Geoarchaeology of Ancient Aulis (Boeotia, Central Greece): human occupation and Holocene landscape changes

Matthieu Ghilardi, Maxime Colleu, Kosmas Pavlopoulos, Sylvain Fachard, David Psmiadis, Pierre Rochette, François Demory, Alex Knodell, Maria Triantaphyllou, Doriane Delanghe-Sabatier, Andrew Bicket, Jules Fleury

a CEREGE, UMR 7330, CNRS, Europôle de l’Arbois, BP 80, 13545 Aix-en-Provence, Cedex 04, France
b University of Paris 1 Sorbonne, Histoire de l’Art et de l’Archéologie, 3 Rue Michelet, 75006 Paris, France
c Harokopeio University of Athens, Department of Geography, Eleftherios Venizelou Street 70, 176-71 Kallithea, Athens, Greece
d Harvard University, Center for Hellenic Studies, 3100 Whitehaven Street, Washington, DC 20008, USA
e University of Aix-Marseille/AMU, France
f Joukowsky Institute for Archaeology and the Ancient World, Brown University, Box 1837, 60 George Street, Providence, RI 02912, USA
g University of Athens, Faculty of Geology and Geoenvironment, Department of Historical Geology – Paleontology, Panepistimiopolis 15784, Athens, Greece
h Wessex Archaeology, Coastal and Marine, 7/9 North Saint David Street, Edinburgh EH2 1AW, Scotland, United Kingdom

A R T I C L E   I N F O

Article info
Article history:
Received 18 May 2012
Received in revised form 4 December 2012
Accepted 9 December 2012

Keywords:
Paleoenvironmental reconstruction
Borehole study
Geoarchaeology
Shoreline migration
Recent Holocene
Aulis
Boeotia
Euboean Gulf
Greece
Mycenaean period

A B S T R A C T

This article presents the results of a coring operation which brought to light new evidence for the evolution of the coastal plain of Aulis (Boeotia, Central Greece) in the Holocene. Thanks to Homer, Aulis is best known as the gathering point of the Achaean fleet before it sailed to Troy and a sanctuary of the goddess Artemis. Ancient sources and archaeological evidence suggest the presence of an ancient marine bay, potentially used as a harbor. In the course of investigation, we drilled two cores, to a maximum depth of 4.20 m in the marshy lowlands and performed mollusc and micro-paleontological identifications, laser grain size analyses, and magnetic susceptibility measurements in order to reveal the facies evolution of the area. We obtained a chronostatigraphy sequence through a series of seven AMS 14C radiocarbon dates. Our study shows that the area was affected by a shallow marine incursion from the first half of the 6th millennium BC and gradually turned into a succession of shallow marine/lagoon environments from ca. 5000 cal. BC to the 2nd Century AD, and into a confined lagoon environment during the Roman and Byzantine periods.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Ancient Aulis is located in southeastern Boeotia, Central Greece (Fig. 1), on the gulf that separates the Greek mainland from Euboea, the second largest island in the Aegean Sea (ca. 3685 km²). The sanctuary of Artemis at Aulis is located on the margin of a small coastal plain ca. 200 m long and 50–100 m wide, and situated at a distance of 300 m from the modern shoreline (Fig. 3). From a geological point of view, this corresponds to a semi-graben, with a NNE–SSW direction, in-filled by red clays (Terra Rossa) and limited on the sides by fault scars composed of dolomitic limestone. During the Holocene, it is obvious that the rapid sea level rise since the Last Glacial Maximum strongly modified the coastline position and the landscape configuration in the study area, this has been also well established in different coastal plains of the Aegean Sea (Kambouroglou, 1989; Lykousis et al., 2005; Pavlopoulos et al., 2010). The study of Holocene shoreline migration within an archaeological context has been the subject of research in the North Aegean (Kraft et al., 1977; Ghilardi et al., 2008a, 2008b, 2010, 2012; Syrides et al., 2009; Vouvalidis et al., 2010), the Cyclades (Evelpidou et al., 2010; Pavlopoulos et al., 2010) and Attica (Pavlopoulos et al., 2006; Triantaphyllou et al., 2003, 2010). However, little research has been conducted in the southern Euboean Gulf (Notios Evoikos), where many archaeological sites are located close to the modern shoreline. The ancient city of Eretria has been investigated more thoroughly, suggesting that an
important shoreline migration occurred in the area over the last six millennia (Kambouroglou, 1989). The first mention of ancient Aulis is found in Homer’s Iliad (2.303), when the bay served as the gathering place of the Achaean ships before they sailed off to Troy. From an environmental perspective, it is noteworthy that wetlands were among the favorite sacred landscapes for sanctuaries of Artemis, often located in marshy coastlands, as was the case in Amarynthos and in Brauron (Cole, 2000; Triantaphyllou et al., 2010), both also situated on the Euboean Gulf.

As part of a larger regional study, a campaign of coring was undertaken in March 2011 between the Artemis Temple and the modern seashore. The goal was to study the evolution and the extent of the bay in the long term, especially how such geomorphological change related to the archaeological remains known in the valley and its immediate surroundings.

