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Geoarchaeological investigation of a prehistoric tell in a coastal environment: the lowest levels at Kirrha (Plain of Delphi, Phocis, Greece)

Antoine Chabrol[a,*], Tara Beuzen-Waller[b], Clément Virmoux[d], Delphine Chavand[a], Eric Fouache[a], Raphael Orgeolet[c]

[a] Sorbonne University, dept. of Geography, UR « Médiations – Sciences des lieux, sciences des liens », Paris, France
[b] Eberhard Karls University, Faculty of Science, "Soil science and Geomorphology Working Group", Tübingen, Germany
[c] Aix Marseille University, CNRS, CCJ, Aix-en-Provence, France
[d] UMR CNRS 8591, Laboratoire de Géographie Physique, Thiais, France

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ABSTRACT

Located downstream of the deltaic plain of Delphi and close to the present-day coastline, the tell of Kirrha is the largest Bronze Age site (Middle to Late Helladic I) in Phocis (Greece), covering an area of around 6 ha. The deepest, and therefore oldest, archaeological levels of the tell have never been reached. A multidisciplinary investigation combining geophysics (ARP and ERT surveys), coring, sedimentological and geochemical analysis (grain-size, $CaCO_3$ content, magnetic susceptibility), observation of the microfaunal remains and radiocarbon dating provided for the first-time capital information about the internal structure of the tell of Kirrha as well as the date of the earliest occupation phase. The results indicate a thickness of occupation layers ranging from 7 to 9 m (until 2 m b.s.l.). While some archaeological indicators found in the cores (such as very isolated pottery fragments) suggest a probable Neolithic occupation, the radiocarbon dating results presented here indicate a first occupation at the very beginning of the Bronze Age (Early Helladic II). Palaeoenvironmental reconstruction reveals that the first inhabitants of Kirrha settled in a coastal-marsh-type environment that was being filled in by fine-grained alluvial deposits from the Pleistos and Hylaithos rivers. Geophysical surveys also revealed that parts of the tell have been eroded by a palaeochannel or buried under alluvial sediments.

1. Introduction

The tell of Kirrha is a major Bronze Age archaeological site found in Phocis, Greece. The area has been the theatre of excavation campaigns since the 1930 s (Dor et al., 1960). Located downstream from the deltaic plain of Delphi, the excavations have uncovered a considerable number of Bronze Age structures and graves, spanning from the Middle Helladic period (around 2000 BCE) to the Late Helladic period (around 1100 BCE) (Dor et al., 1960; Orgeolet et al., 2017; Lagia et al., 2016; Montagné, 2019). Although Bronze Age remains are abundant in Phocis (Müller, 1992; Phialon, 2018), Kirrha is the only tell (or archaeological mound, also known locally as "Magoula" (Skorda, 2010; Dor et al., 1960)) in the region, standing at nearly 8 m a.s.l., and one of the most densely populated prehistoric sites in the area (Fig. 1-**A**). Neolithic to Bronze Age tells (archaeological mounds) are very common in Greece and their formation processes are variable and complex. The significant accumulation of archaeological layers is linked to successive reconstruction phases in the same location over several centuries, sometimes millennia (Matthews, 2014; Andreou et al., 1996). Excavating and understanding the chronology of a tell is not an easy task since the most recent occupations are not necessarily located at the top (for a recent review of the type of problems encountered during excavations of tells, see Lespez et al., 2013, and Rosen, 1986). For several years, the geoarchaeological approach has proven to be highly valuable for studying Neolithic and Bronze Age tells in Greece, as it enables us to comprehend their internal structure and formation processes, as well as date them (Niebieszczański et al., 2019; Lespez et al., 2013; Davidson et al., 2010). The excavation of the tell of Kirrha presents several challenges, including the fact that much of the remains lie beneath the modern village and that the deeper archaeological layers cannot be reached due to the presence of aquifers. The geoarchaeological study presented in this paper attempts to answer two questions that have remained unanswered since the first excavations in the 1930 s: what are the lateral and vertical dimensions of the tell as well as the date of its

* Corresponding author.
E-mail address: chabrol.antoine@yahoo.com (A. Chabrol).

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earliest occupations? This study (which included geomorphological mapping, ARP and ERT surveys, core drillings, sedimentological analysis and radiocarbon datings) is the first attempt at partially overcoming the obstacles encountered in Kirrha, by providing new insights into the whole stratigraphy of the tell. As the morphology and landscapes of Mediterranean coastal deltaic plains have changed significantly since prehistoric times (Carozza, 2011), the retrieval of palaeoenvironmental information about the earliest occupations of the tell also presents a significant challenge for archaeological research in Phocis (Greece).

2. Physical setting

The tell of Kirrha is located in the northern part of the Gulf of Corinth, downstream from the Delphi plain and within 200 m of the current shoreline. The Gulf of Corinth is an active asymmetric rift with some of the highest extension rates in the world (13 and 15 mm/year) (Lykousis et al., 2007; Moretti et al., 2004). The rift is bordered by a series of East-West-oriented faults (including the Delphi/Arachova fault) which have been responsible for locally-destructive earthquakes (Valkaniotis et al., 2016; Valkaniotis et al., 2011) and sometimes tsunamis (Kortekaas et al., 2011). The Delphi plain is part of this regional setting: it is a graben surrounded by active boundary faults (see Chabrol et al., 2020 for a complete geomorphological map of the plain).

Although the exact extension of the tell is uncertain, archaeological estimates based largely on rescue excavations (Skorda, 2010) suggest that it is at least 6 ha in size. The site forms a small hill (Fig. 1-**C**), very prominent in the surrounding low-lying alluvial plain, 8 m above actual sea level at its summit. The tell is flanked by two temporary streams: the Pleistos to the east and the Hylaitos to the west, both of which have been channelised since the 19th century (Fig. 1-**B)**. The lower part of the plain is an asymmetrical delta formed by the alluvial deposits of the Hylaitos River and, to a lesser extent, those of the Pleistos River (Chabrol et al., 2020; Zurbach et al., 2012). The surrounding environment and the site's position relatively to the coastline have likely both undergone significant changes since the Bronze Age, as is the case with many Greek deltaic plains (Ghilardi et al., 2012; Fouache, 2006). A portion of the site may therefore have been eroded or partially covered by the alluvial deposits from these two rivers. Geomorphological surveys have revealed the presence of a recently filled-in coastal marsh east of the site (Kortekaas et al., 2011) and a saline karst spring at the junction between the Paloukaki massif and the plain (Burdon and Papakis, 1963; Zurbach et al., 2012) (Fig. 1-**B**). Shoreline dynamics are currently primarily composed of a redistribution of fine-sized particles towards the east of the bay, with a mostly sandy shoreline near the site (Chabrol et al., 2020) (Fig. 1-**B**).

