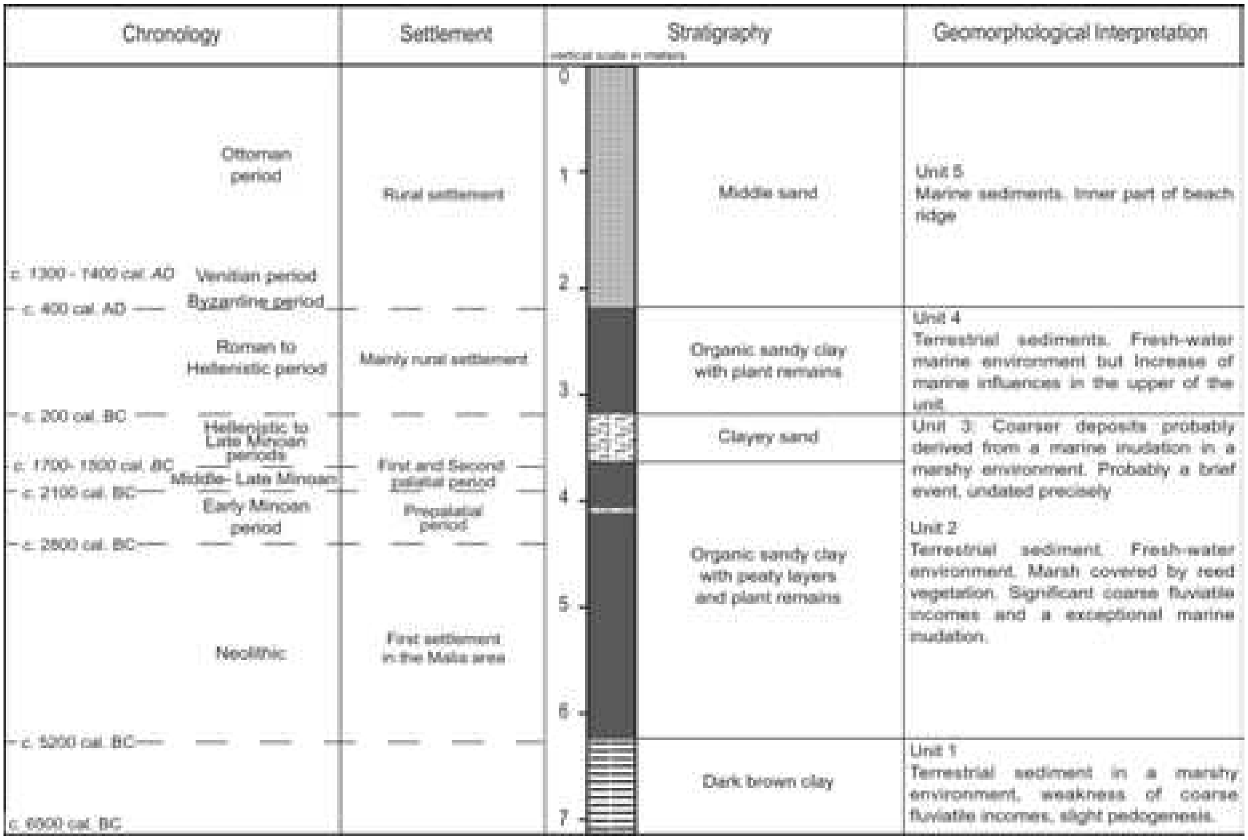


Fig. 6. Core C6, synthesis and interpretation.

consequences of this event are now well known in Northern Crete (Hardy and Renfrew, 1990). A sudden ingression caused by the tsunami (6–11 m wave height at north Crete after the numerical simulation of Minoura et al., 2000) resulting from the Thera explosion could explain the origin of this layer as observed in Gouves, 20 km to the west. In this site, a thin veneer of carbonate sand overlying by 10–20-cm pumice layer had been observed in a late Minoan potter's workshop 2–3 m high above the present sea level (Minoura et al., 2000). The hypothesis of beach ridge destabilisation leading to a receding shoreline in Mill Cove and probably its local and temporary break can be supported.

This deposit has not been identified on the other cores (C9 and C10, *Fig. 2a,c*) and the published data of Malia indicate only one pumices deposit in a coastal position. It has been found in an LM IA stratum in the Aghia Varvara area (Müller, 2000). Even it is probable, there is no proof according to the present data that the layer observed in C6 core corresponds to the sudden tsunami inundation which could have concerned the whole marshy area. In addition, recent study in Aegean area demonstrates that stratigraphical signature of earthquake and related tsunami in coastal wetland is relatively subtle (Cundy et al., 2000) and is consequently difficult to distinguish from other rapid coastal change like storm events and barrier breaching.