2. Geological, tectonic and present day geomorphology settings

The wider region consists of geological formations of the Pela-
gonian zone, mainly Triassic thick-beded limestones and dolo-
mites and Jurassic strongly tectonized limestones and sandstones (Mavrides, 2006). The Eohellenic tectonic nappe is apparent with ultrabasic rock masses, ophiolites, serpentinized peridotites, volcano-sedimentary formations and some limestones with Fe–Ni pisolitic ore deposits. A large area is also covered by Neogene formations, consisting of lacustrine deposits of Upper Miocene origin such as marls, sandstones and conglomerates, brackish deposits of the Lower Pleistocene and clastic deposits of the Middle–Upper Pleistocene covering a large part of the studied area (Fig. 2). In the region of Avlida (the area surrounding the ancient

Fig. 1. Location map of the different sites mentioned in the text.
site of Aulis), the Pleistocene and Holocene deposits (mostly Terra rossa red clays) are overlying Triassic limestones and dolomites (Fig. 3). From a geomorphological point of view, the landscape processes are imprinted by important colluvial activity and the absence of any permanent hydrological network. Studies of sediments scattered in the Euboean Gulf have shown that the fine-grained deposits are affected by tidal currents and distributed throughout the area, while the relatively coarse-grained sediments are related to deltaic progradation in historical times, linked to the rivers Megalo Rema and Lilas (Poulos et al., 2001; Fig. 2). Tidal range at the Euripus, the narrowest point in the Euboean Gulf, has been accurately measured for the last fifty years and shows a maximum amplitude in North Chalkis of 0.56 m with an error of ±0.05 m (Tsimplis and Blackman, 1997; Cundy et al., 2000). Some authors consider it to be the largest tide recorded along the Greek Aegean coastline (Tsimplis and Blackman, 1997). However, Tsimplis (1997)
records a distinction between North Chalkis where daily tide is around 0.5 m, and South Chalkis where values are closer to 0.2 m.

The northern Euboean Gulf is characterized by pronounced faulting tectonics, associated with powerful destructive earthquakes (Philip, 1974; Ambraseys and Jackson, 1990; Pirazzoli et al., 1999; Goldsworthy and Jackson, 2001). Conversely, the gulf’s central and southern parts are considered areas of mild tectonic activity and therefore of moderate seismicity (Drakopoulos et al., 1984, Fig. 2). The main faults that affect the Preneogene and recent geological formations of the study area are normal, oriented WNW–ESE to NW–SE. There are two anticlinitic normal faults with a WNW–ESE direction outcrop in the Avlida region (Fig. 2) and in the plain of the Lilas river, on the opposite side of the gulf (Rondoyanni et al., 2007). The Aulis fault, which has a northeastern dip, affects the Neogene deposits, as well as the Pleistocene, inducing subsidence effects in the coastal areas. This fault continues offshore, as detected in recent sediments by seismic reflection profiles (Perisoratis and van Andel, 1991). Its total length is more than 20 km, and it forms the southern margin of the Euboean Gulf. Considering the thickness of the syn-rift Holocene and upper Pleistocene sediments in offshore seismic reflection profiles (Perisoratis and van Andel, 1991), an average value of the slip rate in the order of 1 mm/yr for the last 150,000 years can be estimated. This slip rate is smaller than that of the faults delimiting the graben of the north Euboean Gulf, which is in the order of 3 mm/yr (Philip, 1974). In the central Euboean Gulf region, there are a number of active faults of moderate seismicity. In some rocky coastal cliffs in the study area, several researchers have detected uplifted Lithophauros burrows (Stiros et al., 1992; Smith, 1994).

3. Historical background and previous archaeological investigations

Aulis appears in the very earliest Greek literature and occupies an important place in myth and legend. It is first mentioned by Homer (Iliad 2.303) as the gathering place of the Greek ships bound for Troy. From an archaeological and geographical perspective, this was considered problematic, even in antiquity, due to the rather small size of the natural harbor (Strabo, Geography, 9.2.8). Yet the attribution of the current place name can be traced at least as far back as the 5th century BC, when the temple of Artemis was built there (Fig. 3). We can also be reasonably certain that this is the location discussed in the earliest Greek written sources, based on the topographical descriptions of Homer and Hesiod. This article is not concerned with questions of the historicity of the Trojan War, but we do aim to address whether this would have been a suitable port in the Late Bronze Age, and we argue that this location was a port of the Mycenaean palatial center at Thebes.

Homer has at least potential relevance in describing the use of this site as a major port on the Euboean Gulf. Aulis also evoked the Greek expedition against Troy for the poet Hesiod, who took a ferry from this port to Chalkis during his own time, in the 8th or 7th century BC (Works and Days, 651–653). In the second century AD, Pausanias visited its Sanctuary of Artemis (Description of Greece, 9.19.6–8). He recalls the well-known story that the Greek ships gathered in Aulis before sailing to Troy, blocked by contrary winds brought on by Artemis, hence the location and dedication of the temple.

This legendary fame naturally attracted early European travelers (e.g., Leake, 1835), whose accounts were compiled in full and studied by Bakhuisen (1970). The temple was discovered in 1941, and systematic excavations took place between 1956 and 1961 under the Greek archaeologist Threpsiadis, on behalf of the Archaeological Society at Athens (Threpsiadis, 1956, 1958, 1959, 1960, 1961; Fossey, 1988; Farinetti, 2011). He uncovered the 5th century BC temple of Artemis Aulideia, as well as other buildings, including two pottery workshops, with a kiln, and a possible hotel. Near the temple, Threpsiadis also discovered an apsidal building of possible late Geometric date (8th century BC). The ancient road leading to the harbor to the north was unearthed, and some buildings were excavated there as well.

Prehistoric occupation of the small valley dates to the Late Helladic period (ca. 1550–1050 BC). A long wall of Late Helladic date, running north–south, was dug east of the temple (Threpsiadis, 1959). According to Hope Simpson (1981), traces of a Mycenaean settlement were observed nearby, some 50 m north of the chapel of Agia Paraskevi. A settlement is also suggested by the presence of a Mycenaean cemetery to the north of the bay of Mikro Vathi. Mycenaean chamber tombs were discovered there in 1928 along with two others in 1954 (Threpsiadis, 1956, 1960).

