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1 Harbour geoarchaeology of Lechaion (Corinth area, Greece)  
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4

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19 **ABSTRACT**

20 Lechaion in Corinth, Greece, is the largest ancient port in Greece. Harbour geoarchaeological  
21 investigations, based on <sup>14</sup>C-dated palaeoenvironmental archives taken from a well-studied inner  
22 basin (Basin 3) and a still unknown outer basin (Basin 4), revealed anthropogenic lead excesses  
23 starting from the 12<sup>th</sup> century BCE, associated with brown coal fragments, for the first time  
24 discovered in such an ancient archaeological context. Given that historical sources trace the  
25 foundation of the port back to the 7<sup>th</sup> century BCE, these results attest to protohistoric industrial  
26 use of the site and push back its chronology by over five centuries. The existence of such ancient  
27 port activity not only extends the chronological horizon for harbour activity in the Corinthian area,  
28 but also provides new insights for the Late Bronze Age/Early Iron Age (LBA/EIA) transition,  
29 including potential trading routes that may have transited through Lechaion, likely spanning across  
30 the Gulf of Corinth and possibly even beyond, to western Mediterranean urban centers.

31  
32 **1. INTRODUCTION**

33 The Late Bronze Age/Early Iron Age (LBA/EIA) transition (12<sup>th</sup>-8<sup>th</sup> century BCE) in Greece is a  
34 pivotal period that laid the foundations for the emergence of Greek civilization in its "classical"  
35 form. Up to recently considered a "dark age", this transition had been seen as a period of decline  
36 in the Aegean world. Research tends to revisit this view (**Lemos, 2006 ; Ben Yosef, 2019**) and  
37 Greek sites from the Early Iron Age show that commercial exchanges, particularly with the Levant,  
38 did not disappear (**Bintliff et al., 2012 ; Mazarakis-Ainian et al., 2012**). During these centuries,

39 port activities have certainly played a central role in the expansion of the Phoenicians and Greek  
40 colonies in the Mediterranean. However, no sedimentary evidence of such ancient port activity has  
41 yet been discovered in Greece. Located in an ancient river outlet, Lechaion was the primary  
42 harbour of ancient Corinth, spanning an area of approximately 0.7 km<sup>2</sup>. It is the largest ancient  
43 port in Greece and its strategic location played a vital role in the economic and military growth of  
44 the ancient city (Rothaus, 1995) (Fig. 1A&1B). While historical sources suggest that the port was  
45 established in the 7<sup>th</sup> or 6<sup>th</sup> centuries BCE, the presence of an older protohistoric, i.e. Bronze Age,  
46 port in the Corinthian region has long been suspected by archaeologists (Blegen, 1920 ; Tzonou  
47 and Morgan, 2019). Evidence of commerce across the Gulf of Corinth during Bronze Age is  
48 provided by remains and settlements established near the Lechaion coastline, such as the  
49 prehistoric site of Korakou (Fig. 1A), which demonstrates contacts with Achaea and Italy until it  
50 was abandoned around 1050 BCE (Tzonou and Morgan, 2019). Although regional archaeological  
51 evidence attests to the continuity of settlement over the centuries of the Late Bronze Age/Early  
52 Iron Age (LBA/EIA) transition (Bintliff, 2012), the question of an active protohistoric port that  
53 could have been open to the Gulf of Corinth and the western Mediterranean remains unresolved  
54 (Tzonou and Morgan, 2019). To address this topic and to shed new light on the "muted" topic of  
55 the LBA/EIA transition (Ben-Yosef, 2019), geoarchaeological investigations took place in the  
56 harbour area of Lechaion in which two sediment cores, Tar11, and Drill2, were taken in harbour  
57 basins 3 and 4, respectively (Fig. 1A). In combination with multivariate analysis (MVA) we  
58 conducted Attenuated total reflectance Fourier transform infrared spectroscopy (FTIR-ATR),  
59 portable X-ray fluorescence spectrometry (pXRF) and sedimentological analyses on core sediment  
60 samples at high resolution. These tools are used to reconstruct palaeo-environmental changes and  
61 Pb palaeo-pollution signal likely to have trapped traces of early port activities (Delile et al., 2017  
62 ; 2018). We also conducted SEM-EDS analyses on brown coal materials found in Drill2 (Fig. 3).