3. Site history and archaeology

The site of Kirrha has been known for its remains from historical times since the 19th century and was visited in the early 1920 s by then young British archaeologist Oliver Davies, who first recognised the site's importance to the prehistoric period. Davies even reported the presence of Neolithic sherds on the surface of the tell, a detail that was to be forgotten for many decades (Davies, 1929). In 1937 and 1938, classicists from the French School at Athens, interested in historic Phocis, carried out a series of excavations which, most notably, uncovered a large "prehistoric sector" to the north of the village's main church, in front of the cemetery (Fig. 2). It revealed an important and long-lived settlement, especially for the Middle Helladic period and the transition to the Late Bronze Age (Dor et al., 1960). Continuous rescue excavations then took place from the 1960 s onwards, confirming the site's importance as a settlement in the Middle Helladic period and particularly as a burial site during the MH III-LH I period. In 2008, a cooperative research project between the French School of Archaeology at Athens and the 9th Ephorate of Antiquities was conducted, aiming to apply a multidisciplinary approach to several important developments in Kirrean archaeology, including environmental reconstruction, habitat and burial practices (Orgeolet et al., 2017; Lagia et al., 2016; Montagné, 2019). The research presented here was conducted within this framework.

4. Material and methods

Our methodological approach combines geophysical surveys, core drillings and sedimentological analyses. Electrical resistivity surveying (both ERT and ARP methods) has proven its efficacy as a method for characterising subsurface structures and materials in diverse environmental and archaeological research domains (Piroddi et al., 2020; Niebieszczański et al., 2019; Siart et al., 2012; Gaffney, 2008), while coring is particularly useful for characterising successive environments within and around an archaeological site (Trebsche et al., 2022; Rick et al., 2022; Garcia-Garcia et al., 2017).

4.1. Geophysical survey

4.1.1. Automated resistivity Profiling (ARP) survey

The survey, carried out in 2008 using the multi-polar ARP03 device (ARP®, Automated Resistivity Profiling, Géocarta SA, Paris, France), aimed to assess the extent of the site and the nature of its various periods of occupation. The spacing of the dipoles, corresponding to the emitter-receiver distance, allows for three different depths of investigation (50 cm, 1 m, and 1.7 m, respectively). The injected current is set at 10 mA and the system enables resistivity measurements at a 20 cm interval regardless of the advancing speed. A surface area of 2.8 ha was surveyed, encompassing four zones (A, B, C, D) of the tell (Fig. 2). The surveyed zones themselves are constrained by the urban sprawl of the houses, private properties, and olive groves of Kirrha.

4.1.2. Electrical resistivity tomography (ERT) section

A 366-meter-long ERT profile (ERT4) of the tell was measured using an ABEM Terrameter LS acquisition system, with an electrode spacing of 1.5 m, and taking into account the topography using DGPS measurements at each electrode (Figs. 1 and 2) (Chabrol et al., 2014). The section was on an East/West axis across the tell (starting point coordinates: 38° 25′ 54.72088″ N; 22° 26′ 31.78923″ E; end point coordinates: 38° 25′ 54.60641″ N; 22° 26′ 46.85820″ E). The collected data was processed through an inversion program, resulting in a 2D resistivity section representing the subsurface.

Table 1
AMS ^{14}C radiocarbon dates calibrated using OxCal (v4.4.4) with the IntCal20 and MarineCal20 calibration curves.

Core	Sample code	Sample name	Depth (cm bs)	Depth (cm bmsl)	Material	Conventional ^{14}C Age BP	2σ Max and Min Cal. Age		Study
Tell 1	Lyon - E822	Ech4	−822	101	charcoal	5670 ± 230	5056 BCE	4038 BCE	This study
Tell 1	Lyon - E837	Ech3	−837	116	charcoal	3780 ± 40	2344 BCE	2122 BCE	This study
Tell 1	Lyon - E876	Ech2	−873	155	wood	4205 ± 35	2816 BCE	2668 BCE	This study
Tell 1	Lyon - E1000	Ech1	−1000	279	charcoal	4510 ± 35	3359 BCE	3097 BCE	This study
4	Beta-172750	T2	122	0.05	Shell	4670 ± 40	2831 BCE	2388 BCE	Kortekaas et al., 2011