More Mycenaean remains were found near the chapel of Aghios Nikolaos, southwest of the sanctuary, in both trial trenches and on the surface (Papadakis, 1911, 1915). The nature of this site is unclear, but seems to be related to the settlement at Aulis. Both sites suggest that Mycenaean Aulis had two natural harbors, although the larger Megalo Vathi might have been subject to flooding. This is also the large port that Strabo calls Vathi Limen, in contrast with the smaller port of “rocky” Aulis, which could only hold 50 ships (Strabo, Geography, 9.2.8).

Mycenaean Aulis must have had close ties with the larger site located north of the modern village of Paralia Avlidos (previously Dramesi, Fig. 2, Bakhuisen, 1970), as well as Glypha, which also had a substantial Late Helladic occupation.

In the Mycenaean period, the bays of Aulis were part of the kingdom of Thebes (Sergent, 1994; Godart and Sacconi, 1999; Aravantinos et al., 2001; Latacz, 2004). Aulis itself would have been one of the harbors, if not the main harbor of the city. Aulis was among the closest possible outlets to the sea for Thebes, and was undoubtedly the easiest to reach for carter ships. The extent of Thebes’ power and the significance of Aulis as the starting point of the Homeric expedition likely resulted in Boeotia being the starting point of Homer’s catalog of ships, and brought Aulis privileged status throughout antiquity. This bay was an important port from the Mycenaean period onward, and the degree of its significance will be better understood through a study of its extent and landscape history.

Little is known about Mycenaean harbors, as no physical remains of port installations (quay walls, docks, moles, etc.) have been excavated and dated. They are not necessarily to be found, as “harbors” need not be built and can function in natural settings, as ships could be simply pulled on the shore. It would have been an obvious choice for any polity seeking a maritime outlet, and is especially relevant to Thebes as the closest harbor along natural land routes. Moreover, the secondary center of Eleon, known from Linear B tablets found at Thebes (Aravantinos et al., 2001), was strategically located along this route between Thebes and Aulis.

4. Methods for reconstructing the paleoenvironment

Two boreholes were drilled between the Artemis Temple and the seashore (Fig. 3, Table 1). Artemis A is 3.20 m deep, and Artemis

<table>
<thead>
<tr>
<th>Core id</th>
<th>Depth (m)</th>
<th>Latitude (WGS 84 UTM 34)</th>
<th>Longitude (WGS 84 UTM 34)</th>
<th>Absolute elevation in m (HMGS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artemis A</td>
<td>3.20</td>
<td>38°26′03.3″</td>
<td>23°35′37.5″</td>
<td>+0.25 m</td>
</tr>
<tr>
<td>Artemis B</td>
<td>4.20</td>
<td>38°26′04.7″</td>
<td>23°35′37.5″</td>
<td>+0.15 m</td>
</tr>
</tbody>
</table>
B 4.20 m. Sampling on both cores was conducted at 5 cm intervals at the Laboratory of Geomorphology of the Harokopio University in Athens. These samples were also used for microfaunal (ostracods/forams) identification at the Kapodistrian University in Athens. Finally, samples were also exported to France for macrofaunal and sedimentological/magnetic analyses at the CEREGE laboratory (Aix-en-Provence).

4.1. Mollusc/foraminifera identifications and AMS dating

All samples were wet-sieved through a wire screen (0.40 mm mesh) and air dried at room temperature. The residue was examined under a binocular microscope and all identifiable shells and characteristic fragments were picked and curated in separate plastic tubes. In addition, paleontological determinations were made on Artemis A (foraminifera) at a general and specific level. 25 samples have been processed for foraminiferal analysis and each core sample (10 g dry weight) was treated with H₂O₂, wet-sieved over a 0.063 mm sieve, and dried at 70 °C. A subset containing at least 300 benthic foraminifera for each sample was obtained using an Otto microsplitter, when possible; otherwise the whole sample was studied when the number of specimens was less than 300. The relative abundances (in percentage) of benthic foraminiferal assemblages were also calculated.

The chronostatigraphy of the cores was determined using a series of seven AMS radiocarbon determinations derived from in situ shells and peat samples (Table 1). These analyses were performed at the Poznan Laboratory for Radiocarbon (Poland) and at the Beta Analytic Laboratory for Radiocarbon dating (Miami, Florida, USA). Marine samples were corrected for the marine reservoir effect according to Siani et al. (2000) and Reimer and McCormac (2002), although it must be emphasized that the real (paleo) reservoir effect—still unknown—varies widely in different marine environments such as lagoons, coastal swamps or littoral zones (Vött, 2007). 14C ages were subsequently calibrated using the Calib6.0 Software (Reimer et al., 2009).

4.2. Magnetic susceptibility measurements

Magnetic susceptibility measurements were performed using the MFK1 magnetic susceptibility meter (Agico) of CEREGE (Aix en Provence, France). The sediment cores were sampled (at ~5 cm resolution, except in levels including reworked material) yielding 70 samples in total. These samples were placed in 10 cm³ plastic boxes, dried and weighed. In addition to the low-field magnetic susceptibility, usually measured at 976 Hz frequency, measurements were taken at 15 616 Hz frequency. The sensitivity of the MFK1 susceptibility meter is of ~3 × 10⁻⁸ SI at 976 Hz.

The magnetic susceptibility values were divided by the density of the dried samples in order to derive specific susceptibilities (χ). The contribution of superparamagnetic particles (<0.03 μm; Dearing et al., 1996) is given by the frequency dependent susceptibility (χfd) where χf and χd are the specific susceptibilities measured at low and high frequencies, respectively.