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## 2. PHYSICAL SETTING

66 The geographical and geomorphological framework of the port of Lechaion has been the subject  
67 of numerous studies since the 1990s. Lechaion is located in the eastern part of the Gulf of Corinth,  
68 less than 3 kilometers north of the ancient city. The Gulf of Corinth is an active asymmetric rift  
69 zone (with some of the highest extension rates in the world), and seismic activity is significant in  
70 the area (Armijo et al., 1996 ; Charalampakis et al., 2014 ; Moretti et al., 2003). At this location,  
71 the northern shore of the Peloponnese experiences ongoing uplift during the Quaternary period  
72 (numerous uplifted marine terraces are present in the Corinth region), and the coastline of  
73 Lechaion, as well as the harbour itself, have experienced multiple co-seismic uplift events during  
74 historical periods (Apostolopoulos et al., 2015; Morhange et al., 2012; Stiros et al., 1996).  
75 Marine dynamics such as longshore drift, swells, and waves are powerful and occasionally  
76 morphogenic in this area (Hadler et al., 2013; Vött et al., 2018; Mourtzas et al., 2014).

77

78 Nowadays, the area corresponding to the ancient harbour extends both on land and underwater.  
79 Recent excavations (Lechaion Harbour Project) have allowed for the identification and naming of  
80 visible port structures (Loven et al., 2018 ; Athanasopoulos, 2020) (Fig. 1A). The inner port  
81 consists of three basins interconnected by canals. The connection to the sea is also facilitated by a  
82 canal. The outer port comprises 5 moles (L-M1 to L-M5) that are mostly submerged. The existence  
83 of a fourth basin (Basin 4) located between moles L-M1 and L-M2 was first revealed in this study.  
84 The meandering shape of the inner basins suggests that they were constructed downstream of a  
85 former river channel, perhaps in a small estuary or pre-existing delta or coastal marsh (Hadler et  
86 al., 2013; Vött et al., 2018; Morhange et al., 2012; Kolaiti et al., 2017)

87

### 88 3. MATERIALS AND METHODS

#### 89 3.1 Coring and <sup>14</sup>C sampling

90

91 Tar11 core was performed in Basin 3 using a hand auger in order to minimize sediment compaction  
92 and Drill2 using a geotechnical drilling rig. In the field, the sediments were photographically  
93 documented into stratigraphic units based on texture and colour (using the Munsell code). For each  
94 <sup>14</sup>C sample, 20 g of sediment were collected and sieved (500 µm mesh) with distilled water.  
95 Organic remains were then individually identified (micro-charcoals, wood and plant remains)  
96 under a binocular microscope, extracted and sent for AMS dating.

97

#### 98 3.2 Sedimentology and harbour units identification

99

100 110 samples were analyzed (60 from Tar11 and 50 from Drill2). Grain size-analyses were  
101 conducted by Laser Diffraction Spectroscopy and the organic content of the sediment was  
102 measured by LOI (Loss On Ignition) (Supplemental Material A and B).

103 Based on pXRF and FTIR-ATR analyses, we followed the methods of (Delile et al., 2014) and  
104 (Martinez et al., 2021), respectively, to decipher geochemical and mineralogical compositions  
105 involved in the formation of sedimentary deposits of the ancient harbour basins of Lechaion  
106 (Supplemental Material D, Tab. S1 and Fig. S1). We also used Pb enrichment factors (EF<sub>Pb</sub>) to  
107 identify harbour deposit levels from pre-harbour environment in the stratigraphy of cores  
108 (Supplemental Material C). Indeed, it has been established that ancient port sediments are  
109 characterized by traces of human activities, such as Trace Metal Element (TME) and lead (Pb)  
110 pollution seen as an urban change proxy of ancient cities (Delile et al., 2014, 2016, 2017).