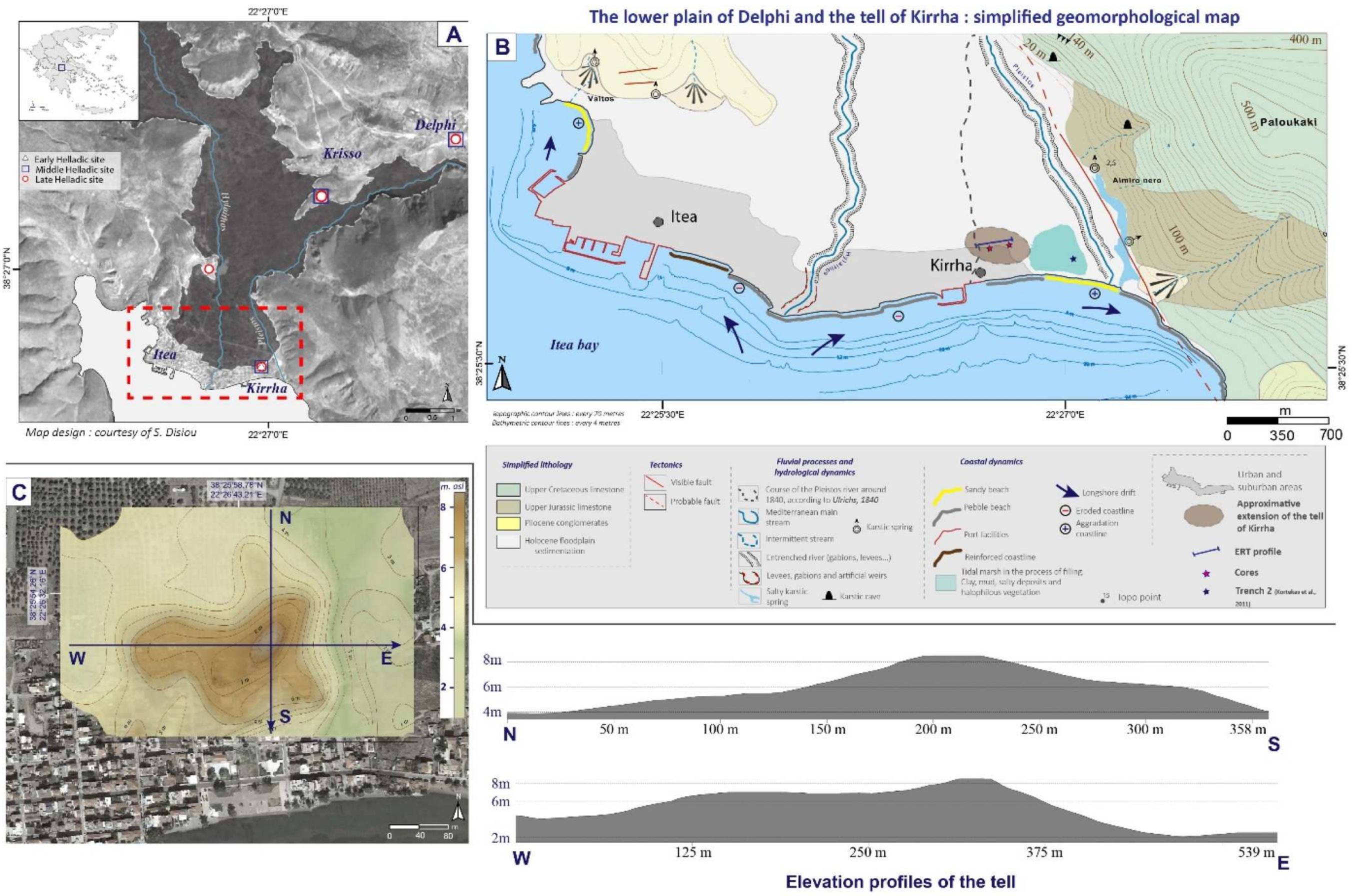

Fig. 1. Location and environmental context of the study area (A. General morphology and extent of the plain of Delphi. B. Simplified geomorphological map of the plain of Delphi. C. Topography and elevation profiles of the tell of Kirrha.

4.2. Sediment core sampling and Seismic Cone penetrometer testing (SCPT)

Two six-centimetre diameter cores were obtained from the tell. Their location corresponds to the two sectors excavated by the French School at Athens since 2009. Core Tell1 was located at the top of the eastern part of the tell (7.3 m a.s.l) (38°25′52.3″N; 22°26′45.99″E), while core Tell2 was placed in its western part at a lower elevation (5.7 m a.s.l) (38°25′52.66″N; 22°26′37.19″E) (Fig. 2). The method used was percussion coring. Both cores reached a depth of 10 m. SCPT (Seismic Cone Penetration Test) measurements were simultaneously conducted on Tell1. This method is valuable for assessing the hardness of archaeological and geological layers (Audibert et al., 2005). In the field, the cores were photographically documented into stratigraphic units based on texture and colour (using the Munsell code), and gaps created by compaction were recorded on the logs. The numerous ceramic fragments found inside the cores were handed over to specialised archaeologists for identification.

4.3. Sedimentological laboratory analyses

4.3.1. Laser grain size analyses

While the sediment fraction > 2 mm was simply sieved manually using several sizes of sieves, the fraction < 2 mm was measured by a Malvern Mastersizer1000 laser granulometer. Grain size measurements were performed at various intervals: every 10 cm from the surface to a depth of 8 m below the surface, and every 5 cm for the last two meters in core Tell1 (8–10 m b.s). In core Tell 2, only the final 2 m (8–10 m b.s) were sampled and analysed. Every sample was weighed and dried (24 h at 40° C) and organic matter was removed (4 h with H_2O_2 treatment). Particles were then dispersed using 0.1 % of sodium hexametaphosphate and left in a deionised solution for 4 h. Each sample was exposed to ultrasounds for 4 min before measurement.

4.3.2. Magnetic susceptibility

Magnetic susceptibility is used to identify mineralogical differences between visually homogeneous stratigraphic units. Changes in sediment magnetism can indicate a mechanical or chemical alteration in the process of grain deposition or sedimentation (Ghilardi et al., 2008). In archaeology, and particularly in the case of a tell where a significant portion of the deep stratigraphy is unknown, this method is highly useful (Rosendahl et al., 2014). The magnetic characteristics of sediments depend on the soil's history (Dearing et al., 1996): an anthropogenic or calcined layer may experience a modification of its magnetic field due to the increased temperature of its constituents (Djerrab A., 2002). The measurements were conducted using a Bartington MS2/MS2K dual frequency sensor (at low and high frequencies) every 2 cm, directly on both the cores and the core-catchers.

4.3.3. $CaCO_3$ content

The $CaCO_3$ content was measured using hydrochloric acid and a Bernard calcimeter (Fournier et al., 2012).

4.3.4. Micropalaeontological analyses

Sediment samples were collected from the last two meters of core Tell1. Foraminifera were isolated through wet sieving (between 500 and 63 μm) and collected using the trichloroethylene method (Murray, 2006). A dry splitter was used to divide the samples during counting (Emmanouilidis et al., 2020). It has to be noted that, due to the small number of samples, only a simple identification and count was

Fig. 2. Topography of the tell of Kirrha and location of the geophysical surveys (ARP and ERT), core samples and areas excavated since 1937. Isoline interval: 0.5 m.

performed.