Coarse magnetic particles were extracted using a magnet from two samples responsible for spikes in the magnetic susceptibility profile. Both magnetic extracts were subjected to low-field magnetic susceptibility measurement versus temperature under argon atmosphere using the furnace apparatus CS3 of the susceptibility meter MFK1. Bulk chemical analyses were made using a Micro X-Ray Fluorescence (XRF) microscope (Horiba XGT-5000 at CEREGE, accelerating voltage 30 kV). A selection of grains was mounted in epoxy to obtain polished section for scanning electron microscopy. Chemical analyses were performed in the Scanning Electron Microscope (SEM) using Energy Dispersive Spectrometry (EDS).

4.3. LASER grain-size analyses

Grain size determinations were conducted at CEREGE. Many displayed significant organic matter content (Figs. 4 and 5). Organic matter is often removed in laser-diffraction particle size studies. These pre-treatments for grain-size analysis frequently use oxidative treatments (Fullen et al., 1996; Buurman et al., 1996; Blott et al., 2004; Scott-Jackson and Walkington, 2005; Wang et al., 2006). However, the addition of such solutions does not completely remove organics and presents bias possibly affecting mineral phases with, for example, mica destruction or manganese oxides decomposition (Mikutta et al., 2005; Gray et al., 2010). All of the samples of this study were first heated at 450 °C during two hours and mixed with a dispersing agent (0.3% sodium hexametaphosphate) in order to disperse the clay particles. The grain-size distribution was measured using a Beckman Coulter LS 13 320 laser granulometer with a range of 0.04–2000 microns, in 132 fractions. The calculation model (software version 5.01) uses Fraunhöfer and Mie theory. For the calculation model, we used water as the medium (RI = 1.33 at 20 °C), a refractive index in the range of that of kaolinite for the solid phase (RI = 1.56), and absorption coefficients of 0.15 for the 780-nm laser wavelength and 0.2 for the polarized wavelengths (Buurman et al., 1996).

Samples containing fine particles were diluted, so that we measured between 8 and 12% of obscuration and between 45 and 70% PIDS (Polarization Intensity Differential Scattering) obscuration.

5. Results

5.1. General stratigraphy

Facies identification of the two boreholes Artemis A and Artemis B provided well-distinguished lithostratigraphical sequences and allowed us to distinguish nine bio-sedimentary units, which can be described as follows (Figs. 4 and 5):

In the lowest part of Artemis A (Fig. 4), from 3.20 to 2.95 m in depth, unit P is composed of a mixture of reddish clays and angular fragments of gray limestone. The magnetic susceptibility measurements provide signals oscillating from 13 to 80 × 10⁻⁸ m² kg⁻¹ and the mean grain size (for the fraction below 2 mm) is characterized by fine sands and silts, decreasing in size toward the top of the sequence. It is important to note that the sedimentary unit P is not present in Artemis B and was deposited under continental conditions, probably as colluvial debris (multi-modal distribution with peaks in fine -clays- and coarse -medium sands- particles). According to the radiocarbon dates from the overlaying sequence (~5200–4800 cal. BC), it is clear that this level reaches the pre-transgressive sub surface, dated from Early Holocene.

Above this continental environment of deposition (Unit P), the second bio-sedimentary unit (TS) is composed of grayish silty clays and is found in both boreholes, from 2.95 to 2.60 m in depth for Artemis A and from 4.20 to 3.80 m for Artemis B. Mollusc identification revealed a few recognizable shells, which mainly belong to the lagoonal mollusc assemblage (Cerastoderma glaucum, Abra segmentum, Loripes lacteus, Cerithium vulgatum) with juvenile Bitium reticulatum and Rissoa ventricosa gastropods. This is characteristic of a hard and sandy substrate macrofauna assemblage (Ghilardi et al., 2010). Foraminiferal identification for core Artemis B reveals the prevalence of closed lagoon assemblage where Ammonia tepida (small) and Humesina germanica are abundant, with respectively 50% and 8% of the total of the specimens found in situ. Forams from open lagoon assemblages are less represented: Milolids are comprised between 10 and 20% of the total of the specimens. The magnetic susceptibility signal is very low and
Fig. 4. Artemis A core profile with macrofauna and paleontological identifications and LASER grain-size analyses. Radiocarbon dates are expressed in calibrated ages.

Fig. 5. Artemis B core profile with macrofauna results and LASER grain-size analyses. Radiocarbon dates are expressed in calibrated ages.
values are around $5 \times 10^{-8}$ m$^3$ kg$^{-1}$. $^{14}$C dates from in situ lagoonal shells (Table 2) situated in the lower part of the unit reveal an age between $\sim 5200$–$4800$ cal. BC (Artemis A) and $\sim 5000$–$4700$ cal. BC (Artemis B). Based on the dates and bio-sedimentary characteristics, we consider this unit to be transgressive, and it must correspond to a confined environment of deposition (lagoon) with a gradual development toward the southwest.

The third bio-sedimentary unit (SM1) is about 0.20 m thick and is recorded along both cores, from 2.40 to 2.60 m deep for Artemis A and from 3.60 to 3.80 m for Artemis B. Mollusc identification highlights the important presence of full marine gastropods such as *B. reticulatum*, *Nassarius reticulatus*, *Tricolia speciosa*, *R. ventricosa*, *Conus mediterraneus* and *Gibbula* sp. There is an increase of shallow marine to open lagoon foraminifera assemblages where Miliolids are very abundant (almost 60% of the total of the counted specimens) and a strong decrease in the representation of closed lagoon foraminifera assemblage: *H. germanica* specimens are not found and we have less than 20–35% of *A. tepida* of the total amount. Textural class corresponds to fine material, ranging from silts (20 $\mu$m) to very fine sands (70–80 $\mu$m for the mean grain size). Bio-sedimentary unit SM1 is characteristic of shallow marine environments but its paleo-depth must not have exceeded 1–2 m since alteration of the marine status to lagoon can be observed at the top of the sequence (presence of bivalves and of gastropods from the lagoonal assemblage). Due to the lack of additional radiocarbon dates for this layer (SM1), providing an accurate age is difficult, but according to the existing dates, it can be reasonably placed between 3000 and 2000 cal. BC.