111

112

#### 113 3.3 Brown coal fragments analyses

114

115 After ultrasonic cleaning for 10 minutes, followed by drying during 24 hours, the materials (n=5)  
116 were analyzed using SEM-EDS (Scanning Electron Microscopy with Energy Dispersive X-ray  
117 Spectroscopy). Analyses are expressed in X-ray spectrum as well as weight percentage of oxides

118 **(Fig. 3)**. The method is only semi-quantitative, identifying the major elements present in the object.  
119 The mineral fraction, composed by Na, Mg, Al, Si, S, Cl, K, Ca and Fe remains below 5wt.% for  
120 all the EDS analyses. It should be noted that, due to the extremely high carbon content, the analyses  
121 were carried out under non-ideal conditions. The mass balances are therefore only overestimated  
122 (for O content) and in no way represent the precise content of the elements from the mineral  
123 fraction. Nonetheless, these results provide ample information on the present elements and their  
124 relative proportions.

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#### 4. RESULTS

128 The port facilities that are visible today mainly date back to the Roman period and consist of three  
129 interior basins (Harbour basins 1, 2, 3) and an outer basin open to the sea (Harbour basin 4) **(Fig.**  
130 **1A)**. The morphology of the port during pre-roman periods is widely unknown. In both Tar11 and  
131 Drill2 cores, the radiocarbon datings, Pb enrichment factors ( $EF_{Pb} > 1.5$ ) and geochemical  
132 compositions (redox conditions) of the sediments allow us to subdivide the stratigraphy into three  
133 main sedimentary units: pre-harbour (unit A), harbour (unit B), and post-harbour (unit C) **(Fig. 2)**.

134

135 Pre-harbour deposits (Unit A) in Tar11 and Drill2 cores, ranged at a depth of 2.5 to 3.1 m below  
136 sea level (b.s.l.) and 2.3 to 9.3 m b.s.l., respectively, show lowest  $EF_{Pb}$  values ranging from 0.7-  
137 1.3 (mean value of 0.9) in Tar11 core, and 0.5-2.5 in Drill2 core (mean value of 1.2). These  
138 sediments of sandy muds and gravely muddy sands refer to detrital inputs dominated by silicate  
139 minerals (and carbonates in Drill2 core between 7.6 and 2.3 m b.s.l.) under weak anoxic water  
140 column conditions **(Fig. 2)**. These alluvial deposits corroborate the hypothesis that the ancient port  
141 of Lechaion was built at the mouth of a coastal temporary stream **(Stiros, 1996 ; Morhange et al.,**  
142 **2012 ; Kolaiti et al., 2017)**.

143

144 Both for the inner and the outer harbour basins, a surge of anthropogenic lead excesses (consistent  
145  $EF_{Pb} > 1.5$ ) and an oxygen depletion in the water column reveal unambiguously harbour deposits  
146 at 0.6-2.5 m b.s.l. depth in Tar11 core and 0.3-2.3 m b.s.l. depth in Drill2 core **(Fig. 2)** (Unit B).  
147 According to the radiocarbon dates **(Table 1)**, harbour basins were in use from Late Bronze Age  
148 (1381-1056 cal BCE and 1122-927 cal BCE in Tar11 and Drill2 cores, respectively) to Late  
149 Antiquity (333-753 CE in Drill2 core). Five medium size pieces of brown coal (B-axe 2 to 5 cm;  
150 radiocarbon age >45000 Cal BP) were discovered at 0.9 m b.s.l. depth in Drill2 core. According  
151 to the C content, these materials are situated between lignite (C content of 66wt.% ; n=6 analyses)  
152 and bituminous coal (C content circa 81wt.% ; n=2) **(Fig. 3)**.