4.4. Radiocarbon datings (Table 1)

Three charcoal and one wood samples taken from core Tell1 were dated using the AMS method. A previous sample ("T2, marine shell") obtained from the former coastal marsh east of the tell, initially published in 2011 (Kortekaas et al., 2011), was reused in this study. Tell1 samples were calibrated using the IntCal20 atmospheric curve, while T2 (marine shell) was recalibrated using the Delta_R 143 ± 41 and the MarineCal20 curve (Reimer et al., 2020). The calibrated results and their visual presentation were produced using the OxCal v.4.4 program.

5. Results

5.1. Geophysical survey

Four main zones (A, B, C, and D) (Fig. 3-**b**) were surveyed using ARP (Automated Resistivity Profiling). The apparent resistivity values show distinct patterns (Fig. 3-**a**): in the northern part of Zone A, the values at a depth of 0.5 m range between 80 and 182 Ohm.m, indicating a high density of shallow-depth remains. However, the values are very low (between 8 and 17 Ohm.m) in the eastern part of that same zone, corresponding to the edge of the former coastal marsh of Kirrha, which was primarily composed of fine-grained sediments (Chabrol et al., 2021, Kortekaas et al., 2011). It should also be noted that the apparent resistivity in this zone clearly increases from a depth of one meter and below, suggesting that at least part of the deepest levels of the tell may have been buried under fine alluvial sediments deposited by the Pleistos River.Analysis of Zone B reveals a concentration of strong resistivity values at very shallow depths. This is not surprising as the zone is located near the current excavations as well as those from 1937 to 1938.

Zone C is divided into two parts. The eastern part, with consistent resistivity values ranging between 80 and 182 Ohm.m and persisting at depth, also corresponds to the continuity of the remains discovered during the 1937–1938 excavations. The survey in the western part is less dense due to the presence of olive groves but shows some surface anomalies that tend to disappear with depth. It is likely that here, too, the remains have been covered by alluvial sediments.

Zone D, located in the southwest, strengthens this hypothesis: the very high surface values (>170 Ohm.m) delineate what appears to be a palaeochannel, which can be followed at least down to a depth of 1.70 m and extends for about 60 m in length.

The ERT 2D section (Fig. 3**b)** shows a series of low electrical resistivity values (2 to 5 Ohm.m) in its upper section, extending from east to west and corresponding to the prehistoric tell. These low values are believed to result from the porosity of the archaeological layers composed mainly of silts and clays, potentially originating from the prehistoric mud structures. This unit is between 7 and 9 m thick, which means that the lower levels of the tell are now below the current sea level, with the deepest archaeological layers estimated to be around 2 to 3 m below sea level. Close to the surface, the section shows several areas of higher resistivity values, ranging from 35 to 105 Ohm.m (no. 1 and 2, Fig. 3**b**), which could indicate the presence of massive ancient structures, lying just below the surface and already excavated during the 1937–38 excavations. To the west of the profile (no. 3, Fig. 3**b**), another area of high resistivity corresponds to a possible palaeochannel composed of pebbles aand gravels. This palaeochannel can again be identified further south (Zone D) in the apparent resistivity maps obtained from the ARP surveys (Fig. 3**a**).

By contrast, the resistivity values below the tell (10 to 35 Ohm.m) can be associated with sandy marine sediments. An attempt to correlate the cores with the ERT section clearly indicates that these values correspond to sandy sediments (Fig. 3**c**). The tell of Kirrha is located in a specific geomorphological setting, between Holocene marine transgression and more recent coastal progradation alluvial deposits.