The fourth unit (L1) is overlaying SM1 and is 0.15–0.30 m thick. This layer is poor in terms of mollusk; and gastropods such as *C. vulgatum* and bivalves such as *C. glaucum* and *L. lacteus* are the most abundant specimens. There is also a contrast in foraminifera composition from the bottom to the top of the bio-sedimentary unit. Indeed, the foraminifera assemblage indicates a closed lagoon assemblage in the uppermost part of the sequence where *H. germanica* is an abundant specimen (almost 8% of the total amount); this specimen is lacking at the bottom where a radiocarbon date in core Artemis A provides an age of 1747–1434 cal. BC. In addition, Miliolids are poorly represented along the sequence with a strong decrease close to the top, with less than 20% of the total amount of foramin specimens. It is evident that unit L1 is characteristic of a lagoonal environment where we observe an abrupt change toward the upper part of the sequence, with transition from an open to a closed lagoon. Recent literature (Pavlopoulos et al., 2006; Triantaphyllou et al., 2010; Koukousioura et al., 2012) indicates that, ca. 1500 cal. BC, some open lagoons from Central Greece (in the coastal area of Marathon) turned into closed lagoons. It seems that we observe a similar phenomenon in the bay of Aulis during this period.

The fifth unit (SM2) is about 0.20–0.25 m thick and is directly overlaying closed lagoon environments of unit L2. A marine shells assemblage was recognized with abundant representation of *B. reticulatum* and *R. ventricosa*, which belongs to the subtidal sands and hard substrate molluscan assemblage (Marriner et al., 2008). Some forams from the closed lagoonal assemblage, such as *H. germanica*, are missing. Mean grain-size is about 40–60 $\mu$m and indicates a calm environment of deposition. The age range of unit SM2 is from ca. 1500 cal. BC for the lower part of the sequence to 1000 cal. BC for its upper part. $^{14}$C dates from the top of the unit in core Artemis A provide an age of 1441–1118 cal. BC (Fig. 4). Despite very low values of magnetic susceptibility (less than $10 \times 10^{-6}$ m$^2$ kg$^{-1}$), it is interesting to reveal that a peak in the magnetic susceptibility values is observed ($\sim 250 \times 10^{-6}$ m$^2$ kg$^{-1}$), associated to a low frequency dependence (2.5%) at a depth of 3.30–3.45 m only in Artemis B (Figs. 5 and 6). The origin of the magnetic contamination responsible for this peak is discussed below.

The sixth unit (L2) is mainly composed of shallow marine to lagoonal gastropods and bivalves such as *C. glaucum*, *Abrase gmentum*, *L. lacteus* and *C. vulgatum*. The presence of combined species from the hard/sandy substrate and of the lagoonal assemblages indicates an alteration of the marine conditions and the gradual transition to a confined to shallow marine environment of deposition (strong decrease of *B. reticulatum* and of *R. ventricosa* with a simultaneous increase of lagoonal species toward the top of the bio-sedimentary unit). The top of the unit L2 (~1.30–1.50 m deep in both cores) is characterized by a quasi disappearance of hard/sandy substrate mollusc assemblage and only lagoonal bivalves such as *C. glaucum* and *L. lacteus* and gastropods such as *C. vulgatum* (most of the population is composed by juvenile specimen) still remain. $^{14}$C dating of the uppermost part of the Unit L2 indicates an age ranging from ~150/440 to 460/690 cal. AD, corresponding to Late Roman to Byzantine Times. Thus, unit L2 indicates a shallow marine environment gradually turning into a lagoon. Obviously, the open marine bay gradually changed into a semi-open and, later, confined lagoon.

The seventh unit (CS) overlays unit L2 and is identified in both cores, though in Artemis B, the sediments were strongly affected by 20th century human activities. It is composed of stiff gray clays, and mollusc identification indicates the presence of typical gastropods from ponds (*Planorbis planorhosis*). Rootlets and organic matter help to identify this unit as coastal swamps with local ponds. $^{14}$C dating of the transition between the lagoon (unit L2) and the continental environment (unit CS) of deposition gives an age of ~150/440–460/690 cal. AD which approximately corresponds to the Late Roman to Early Byzantine periods.

The eighth unit (C) is composed by homogeneous reddish clays (Terra Rossa) and overlays the coastal swamps environment, its thickness is about 0.45 m, from 0.45 to 0.90 m in a depth, exclusively in Artemis A. The close location of the boreholes from the bedrock could explain this major income of fine-grained colluvial material. ($\chi$) indicates values ranging from ~125 to $200 \times 10^{-6}$ m$^3$ kg$^{-1}$.