153 As in many ancient Mediterranean ports, the post-harbour unit (0.6 to 0.1 m b.s.l. in Tar11 core  
154 and 0.2 to 0 m b.s.l. Drill2 core) is characterized by a major environmental change with an oxygen-  
155 deficient eutrophic regime evolving towards a submerged aquatic environment (Unit C) **(Fig. 2)**.  
156 Post-harbour deposits record the highest  $EF_{Pb}$  values ranging from 3.9-335.2 (mean value of 58.1)  
157 in Tar11 core, and 5.9-12.4 in Drill2 core (mean value of 8.1). This sharp increasing trend of Pb

158 contamination in the post-harbour unit has been recorded in numerous fillings of ancient harbour  
159 basins, especially during Medieval times (e.g. Rome, [Delile et al., 2017](#); Neapolis, [Delile et al.,](#)  
160 [2016](#); Ephesus, [Delile et al., 2015](#)), and may correspond to other inland local or regional industrial  
161 activities related to the reassignment of harbour activities.  
162

## 163 5. DISCUSSION

164 The dated stratigraphic connection of the brown coal materials with high Pb excess in Drill2 core  
165 seem to highlight, for the first time, a palaeo-metallurgical activity in a harbour area during the  
166 LBA/EIA transition and/or a regional trade of metals (as ingots shipping or local metallurgical  
167 transformation close to the harbour) and/or coal. Even if the use of brown coal in LBA/EIA Greek  
168 metallurgy has not yet been demonstrated by mining and metallurgical archaeology, its high C  
169 content (> 65wt.%) coupled with an alkaline mineral fraction with little sulfur content (**Fig. 3**)  
170 make it relevant for metallurgical use favoring slag formation directly from the lead-silver ores  
171 loaded in furnaces. The presence of these fragments of brown coal in a level dating from the end  
172 of the Bronze Age completes recent discoveries. : the exploitation and the use of brown coal as a  
173 combustion source during LBA has recently been indirectly identified in mycenaean Tiryns  
174 (Peloponnese) ([Buckley et al., 2021](#)) and there are lignite sources in the Peloponnese ([Kavvadas](#)  
175 [et al., 2020](#)) (**Fig. 1B**).

176 On a broader regional scale, this study raises questions about the potential connections that may  
177 have existed between local metallurgical activities (attested during the LBA by recent excavations  
178 around Lechaion, [Xanthopoulou et al., 2020](#)), regional mining operations, metal trade and the  
179 development of extensive maritime commercial exchanges. Indeed, there is evidence of silver-lead  
180 mining as early as the 3<sup>rd</sup> millennium BCE at Laurion (Attic peninsula) ([Morin and Photiades,](#)  
181 [2005](#)), Sifnos, Syros, Milos (Cyclades) and South Euboea ([Vaxevanopoulos et al., 2022](#)) (**Fig.**  
182 **1B**). Recent studies highlight the continuity of metal exploitation in the Eastern Mediterranean and  
183 their diffusion towards the west after the collapse of Bronze Age civilizations at the beginning of  
184 the Iron Age, primarily through maritime trade ([Eshel et al., 2019 ; 2023](#)).

185  
186 This ongoing harbour activity during the centuries of the LBA/EIA transition would have made  
187 Lechaion a central site in Eastern Mediterranean, whose economic significance led to its likely  
188 expansion and the construction of monumental port structures from the 7<sup>th</sup> century BCE onwards.  
189 Up to now, however, the only visible harbour remains at Lechaion date to historical periods and  
190 any protohistoric port structures, if they exist, are yet to be discovered.

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197 **Data availability statement :**

198 *Datasets related to this article (XRF and laser granulometry raw data) can be found at :*

199 <https://data.mendeley.com/datasets/rkd5vpbtv5/1>

200 Chabrol, Antoine; Delile, Hugo (2023), "Harbour geoarchaeology of Lechaion sheds new light on  
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203