3.4. Unit 4: a marshy sedimentation with marine influences (ca. 200 cal. AD to 400 cal. AD, Hellenistic to the end of the Roman period)

The upper part of the middle portion of core C6 (2.2–3.2 m) is characterised by a marshy sedimentation indicating a reversion to marshy environment cover by reed. But marine influence increase can be suggested by sand and Foraminefera analyses. This influence is limited, related to short- and small-scale marine ingressions and/or reworking of marine sand by wind. The establishment of lagoon-type environment is never assessed and the increase of marine influence instead indicates a receding of the shoreline. Its position was probably similar to the current one.

The rate of sedimentation increase compared to what it was in the previous unit (about 1 mm/year). This could derive from deposits of marine sand but also from an increase of alluviation and soil erosion. This last hypothesis is supported by an increase of land use inferred by pollen analyses (*Fig. 5*; Noirel-Schutz, in press).

3.5. Sequence 5: a marine sedimentation on the border of a coastal marsh (after 400 cal. AD)

The scene has changed. The sedimentation is mainly composed of marine sand partly reworked by wind. This reveals a significant receding of the shoreline compared to the previous period but also to the present one. Indeed, core C6 is today clearly localised in the marshy area. This recess of the beach ridge dates from the end of the Roman period and the Venetian period (40–414 and 1297–1480 cal. AD) according to a radiocarbon dating obtained from an organic clayey layer at the bottom of this unit. The change of sedimentation is sudden and the hypothesis of an exceptional marine event can be supported even if it is difficult to identify and date.

4. Discussion

The palaeo-environmental reconstruction of the marsh of Malia mainly based on the analyses of core C6 demonstrates that this area was a freshwater marshy area during the whole of Holocene. Nevertheless, we wish to underline three main problems.

4.1. The extension of the marshy environment and tectonic control

The field and laboratory analyses of the six cores provide an idea of the marsh extent during the last seven millennia. In general, a significant stability is observed. Cores C6 and C10 give evidence of the continuity of the marshy environment in the north-eastern and south-western part of the marsh since 6000 BP around (*Fig. 2a,c*). Furthermore, core C9 (*Fig. 2a,c*) indicates a stability of the western border of the marsh during the same period. After a first stage characterised by a small increase of the marshy deposits located just behind the barrier constituted by the Tyrrhenian calcarenites (C6), the marsh has expanded inland to the south as revealed by C10 and C9.

In a coastal marsh, peat corresponds to a state of equilibrium between the water tables output and sea level (Vella and Provansal, 2000). The present top surface of the peat deposits is between around 0.1 and 0.5–0.6 m. This margin of error has to be taken into account as it derives from the compaction of the deposits. Nevertheless, fossilised peat deposits in a coastal plain are considered to be reliable markers of successive relative sea level (Vella and Provansal, 2000). In the marsh of Malia, they indicate a low and progressive subsidence of bedrock during the last five millennia. This low subsidence leads to dismiss the hypothesis of sudden subsidence caused by regional or local tectonic event suggested in a previous article (Dalongeville et al., 2001). Nevertheless, a slight increase in the rate of subsidence related to a slight increase of the sea level (Dalongeville et al., 2001) could be a convincing account to explain the receding seashore and the increase of marine influences in C6 since the end of the Roman period. This remains a hypothesis but in the local context, it is difficult to consider a natural decrease of sediment supply during the historical periods as a cause for destabilisation of the beach ridge.

4.2. The marine exceptional events

Core C6 reveals a succession of three events characterised by increase of marine influence.

Sample S45 (4.04–4.07 m, ca. 2500–2040 cal. BC) interbedded in a marshy sedimentary unit does not reflect a long-term change in the sedimentation trend but indicates a sudden event of probably marine origin. The nature of sedimentary material does not lead to be more precise. Nevertheless, this observation is consistent with another analysis made by Dominey-Howes (1997). Dominey-Howes has conducted Foraminifera analysis of a core located around 40 m to the north of C6. This core is not dated but the general stratigraphy reveals by the Foraminifera analysis is consistent with C6. Dominey-Howes observed an exceptional layer (4.59–4.60 m) with a high total number of Foraminifera (300) and a quite varied assemblage. This a ssemblage is dominated by shallow marine forms but also by the presence of low and high marsh forms. For Dominey-Dowes (1997), this layer indicates a clear transgression into a freshwater environment. Compared to C6, this layer probably dates back from a long period between 4000 and 2000 cal. BC. The possibility of short time marine ingressions is suggested by sample S45 and the marine layer identified by Dominey-Howes (they could refer to the same event) but they have never altered for a long time the freshwater environment.