The ninth and last unit is found in both Artemis A and Artemis B and is observed in the uppermost part of the sequence: it corresponds to modern soils (from the surface to 0.50 m deep for

<table>
<thead>
<tr>
<th>Core id</th>
<th>Sample type</th>
<th>Depth below surface (m)</th>
<th>Depth about sea-level (m)</th>
<th>Dating method</th>
<th>Laboratory reference</th>
<th>Age ($^{14}$C BP)</th>
<th>± Cal. BC/AD (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artemis A</td>
<td>Shell (Loripes lacteus)</td>
<td>1.45</td>
<td>-1.20</td>
<td>AMS</td>
<td>Beta-297628</td>
<td>1960</td>
<td>30 460/690 AD</td>
</tr>
<tr>
<td>Artemis A</td>
<td>Shell (Abra segmentum)</td>
<td>1.90</td>
<td>-1.65</td>
<td>AMS</td>
<td>Poz-45543</td>
<td>3500</td>
<td>35 1441/1118 BC</td>
</tr>
<tr>
<td>Artemis A</td>
<td>Shell (Tricolia speciosa)</td>
<td>2.15</td>
<td>-1.90</td>
<td>AMS</td>
<td>Poz-45544</td>
<td>3760</td>
<td>35 1747/1434 BC</td>
</tr>
<tr>
<td>Artemis A</td>
<td>Shell (Loripes lacteus)</td>
<td>2.79</td>
<td>-2.54</td>
<td>AMS</td>
<td>Beta-297631</td>
<td>6630</td>
<td>40 5200/4840 BC</td>
</tr>
<tr>
<td>Artemis B</td>
<td>Shell (Bittium reticulatum)</td>
<td>1.44</td>
<td>-1.03</td>
<td>AMS</td>
<td>Beta-297619</td>
<td>2220</td>
<td>30 150/440 AD</td>
</tr>
<tr>
<td>Artemis B</td>
<td>Shell (Bittium reticulatum)</td>
<td>3.45</td>
<td>-3.30</td>
<td>AMS</td>
<td>Beta-297621</td>
<td>3490</td>
<td>40 1410/1050 BC</td>
</tr>
<tr>
<td>Artemis B</td>
<td>Shell (Cerithium vulgatum)</td>
<td>4.00</td>
<td>-3.85</td>
<td>AMS</td>
<td>Beta-297622</td>
<td>6500</td>
<td>40 5030/4700 BC</td>
</tr>
</tbody>
</table>
Artemis A and from the surface to 1.40 m down for Artemis B), strongly disturbed by recent human activities (farming and firing). Sediment analyses are not relevant to natural dynamics and processes and cannot be accurately interpreted.

5.2. Magnetic parameters and their significance

The magnetic level of core Artemis B revealed a dozen millimeter size dark granules (from 3.30 to 3.50 m in depth and dated ca. 1200 ± 200 cal. BC) that were extracted from the sediment. Microscopic examination revealed a rounded pumice-like aspect that suggested the projection of liquid droplets quenched in the air rather than mechanical fragmentation of a larger glassy material. μXRF analyses on the raw fragments show a silicate glass composition, rich in Mg, Al, Fe, Ca with trace of Ti, Cr, Ni. Two fragments collected at 3.32 m and 3.44 m present high field magnetic susceptibility at room temperature of 800 and 600 × 10^−8 m^3 kg^−1, respectively. Their thermomagnetic curve up to 700 °C (Fig. 6A–C) showed the 580 °C drop typical of magnetite but also a significant signal remaining at 700 °C, representing 50% and 30% of the initial susceptibility signal of fragments collected at 3.32 m and 3.44 m, respectively. One sample reheated to 800 °C revealed a distinct Curie point near 780 °C (Fig. 6C), i.e., the presence of metallic iron (see Van de Moortène et al., 2007, for identification of metallic Fe by such technique).

SEM examination revealed a mixture of Fe-rich bubbly glass, sometimes with microcrystalline textures, and spongy foliated Fe-poor zones containing some remaining relict crystals (Fig. 7). These crystals were identified based on chemical composition as quartz, chromite, rutile and zircon. Dense droplets of all sizes (from 1 μm to 1 mm diameter) were observed in the Fe-rich glass or at interfaces. Their composition is mostly Fe and S, with variable Ni content (from 0.5 to 24%, higher amount being found for smaller droplets). S/(Fe + Ni) atomic ratio varies from ≈1 (i.e., pyrrhotite–pentlandite composition) to near zero (i.e., metal).

6. Discussion

6.1. Landscape reconstruction of Ancient Aulis along the Holocene

Holocene marine incursion, linked to the general trend of the last post-glacial sea level rise, is well known in the northern and southern Aegean (Lambeck and Purcell, 2005). However, the unique conditions of the Euripus strait at Chalkis (only 3.5 km north of Aulis), well known for its puzzling tidal pattern (Tsimplis, 1997), necessitated an independent study, rather than reliance on previous research. The paleolandscape of the Aulis modern lowlands during Early Holocene (ca. 8000–5200 cal. BC) consisted in a narrow valley mainly filled by colluvial deposits deriving from the surrounding limestone erosion (Fig. 8a). No evidence of human occupation has been attested.

From ca. 5200 years cal. BC until ca. 3000 cal. BC (the Middle Neolithic to Early Bronze Age [Early Helladic]) a lagoon environment developed in conjunction with the gradual and constant sea-level rise since the end of the Last Glacial Maximum (LGM, Fig. 8b), and occasional slope debris modified the grain size of the sediments. It is obvious that a confined environment with shallow depth predominated in the bay with very low sediment accumulation: less than 1 m for a period of ca. 3000 years. Local tectonics could have played a role with an uplift movement and further regional information can be taken from the presence of uplifted Lithophaga on the southern edge of Vathi Limen (Fig. 2).

From ca. 3000 cal. BC to 2000 cal. BC (Early Helladic period), shallow marine conditions prevailed, creating a shallow marine bay, open to the NE and receiving marine sediment infuences.

Between ca. 2000 and 1400 cal. BC (Middle Helladic to Early Mycenaean period) the developing lagoon environment can be linked with the 4000–3000 cal. BP deceleration of sea-level rise in the Aegean Sea, which favored coastal sedimentation (Psomiadis, 2011). It is important to note that by ca. 1500 cal. BC, an
abrupt transition from open lagoon conditions to closed lagoon environments is revealed (disconnection with the sea), based on the foram identification. This feature fits well with other regional observations (Koukousioura et al., 2012). The origin of this environmental alteration is not certain and several factors may be related, such as the silting-up of the lagoon by important marine sediment influx carrying deltaic sands from the Lilas River and a phase of stability of the sea-level rise.