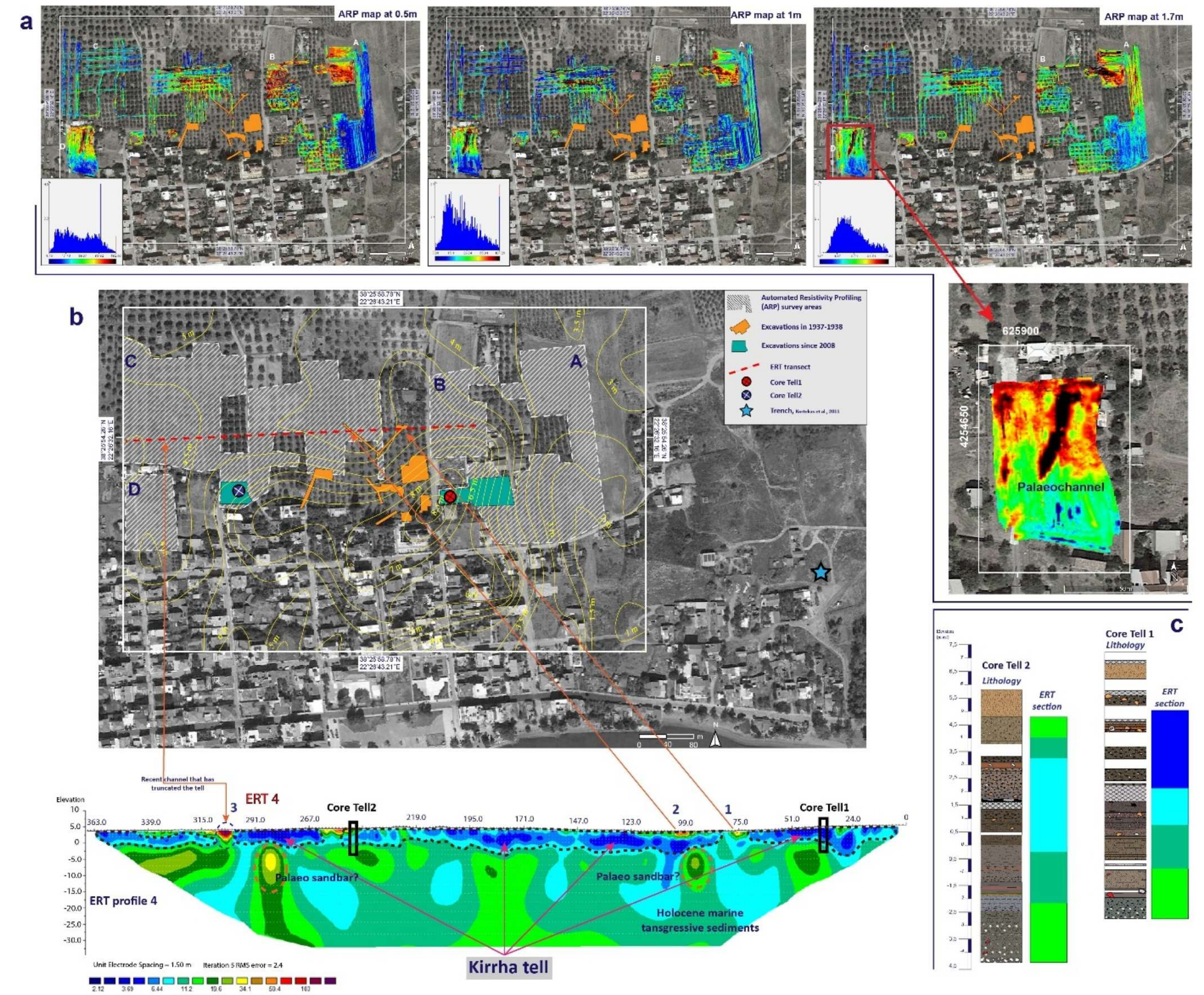

Fig. 3. a/ results of the ARP surveys (in Ohm.m) at three different depths: 0.5, 1 and 1.7 m. b/ results and interpretation of the ERT transect. c/ correlation between cores Tell1 and Tell2 and the ERT values.

5.2. Stratigraphic units identified in cores Tell1 and Tell2stratigraphy of the cores

Cores Tell1 and Tell2 reached depths of 2.7 m b.s.l. and 4.3 m b.s.l., respectively. Despite their different elevations, the drill cores exhibit significant stratigraphic similarities and both penetrated the archaeological layers.

Four main lithological units were recorded in both cores and called from bottom to topSU1, SU2, SU3 & SU4.

5.2.1. Stratigraphic unit 1 (SU1) (Fig. 4)

SU1 (between 2.7 and 2.5 m b.s.l. in Tell1 and between 4.3 and 3.3 m b.s.l. in Tell2) mainly consists of medium to coarse sands (74 %). Numerous marine shell fragments were found. The high $CaCO_3$ content (reaching>50 % in some samples) of this unit may be attributed to marine carbonates. The low magnetic susceptibility values could also be associated with these carbonate contents, although the general magnetic susceptibility of the alluvial deposits in the plain of Delphi is expected to be low due to the predominance of sedimentary rocks in the watershed (Valkaniotis, 2009). Within this unit, benthic foraminifera are primarily composed of infralittoral shallow marine and rich algal vegetation species, including *A. beccari*, *Elphidium* spp., *rotaliids* (*Rosalina* sp., *Nonions* sp.), and *miliolids* (*Quinqueloculina seminulum*). A few planktonic specimens have also been identified (Globigerinidae sp.). While two Neolithic pottery sherds were found at the base of Tell2, SU1 consists of a pre-tell unit that can be dated back to at least 3359–3097 Cal. BCE (^{14}C sample Ech1).

5.2.2. Stratigraphic unit 2 (SU2) (Fig. 4)

SU2 (between 1.9 and 1.6 m b.s.l. in Tell1 and between 2.5 and 1.45 m b.s.l. in Tell2) mainly consists of grey silty sediments with a minor proportion of fine-to-medium sand (25 %). No foraminifera were found within this unit. Plant remains were observed in Tell2. Some evidence of human influence is present, albeit diffuse: a fragment of Neolithic pottery in Tell1 and a few traces of burnt sediments in Tell2. The magnetic susceptibility values are slightly higher and more irregular than those in SU1. Contact between SU2 and SU3 occurred around 2816–2668 Cal. BCE (^{14}C sample Ech2).

5.2.3. Stratigraphic unit 3 (SU3) (Fig. 4)

SU3 (between 1.6 m b.s.l. and 0.25 m a.s.l. in Tell1 and between 1.45 m b.s.l. and 0.3 m a.s.l. in Tell2) mainly consists of light-brown silty