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219

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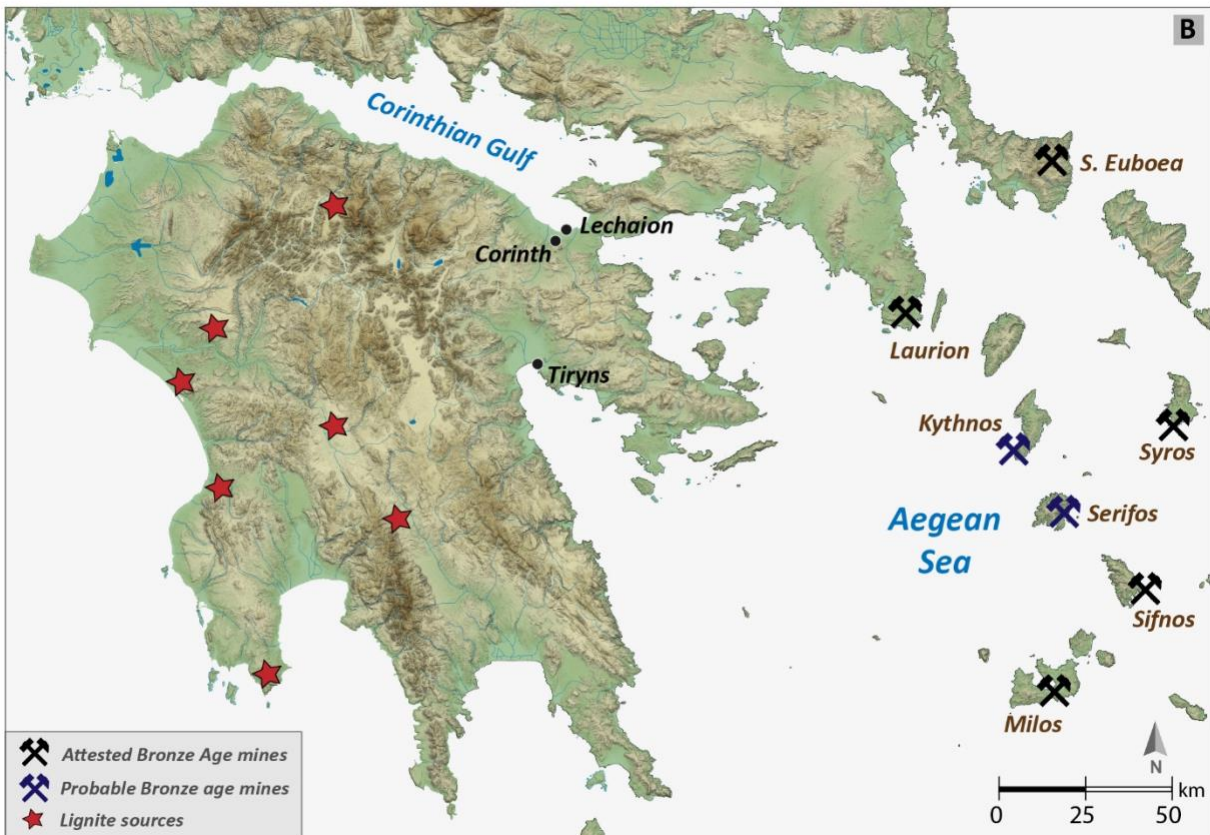
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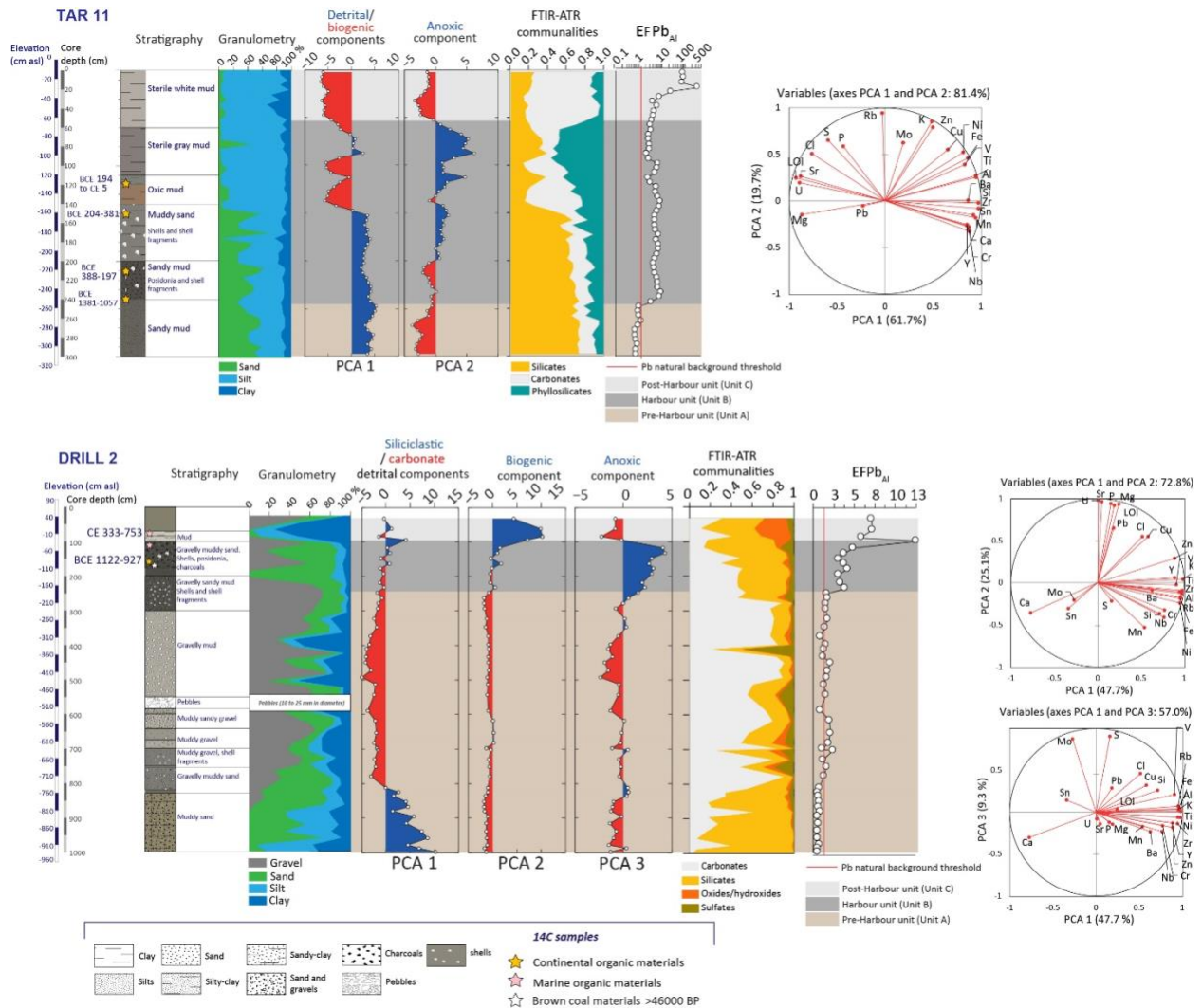
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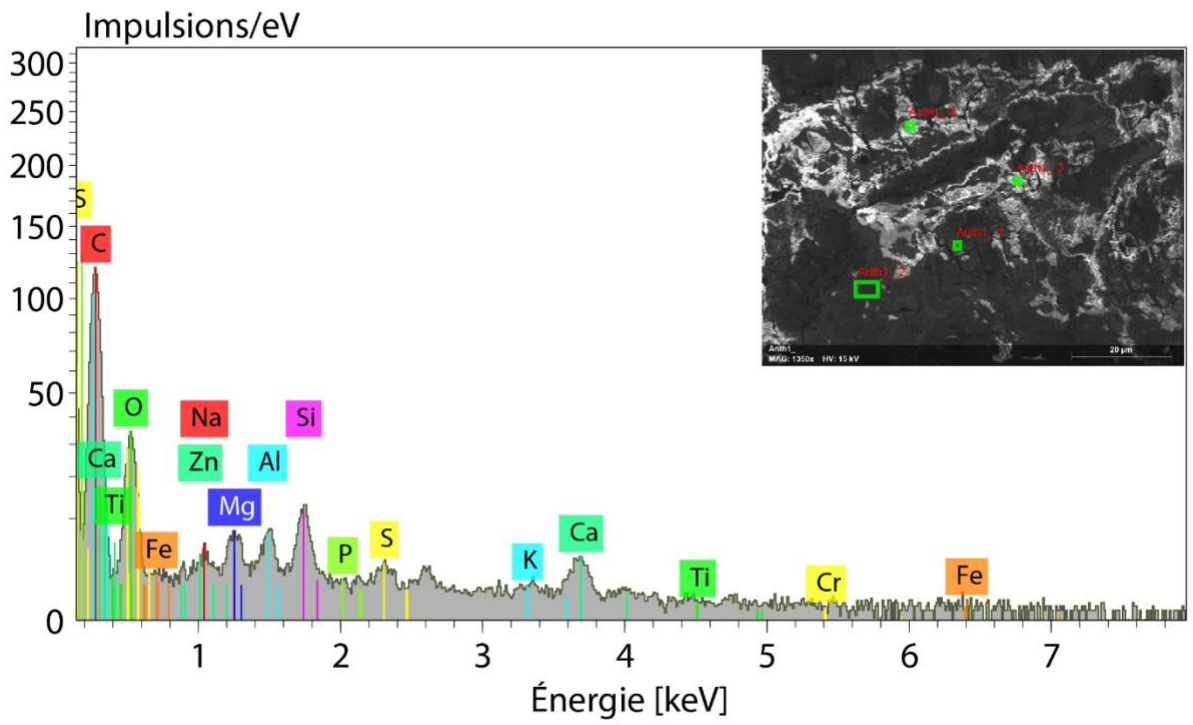
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332 **Figure 1. A.** The Lechaion harbour area and the drilling locations. The pre- and protohistoric site  
 333 of Korakou, which was occupied until the end of the Bronze Age, is located on top of a hill, west  
 334 of the harbour area. **B.** Location of the sites and pre- and protohistoric silver-lead mines mentioned