From ca. 1400 to 1050 cal. BC (Late Helladic/Late Mycenaean period), a new phase of marine intrusion is revealed and a Mycenaean site could be directly reached by boat (Fig. 8c). It is also possible that boats could have anchored in this shallow marine bay during the 13th century BC.

Gradually, from ca. 1050 cal. BC until 400 cal. BC (the Early Iron Age to the Classical period), fine grained deposits coming from local sediment sources, such as Lilas River (Poulos et al., 2001) changed the full marine conditions of deposition into a lagoonal environment (Fig. 8d). This implies that the environment in Aulis changed through time, specifically the boundaries of the bay. The construction of the Artemis Temple coincides with this lagoonal stage, and paleolandscapes during Archaic to Classical times are characterized by salty to brackish environments. Moreover, the construction of the temple is probably related to the importance of this location as a land route and place of mytho-historical significance.

Finally, from the end of the Roman period to the beginning of the Byzantine period (ca. 200–500 cal. AD), the lagoon turned into a coastal swamp where occasional salt intrusion could happen (Fig. 8e). During Late Byzantine, Venetian and Ottoman periods, the coastal swamps were frequently affected by colluvial deposition.

6.2. Evaluating the human impact on the landscape and a Mycenaean harbor at Aulis

Based on the coring results, there is evidence for very shallow marine to lagoonal environments from Neolithic to Late Roman Times. However, the chronostratigraphy exhibits a period of fast vertical sediment accretion, dated from the Mycenaean period to the end of Roman times: Artemis B records a fast sand accumulation of ca. 2.10 m thick (from 3.40 to 1.30 m in depth below the surface), while a thin layer (ca. 0.50 m thick) of very fine material (mainly silty clay sediments) has been deposited from Neolithic to Mycenaean Times (ca. 5800–1400 cal. BC). The difference in terms of vertical sedimentation accretion, coincides with the development of human settlements during Mycenaean period in the area surrounding Ancient Aulis. This accretion suggests that vegetation clearance and development of the agriculture on the hill slopes surrounding the former lagoon/shallow marine cove occurred. In this case, the main consequence of human stress on the slope is erosion, and the deposition in the bay of a large amount of detritus, which overlies the bedrock, mainly Terra Rossa (clay material derived from the chemical dissolution of the carbonate bedrock that composes Megalo Vouno, Fig. 3). The mean grain size of the sediments recorded in Artemis B, dated from Mycenaean to Roman Times, is gradually increasing and several peaks are observed and could be linked with the human occupation of the area surrounding the former bay. Given this influx of colluvial debris, it is possible that marine sediments transported by local rivers (Megalo Rema and Lilas Rivers, Fig. 2), which created deltas during historical times (Poulos et al., 2001), were transported by wave currents to the Mikro Vathi shallow marine/lagoonal environments. As a result, a gradual silting up of the bay and a final fossilization are both
attested. These different parameters probably contributed to increase the vertical sediment accretion. Other parameters such as abrupt subsidence and sea-level rise should be taken into account and could be combined with the anthropogenic factors to explain the abrupt change in terms of vertical sedimentation accretion observed from Mycenaean Times onward.

The definition of Mycenaean harbors is little debated from an archaeological point of view since there are a few case studies of detailed descriptions of harbor for the Mycenaean period. According to our paleoenvironmental data, Aulis Bay (Mikro Vathi) was much larger than the modern one and corresponded to a shallow marine cove/open lagoon (depth was probably not exceeding 2–3 m). The limits of olive fields (illustrated as dashed white line on Fig. 3) reveal the maximal extension to the south. Boats would have been naturally protected from storms and strong wave currents due to the configuration of the bay. It is also possible that the southern margin of the shallow marine cove was used for landing ships on the beach itself, which would exclude the presence of any permanent structure (mole, basin built with stones, mooring loops, etc.). Future research, especially in the form of geophysical survey could shed further light on this, possible to reveal the subsoil configuration.

6.3. Interpretation of the magnetic granules

The microscopic observations and the thermomagnetic measurements preclude a natural origin of the identified magnetic fragments. Their composition is not volcanic, and a natural catastrophic fire cannot generate sulfide and metal bearing glasses: sulfides do not occur naturally when oxidized. Moreover, reducing conditions necessary for metal production are not found in natural fires. Moreover, a catastrophic fire should have generated a synchronous charcoal-rich layer, which has not been recognized within the sediments. The production of superparamagnetic grains (<0.03 \( \mu \)m) is generally preponderant with fire and generates a strong increase of the frequency dependence due to the presence of fire induced magnetic oxides (Rummery et al., 1979); values are generally superior to 5% (Oldfield, 1994; Oldfield and Crowther, 2007) but the material found in Aulis shows very low percentage (ca. 2.5%) and implies a very low contribution of superparamagnetic grains. Therefore, the production of these granules due to anthropogenic activity is the most likely explanation. One hypothesis for high temperature treatment of a sulfide-bearing material is metallurgical activity. Notable Fe and Ni content of metal droplets and an abundance of sulfide, Mg, Ca and chromite relics point toward a pyrrhotite–pentlandite rich ophiolitic ore, possibly mixed with a sedimentary ore (responsible for the presence of quartz). As no other metal extracted during the Mycenaean period (Cu, Ag, Pb) was detected, a possible interpretation is that these fragments may be the result of an unsuccessful attempt at iron metallurgy (while this layer of the core dates to the Bronze Age, iron metallurgy was practiced, albeit very rarely (Popham et al., 1980; Snodgrass, 1980; Waldbaum, 1990)). However, the presence of sulfide and the composition is not typical of normal iron slags. A likely source of