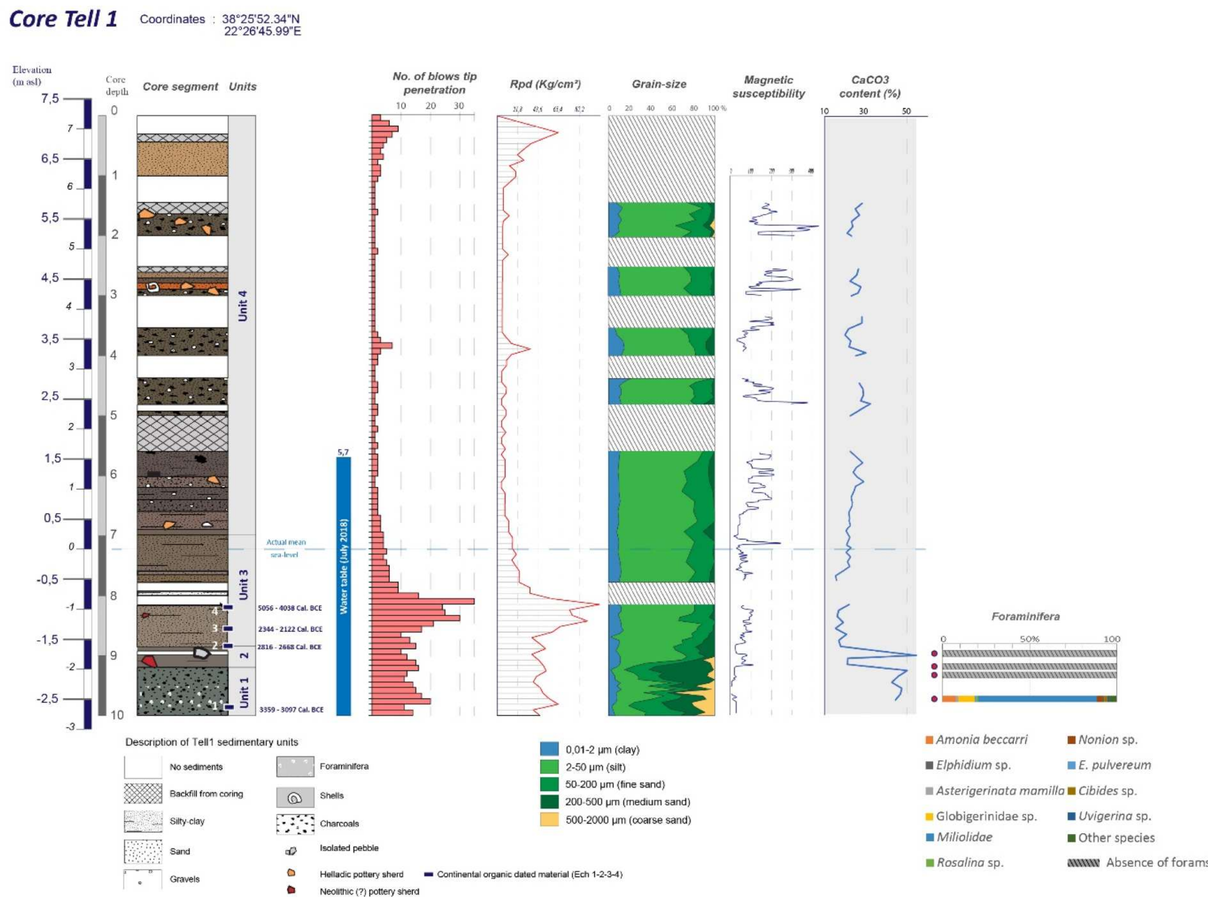

Fig. 4. Stratigraphical and sedimentological chart of core Tell1.

sediments with a small fraction of fine sand (20 %). The proportion of sand decreases from the base to the top of the unit. In both Tell1 and Tell2, evidence of human influence is present: fragments of neolithic ceramics, burnt sediments, and a large quantity of macro-charcoal. The magnetic susceptibility values are slightly higher than in SU2 and remain irregular. By contrast, the sediment's $CaCO_3$ content is lower than in previous units (around 20 %). One of the two obtained dates (2344–2122 Cal. BCE (sample Ech3) is chronologically consistent with the date obtained at the top of SU2. However, the other dated sample, despite being higher in the stratigraphy, resulted in an older date (5056–4038 Cal. BCE (sample Ech4)): further discussion regarding its validity is required (**see Discussion 6.1**).

5.2.4. *Stratigraphic unit 4 (SU4) (Fig. 4)*

SU4 (between 0.25 and 7.3 m a.s.l. in Tell1 and between 0.3 and 5.7 m a.s.l. in Tell2) corresponds to successive anthropogenic levels within the tell. The sediment grain size is highly consistent (10 % clay, 70 % silt, and 20 % fine sand), likely indicating collapsed structures that were originally constructed with mud bricks. The gaps in the stratigraphy are due to the porosity of the sediments, which were easily compacted during coring. The magnetic susceptibility values are higher than in previous units, but also very irregular, highlighting the significance of anthropogenic activity. SU4 contains numerous fragments of charcoal and Helladic ceramics, occasionally associated with gravel, isolated stones and burnt sediment.

6. Discussion

6.1. *Radiocarbon results and archaeological chronology*

The three samples *Ech1*, 2 & 3 provide highly accurate dates, with BP error margins of about thirty years. Their 2σ-calibration yields calendar ages with a range of 160 to 250 years (Table 1). Sample *Ech1* was collected in stratigraphic unit SU1, below the anthropogenic layers. Samples *Ech2*, *Ech3* and *Ech4* were all taken within the anthropogenic layers: they are framed by pottery sherds and the grain size is consistent with that of the upper levels (Fig. 4). According to the Early Helladic Mainland chronology of Cavanagh, Mee & Renards (based on the tell of Kouphovouno) (Cavanagh et al., 2016), and knowing that the dated samples are not strictly related to any archaeological artifacts due to the drilling method used, the deepest layers of the tell would thus correspond to a settlement of the Early Helladic 2 period (Fig. 5). This observation is consistent with the admittedly inaccurate description of the stratigraphy of the site by the French excavation team in the 1930s (Dor et al., 1960). In contrast, sample *Ech4* stands out from the others: its dating is much older (5056–4038 Cal. BCE, Late Neolithic I & II to Final Neolithic). While some archaeological indicators (such as very isolated pottery fragments) found during the excavations suggest a probable Neolithic occupation (Orgeolet et al., 2017), sample *Ech4* does not allow us to formally address this question. Its stratigraphic position above the others (Fig. 4**; 5**) does not exclude the possibility of reworked sediments, very common in Mediterranean coastal alluvial plains (O'Donnell et al., 2020; Carroll et al., 2012). Likewise, the uncertainty of almost 1000 years in the calendrical age of this sample does not allow us to draw reliable archaeological outcomes.

6.2. *General palaeoenvironmental reconstitution of the tell of Kirrha*

In order to attempt an initial description of the major stages of the formation of the Tell of Kirrha, it is necessary to consider its specific geomorphological setting, at the interface between a deltaic plain and the coastline.

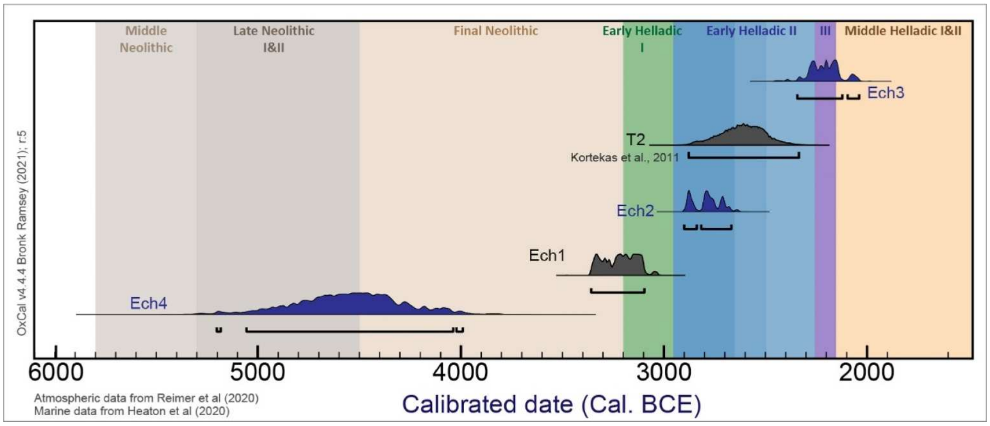

Fig. 5. Chronocultural attribution of the radiocarbon dates published in this paper, according to Cavanagh et al., 2016 for the Early Helladic chronology. Blue-coloured samples (Ech2, Ech3 and Ech4) were collected within anthropogenic layers of the tell. Ech1 was collected in SU1 under the tell (Fig. 4) and T2, 350 m west from the tell (Fig. 1; 2).