335 in the text (Vaxevanopoulos et al., 2022 ; Morin and Photiades, 2005). The brown coal (lignite)  
 336 sources in the Peloponnese (Kavvadas et al., 2020)  
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 339 **Figure 2.** Stratigraphic log of the Tar11 and Drill2 cores showing granulometry, Principal  
 340 Component Analysis (PCA) of major and trace element concentrations, fractionation of Fourier  
 341 transform infrared spectroscopy (FTIR-ATR) communalities, and Enrichment Factor of Pb  
 342 (normalized to Al). Right panels show correlation circles of the PCA.  
 343



Spectrum	C	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Cr	Fe	Zn
Anth1_1	68.3	27.5	0.1	0.8	0.7	1.3	0.0	0.2	0.1	0.8	0.0	0.0	0.1	0.0

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**Figure 3.** The five brown coal materials recovered in Drill2 core and SEM-EDS analyses

Sample code	Sample #	Elevation (cm bmsl)	Material	$\Delta^{13}\text{C}$	$^{14}\text{C}$ Age (BP)	2 $\sigma$ Max and Min Cal. Age		Median prob. age
Poz#2-141434	Tar11-1	-127,8	charcoal	-16	2085 $\pm$ 30	194 BCE	5 BCE	94, BCE
Poz-140728	Tar11-2	-151,8	charcoal	-26	1785 $\pm$ 35	204 CE	381 CE	292,5 CE
Poz-140677	Tar11-4	-223,8	charcoal	-26,1	2225 $\pm$ 35	388 BCE	197 BCE	292,5 BCE
Poz-140741	Tar11-5	-246,8	plant remains	-17,8	2985 $\pm$ 35	1381 BCE	1056 BCE	1218,5 BCE
Poz#2-141023	Drill2-2	-8,1	marine shell	3,4	2135 $\pm$ 30	333 CE	753 CE	543 CE
Poz-157392	Drill2-2'	-63,1	charcoal	-30,2	2860 $\pm$ 30	1122 BCE	927 BCE	1024,5 BCE
Poz-140727	Drill2-5	-88,1	lignite	-24,1	>46 000 $\pm$ 6180	46990 BCE	45685 BCE	46337,5 BCE

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354 **Table 1.** Radiocarbon dating. AMS  $^{14}\text{C}$  radiocarbon dates calibrated using OxCal (v4.4.4) with  
 355 the IntCal20 and MarineCal20 calibration curves

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