![Fig. 8. Holocene paleogeographic reconstruction of the Aulis coastal plain. a is mainly inferred from sedimentological results of core Artemis A. b–e are drawn based on data from both cores studied in this paper.](image-url)
the fragments is the pyrrhotite–pentlandite rich ores with associated chromite that are common in central Greek ophiolites (Economou and Naldrett, 1984; Sovatzoglou-Skounakis and Economou-Eliopoulos, 1997). Ophiolitic outcrops are found throughout Boeotia and Euboea. Bakhuizen (1976) has discussed the importance of the FeNi deposits of Euboea and Boeotia and their potential significance for an iron industry at Chalkis, based on historical accounts. Until recently, this seems to have had little grounding in archaeological evidence, though early iron smelting remains from Eretria, Lefkandi, and Oropos lend strength to the historical and geological arguments that these ores were exploited at an early date (Verdan, 2007; Doonan and Mazarakis Ainian, 2007). It must be noted, however, that the Eretria and Oropos material date to the 8th century BC. The earliest evidence of iron from Lefkandi is a single iron knife, likely imported from Cyprus and dated to the 12th century — other iron objects date to later periods (the 10th century onward) and there is no evidence of iron production at Lefkandi (Evely, 2006). Moreover, Photos (1989) reports Ni content in iron artifacts from the Mycenaean period, as well as from Troy, and presents evidence from experimental archaeology that Ni bearing iron can be produced using Greek ores and the smelting techniques of the Late Bronze Age.

While it is possible that Artemis B contains metallurgical slags, any evidence for an iron production at this point remains fairly ambiguous. For example, it is also possible that the observed material came from aborted copper smelting, during a test smelt of newly discovered local ore. Pyrrhotite–pentlandite ores can be confused with associated chalcopyrite-rich ores that were used for copper extraction (Economou and Naldrett, 1984; Sovatzoglou-Skounakis and Economou-Eliopoulos, 1997). Alternatively, iron ores are sometimes used as fluxes in copper smelting (Charles, 1980; Kassianidou, 1994). It is also possible that these fragments, though definitely anthropogenic, did not come from metallurgical production at all, and are the unintentional result of some other high-temperature activity. Although local production on the harbor shore is one interpretation, we cannot exclude the possibility that the material was produced elsewhere and brought to the harbor through erosional processes or by marine currents. A program of further coring or limited excavation could reveal further metalliferous debris and is desirable to fully understand the nature of the magnetic granules from Artemis B.

7. Conclusion

This study provides a better understanding of the geomorphological evolution of the Ancient Bay of Aulis. The results presented here are generally in accordance with other paleoenvironmental research in the eastern Mediterranean and Aegean in particular, which attempted to estimate the spatial limits of the Holocene sea incursion in Greece (Pavlopoulos et al., 2006; Triantaphyllou et al., 2010; Ghiardi et al., 2012; Koukosiuoura et al., 2012) and in Egypt (Flaux et al., 2011). Paleoenvironmental analyses show the evolution of the coastline during the Holocene, with a more detailed focus on the Late Helladic times and Classical to Roman periods. The different laboratory analyses (magnetic susceptibility measurements, LASER grain-size, macro and microfaunal identifications) performed on the two boreholes drilled in the modern lowlands reveal a gradual transition from Early Holocene (8000–5200 BC), dominated by continental dynamics, to Middle-Late Holocene (5200 BC to modern) marine-lagoonal environments. Fast changes from shallow marine to lagoon stages characterize the Bronze Age (3000–1050 cal. BC). A focus on the Late Mycenaean period (ca. 1400–1050 cal. BC) indicates that shallow marine conditions prevailed with easy access to the sea. Indeed, after closed lagoon phase, dated ca. 1500 cal. BC, an abrupt transition to full marine conditions is observed. The magnetic granules found in this period also raise interesting possibilities for high temperature industries operating in this area based on magnetic parameters and μXRF/SEM techniques, though the type of high temperature process remains ambiguous.

An important distinction is seen between sediment accumulation from Pre-Helladic times, characterized by a very low deposition (less than 1 m for a period of ca. 3200 years), and Middle Helladic to Roman Times (2000 BC–400–500 AD), where fast accretion is observed during Late Mycenaean and classical periods, which may correspond to important phases of human activity in combination with changes in local, active tectonics (uplift and subsequent subsidence) and sediment supply from local sources such as the Lias River. In sum, this multidisciplinary, geoarchaeological approach illustrates the advantages of assembling different categories of data for measuring the impact of environmental evolution on archaeological landscapes.

Acknowledgments

This article is a contribution of the Fonds Incitatifs de Recherche research programme (period 2010–2012), supervised by Matthieu Ghiardi (CNRS) and Christophe Morhange (University of Provence, France), which is directed toward reconstructing the past landscapes of eastern Mediterranean islands (Cyprus, Crete, and Euboea). It is funded by the University of Provence (Aix-en-Provence, France). The authors would like to thank Institute of Geology and Mineral Exploration (IGME) in Greece, in particular Konstantinos Nikolakopoulos and Nikolaos Carras for delivering work permits in March 2011 for geomorphological investigations in the Boeotia/Euboea areas. Stamatis Katsiadramis, Dimitris Vandarakis, Christoper Collana and Yannick Crest are acknowledged for their precious help during fieldwork in March 2011. Their kindness was greatly appreciated as well. Finally, the authors would like to thank two anonymous referees and JAS editor Thilo Rehren who provided fruitful comments and contributed to improving this manuscript.

References