ERT section and sedimentological evidence indicate that the deepest archaeological levels of the tell are found up to approximately 2 to 3 m below sea level. Taking into account the current topography, this results in a maximum archaeological occupation thickness of 7 to 9 m. The pre-tell levels are mainly composed of sands with the presence of foraminifera (between 11.2 and 19.6 Ohm.m in the ERT section): marine species associated with algal species (*miliolids*). Around 3359–3097 Cal. BCE (Final Neolithic/Early Helladic 1 transition), the Kirrha area consisted of shallow marine environments with low hydrodynamics. This part of the gulf could have been protected from the waves by a barrier beach, creating vast areas of shallow marine water that would be progressively filled in by alluvial deposits and deltaic progradation. Settlements near lagoonal environments were common during the Neolithic and Bronze Age in Eastern Mediterranean (Fontana et al., 2017) and this type of environment is often found in the Greek deltaic plains during Bronze Age (Emmanouilidis et al., 2020; Pavlopoulos et al., 2006; Brückner et al., 2005).

Between 3359 and 3097 Cal. BCE and 2816–2668 Cal. BCE (Early Helladic II), changes took place in the surroundings, presumably associated with coastal progradation. Marine sediments were replaced by

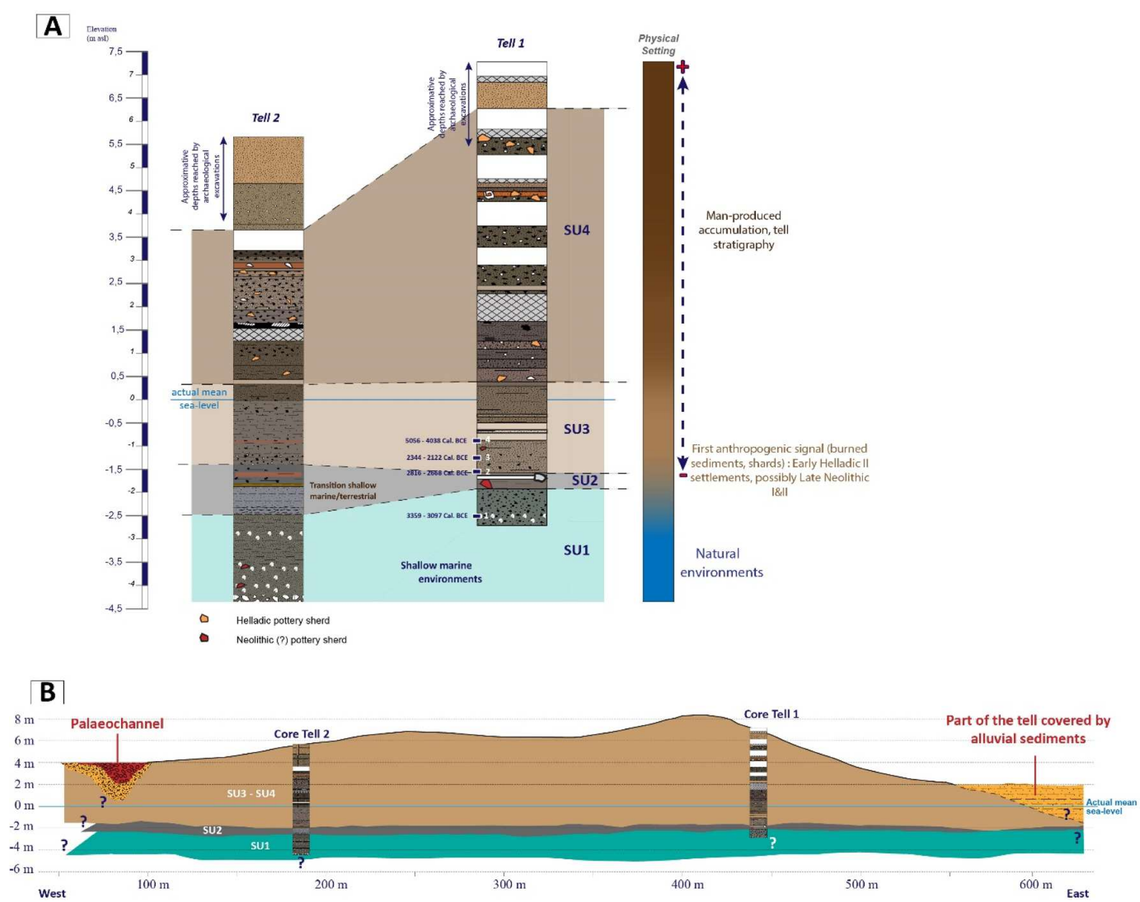

Fig. 6. A/ Stratigraphic correlation attempt between Tell1 and Tell2. B/ Transect along the axis of cores Tell1 and Tell2 taking into account sedimentary and geophysical results (both ARP and ERT).

terrigenous sediments (no longer containing foraminifera), and the grain size indicates less energetic depositional dynamics (between 10 and 11.2 Ohm.m in the ERT section). In the context of deltaic progradation, the early inhabitants of the site (initial, diffuse traces of anthropogenic activity were found) likely settled in a coastal marsh environment that gradually filled up with fine alluvial deposits from the Pleistos River. These wetlands, rich of biodiversity, were probably able to provide the natural resources needed for an initial permanent settlement. The essential supply in freshwater could have come from the outflow or underflow of the Pleistos, whose exact course during the Bronze Age is still unknown. It could also have come from the (now saline) spring at the foot of Mount Paloukaki, 300 m to the east of the tell: of karstic origin (Burdon et al., 1963), the salt water is the result of a mixture of fresh and sea water that could be related to the Holocene sea-level rise (Arfib et al., 2004; 2006). In the Bronze Age, when the sea level was around 3 to 4 m lower (Lambeck and Purcell, 2005), water from this spring could potentially still have been drinkable.