The two others periods of sudden recess of the coastline are also uncertainly dated. The first took place between 1739–1513 cal. BC and 190–414 cal. AD and the second, between 40 cal. BC to 414 cal. AD and 1297–1480 cal. AD. The data available indicates that these two events are not characterised by significant and long-term marine ingressions but by a sudden destabilisation of the beach ridge. The role of a local sudden and high magnitude tectonic event can be excluded in respect of the general low subsidence of the marshy area. The sedimentary changes are probably related to hydrodynamic processes. The first sedimentary change is only to be observed on core C6 in the marshy area. The destabilisation of the beach ridge experienced in the Mill Cove may be related to exceptional waves such as this one derived from the Thera explosion. Furthermore, the storm surges on the coast of Aegean Sea are generally agents of erosion and do not produce extensive deposits on land area (Minoura et al., 2002). Nevertheless, the assessment of this hypothesis needs more precise dating control and further analyses.

The second sedimentary event corresponds to more significant changes. The Early Byzantine paroxysm and the of 365 AD earthquake are well known in Crete and have had consequences in the whole eastern Mediterranean (Jacques and Bousquet, 1984; Pirazzoli, 1986; Pirazzoli et al., 1992, 1996). They led to an uplift of the southern and western coast of Crete (Neumeier et al., 2000; Pirazzoli et al., 1996) and in response to an increase of the local subsidence of the northern coast is sometimes invoked (Dalongeville et al., 2001). Nevertheless, the available dating control and analyses do not allow us to identify the specific event which was probably favourable to a slight increase in the subsidence and/or to the destabilisation of the beach ridge by a hydrodynamic process of high energy.

4.3. The marsh, man's impact and the harbour of Malia

The results obtained from the marsh of Malia rule out the presence of any harbour or anchoring area in Minoan times. The spatial stability of the marsh in the last six millennia dismisses the hypothesis of an inner harbour in an open lagoon-type area as suggested by several archaeologists (in Raban, 1991; Van Effenterre, 1980). Also dismissed is the hypothesis that artificial channels incised in the calcarenites were built for navigation (Raban, 1991). These channels constitute only undated artificial channels built to drain the marsh. On the other hand, the hypothesis of a main harbour or anchoring area in Mill Cove (Dewolf et al., 1963;Hue and Pelon, 1991; Van Effenterre, 1980) is convincing and agrees with our results even if the palaeogeographical reconstruction proposed by Hue and Pelon (1991) is not supported. Mill Cove was probably the best anchoring area along a coast that was not well protected from the meltem (north wind) and its powerful swells. The site of Aghia Varvara was probably less favourable, because the cove is smaller and resonance effects were caused by the presence of an island or a tombolo.

The settlement of the Malia area has been attested since the Neolithic period (Neolithic and Early Minoan sites observed on the slopes of the Arkovouno; Müller, 1998). Palynological research also indicates the impact of these first settlers on the vegetation cover around the site of Malia (Dalongeville et al., 2001; Noirel-Schutz, in press). Mixed farming occurred before the first palatial period (ca. 2000 cal. BC, Dalongeville et al., 2001; Noirel-Schutz, in press). It probably explains the increased fluvial sedimentation in the marsh during the Minoan, Roman, and Hellenistic periods while a layer with charcoal indicates the significance of land clearing in the neighbouring areas at the beginning of Minoan times. Nevertheless, human impact on the marsh seems to have been limited. Since the Neolithic period, the landscape of the inner part of the marsh characterised by hygrophilous vegetation dominated by reeds has never changed markedly (C6 and C10, *Fig. 2a,c*). The stability of the marsh was of interest for the Minoan population and their followers. In a region with a great summer water deficit, a freshwater environment supplied by a large and relatively stable aquifer is noticeable. The water resources of this lowland area were probably favourable for cultivating and breeding, as suggested by pollen analyses (Dalongeville et al., 2001; Noirel-Schutz, in press).

5. Conclusion

The palaeo-environmental reconstruction of the marsh of Malia shows that it was always a freshwater environment. There was no lagoon-type evolution that could have led to the presence of an inner harbour even during the periods characterised by a destabilisation of the beach ridge. The three periods of marine influence observed are probably related to hydro-sedimentary changes more than to a sudden and local tectonic event. The marine influences were always limited and do not indicate long-term changes. The direct consequences of exceptional event such as the Thera eruption were probably limited in Malia, as supported by the palaeo-environmental study and the archaeological data in the Minoan town (Poursoulis et al., 2000) and around the marsh where the occupation appears to have been continuous from the Early Minoan to Late Minoan IIIB period (Müller, 2000). The tsunami would have little direct influence on the Minoan civilization as also suggested at Gouves (Minoura et al., 2000) but the indirect effects were probably much more noticeable (Driessen and Macdonald, 2000).

A new integrated biological and sedimentological approach focused on the southern and the eastern part of the marsh would probably be of great interest to assess the precise consequences of the tsunami derived from the Minoan Thera eruption in the marsh of Malia and to understand changes on the border of the marsh related to drainage and land use.

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