From 2344 to 2122 Cal. BCE (Early Helladic II and III) until the end of the prehistoric occupation (Late Helladic I), sedimentation became anthropogenic, and the tell of Kirrha expanded. The porosity of these anthropogenic layers is attested by the light SCPT values and low ERT values between 2 and 10 Ohm.m). Due to the absence of radiocarbon dating and considering the inaccessibility of the deepest archaeological levels, it is not possible to specify the rates of the tell's evolution between the current sea level and the maximum depth reached by archaeological excavations (approximatively 2 m) (Fig. 6). However, archaeological excavations have shown that the site was abandoned during the Late Helladic I period (Orgeolet et al., 2017).

6.3. *A coastal marsh around the site during the Bronze Age?*

The question of the nature of the environment in which the first inhabitants of Kirrha settled is still open. While stratigraphic unit SU1 appears to correspond to a shallow marine environment, first evidence of occupation is found mainly from SU2 unit onwards (from 2 m b.s.l). This unit corresponds to a transitional shallow marine/terrestrial environment. A trench excavated in the early 2000 s to the east of the Kirrha site (Fig. 1**; 2**) allowed for the characterisation and dating of a coastal marsh during the Early Helladic 1 (Kortekaas et al., 2011). Although the sample dated by Kortekaas et al. (recalibrated in this study with the MarineCal20 calibration curve (Heaton et al., 2020)) is slightly higher topographically, the date corresponds to that of the beginning of the occupation of the tell in core Tell1 (Table 1**;** Fig. 4**; 5**). The remains of this coastal marsh are still visible today to the east of the site (Fig. 1) (Chabrol et al., 2020). Similar marshy sediments have also been discovered around the same depths during two separate drilling missions to the north and west of the tell (Chabrol et al., 2014, 2016).

6.4. *Preservation of the tell of Kirrha*

Tells, like all archaeological sites, are subject to the inevitable processes of erosion and sedimentation (Davidson, 1976). These processes can be natural or man-made (Tarolli et al., 2016), and can occur long after the site has been abandoned. They have a major influence on our understanding of these structures: a large part of the site may have been eroded forever or buried deep beneath the sediment (Forti et al., 2023). The tell of Kirrha is no exception. The ERT data associated with the cores indicate an average thickness of the archaeological layers of between 7 and 9 m. To the west of the tell, the ARP data (zone D) revealed the existence of a palaeochannel around 20 m wide (Fig. 3**a**). This palaeochannel can also be seen as a cross-section in the ERT section (values between 35 and 120 Ohm.m), at a depth of around 3.5 m (Fig. 3**b**). It has clearly eroded part of the archaeological layers and would therefore post-date the Bronze Age (Fig. 6**b**). It could be an ancient natural course of the Pleistos dating from before its channelisation in the second half of the 19th century (Zurbach et al., 2012). The 1840 cartographic documents of the traveller Ulrich clearly indicate that the downstream course of the Pleistos passed to the west of the modern village of Kirrha, and thus of the tell (Ulrich, 1840) (Fig. 1**B**).

To the east of the tell, on the other hand, ARP data (Zone A) revealed very low surface resistivity values (between 8 and 20 Ohm.m). These values increase with depth, suggesting that remains are buried under sediment (Fig. 6**b**). This eastern part of the plain, that of a former coastal marsh, is composed of fine-grained Pleistos sediments that were progressively deposited in a context of deltaic progradation. An unknown proportion of the eastern part of the Tell of Kirrha could therefore lie beneath these deltaic sediments. The upper topographic levels of the tell have been preserved from alluvial dynamics but have inevitably been heavily eroded by the construction and development of the modern village of Kirrha: roads, housing, drains, etc.

6.5. *Contribution of the method*

Since the deepest layers of tells are difficult to access, boreholes are a very effective addition to archaeological excavations. In Greece, this approach has often been used successfully, whether in Macedonia (Niebieszczański et al., 2019; Lespez et al., 2013; Darcque et al., 2011), Thrace (Ammerman et al., 2008), Euboea (Davidson et al., 2010) or in the Peloponnese (Mee and Cavanagh, 2014). The main difficulty in coring a Bronze Age tell is to be lucky enough to get through all the archaeological layers without encountering obstacles that would stop the drill. In our case, the high density of limestone blocks, pebbles and graves posed a major risk. Sediment compaction is the second problem with this method. Given the great variety of archaeological layers (clayey, sandy, burned levels, etc.), it is difficult to quantify this compaction accurately and thus reconstruct a continuous and clear archaeological stratigraphy.

7. Conclusion

The geoarchaeological investigation of the tell of Kirrha offers new insights into the history of the site and its environment. It demonstrates the advantages of combining geophysical surveys, penetrometer and percussion drilling to investigate the lowest layers of the site, which cannot be excavated. This study has addressed two main questions: the stratigraphy of the archaeological site, including the lower levels that cannot be reached during archaeological excavations, and the date of its earliest occupations. Indeed, the stratigraphy of the archaeological layers of the site was confirmed to be between 9 and 11 m. The geophysical study also revealed that certain levels of the tell have been eroded by palaeochannels or buried under sediments from the Pleistos River.

The natural environment before the first occupation was a calm and shallow marine environment, at least until 3359–3097 Cal. BCE. The radiocarbon dates of the deepest archaeological layers (SU2) suggest a first occupation at the beginning of Early Helladic II at this place (we must bear in mind that these results were obtained from only one drill core: we cannot exclude the possibility that other areas of the site deviate from the pattern observed here). The question of an earlier Neolithic occupation, perhaps elsewhere on the tell, remains open. It seems that the first inhabitants of the site settled in a marshy coastal environment: this raises questions about the nature of the settlement and opens up new regional discussions about the links between Early Helladic settlements and coastal environments. Altogether, the success and replicability of this approach may support similar initiatives for other prehistoric coastal tells.

CRediT authorship contribution statement

Antoine Chabrol: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Tara Beuzen-Waller:** Investigation, Writing –

review & editing, Funding acquisition. **Clément Virmoux:** Writing – review & editing. **Delphine Chavand:** Investigation. **Eric Fouache:** Writing – review & editing. **Raphael Orgeolet:** Investigation, Writing – review & editing, Supervision, Funding acquisition, Project administration.

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.

Data availability

Data will be made available on request.

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