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1           **Holocene coastal environmental changes and human occupation of the lower Hérault**  
2   **River, southern France**

3  
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13  
14           **ABSTRACT**

15           Sea-level rise, human impacts and climate change have deeply affected coastal environments during  
16           the Holocene. These forcing factors are studied using the Lower Hérault valley, which constitutes a  
17           very representative Mediterranean case study because of (i) its very early, intense and continuous  
18           land use since Neolithic times, and (ii) its sensitivity to sea-level rise and Mediterranean climate  
19           changes over a relatively small watershed. 34 cores and 61 AMS radiocarbon dates, associated with  
20           biological and geochemical analyses, have allowed us to precisely reconstruct the Holocene evolution  
21           of the lower valley. Until 6500 cal yr BP, a wave-dominated morphology and retrogradational  
22           dynamics were reconstructed. During this phase, ephemeral channels and successive river mouths  
23           formed and were rapidly submerged by sea-level rise. The progradational phase began after 6500 cal  
24           yr BP, and the alluvial plain gradually built seawards with the formation of a beachridge system  
25           outside the valley. Growth of the fertile alluvial plain was coeval with the development of Neolithic  
26           agriculture. This alluvial progradation gradually filled the estuary with advances of the mouths,  
27           several shallow lagoons and sandbar. The high density of information collected allows us to  
28           recognize, for the first time, a pronounced fluvial-dominated deltaic morphology, especially 3000  
29           years ago, during the Bronze Age. Lagoonal and coastal shores were continually inhabited. Human  
30           land use continually adapted to geomorphological and environmental changes. Around 300 years  
31           ago, the delta shifted to a wave-dominated system.

32           **Keywords:**

33           Holocene; Coastal change; Western Mediterranean; Neolithic; Bronze Age; Iron Age; Deltaic  
34           evolution; Geomorphology; Ria infilling; Geoarchaeology

35  
36           **1 Introduction**

37  
38           Between the Last Glacial Maximum (ca. 22 ka BP) and ca. 6 ka BP, sea level rise (SLR) displaced  
39           Mediterranean shorelines inland by transgressive dynamics. At a wide scale, the pace and distance of  
40           shoreline migration was mainly mediated by the morphology (geomorphological heritage) of the  
41           transgressive surfaces which were narrow in active margins and/or mountainous areas (Dubar,  
42           1988), or large in passive continental margin (Aloisi et al., 1978; Labaune et al., 2008). At a smaller  
43           geographical scale, fluvial valley incision is also an important factor. In such a geomorphological  
44           fluvial context, the maximum flooding surface can be more than 13 km from the current coastline  
45           (Dubar and Anthony, 1995; Dubar, 2004; Garcia-Garcia, 2005; Devillers, 2008; Traini et al., 2013).

46 These flooded valleys or rias (Goudie, 2018), were subsequently filled by alluvial deposits because of  
47 the slowing of sea level rise, attested in almost all of the geological contexts of the Mediterranean  
48 from around 7000 BP (Pirazzoli, 1991; Bard et al., 1996; Vacchi et al., 2016), in a context of low  
49 accommodation space. The rate and timing of the progradation phase is sensitive to variations in  
50 sediment supply, related to human and/or climatic events (Devillers, 2008; Anthony et al., 2014). For  
51 large river systems, these dynamics led to deltaic construction from the narrow valley to the open  
52 sea (Aloisi, 1986; Stanley and Warne, 1994; Vella et al., 2005; Vött et al., 2006; Amorosi et al., 2004,  
53 2013). For smaller valleys with lower sediment supply, the flooded fluvial valley topography (ria) was  
54 progressively silted but did not exceed the mouth of the valley as illustrated by the present  
55 shorelines of most Mediterranean fluvial embayments (Anthony et al., 2014). Depending on climate,  
56 human history and geomorphological heritage, sedimentation in some systems has not reached yet  
57 the downstream valley, as for example for some small watersheds in the Northern part of the Black  
58 Sea (Dolukhanov et al., 2009).

59 Based on these trends, we can formulate the following hypotheses. During the transgressive period,  
60 (between ca. 18 ka BP and 7 ka BP) the retrogradational coastal system track could produce a wave-  
61 dominated delta morphology (Galloway, 1975; Anthony, 2015) because of the lack of sedimentation,  
62 the great accommodation space and the rapid sea-level rise.

63 During the first progradation phase (before ca. 7 ka BP), the river-dominated delta morphology  
64 (Galloway, 1975; Anthony, 2015) was favoured by a low accommodation space in the narrow valley  
65 (Homewood et al., 2000). Wave energy was low, because of the distance from the offshore zone,  
66 which concentrated sediment deposition near the river mouth (Allen, 1993). It often resulted in a  
67 deltaic morphology dominated by fluvial channels and lagoon systems (Fig. 1).

68 During the second progradation phase, siltation shifted to offshore areas, and the accommodation  
69 space became more significant, leading to wave-dominated delta morphology. The active delta front  
70 was also more exposed to wave energy, dispersing sediments over wider areas (Allen, 1990, 1993;  
71 Anthony and Héquette, 2007). Much like the present morphology of deltas, the shorelines were  
72 regularized into large concave curves punctuated by the rocky capes. The lagoons were infilled by  
73 sediment supply. For these wave-dominated deltas (Galloway, 1975), offshore dynamics were the  
74 main geomorphological agent.

### 75 **Figure 1: Coastal metamorphosis during the Holocene**

76  
77 Sediment accumulation of river systems at base level, linked to the relative stability of sea level from  
78 7500 cal yr BP (Lambeck and Bard, 2000; Vacchi et al., 2016), led to the formation of fertile soils and  
79 a constant freshwater supply. These environmental conditions were conducive to human settlement  
80 and to the emergence of structured societies and trades along the coast (Day et al., 2007; Guilaine  
81 and Verger, 2008; Garcia and Sourisseau, 2010). Several studies have shown a direct relationship  
82 between the development of deltaic areas and the sedentarization of human societies between 8500  
83 and 6500 yr BP (Stanley and Warne, 1997; Kennett and Kennett, 2006; Hu et al., 2013). Before 5000  
84 yr BP, many archaeological sites were located close to deltaic areas. These rapidly evolving  
85 environments were inhabited by societies that derived their livelihood from the agricultural, fisheries  
86 and trading potentialities (Fokkens and Harding, 2003; Guilaine, 2003; Brückner et al., 2002, 2005;

87 Devillers, 2008; Bertoncetto et al., 2014). In these areas, the environmental and human dynamics are  
88 closely intertwined, in both space and time (Carozza et al., 2012, Brisset et al. 2018).

89 Although our understanding of human-environment interactions and coastal changes in deltaic areas  
90 has advanced significantly in recent years, many questions remain and can only be answered by the  
91 multiplication of coring. What was the chronology of these changes? Beyond the simple change of  
92 shoreline, is the coastal metamorphosis, namely changes in the nature of the coastal environment,  
93 could be proved and measured? Were coastal changes observable at human time-scales? How did  
94 environmental changes affect the economic and agricultural systems until the Neolithic?

95 The landscape changes at Agde area, due to the construction and evolution of the Hérault deltaic  
96 plain, favoured the installation of ancient societies, especially during the early phase of Neolithization  
97 in southern France (Guilaine et al., 2007; Briois and Manen, 2009; Guilaine, 2017). But this area also  
98 attests to a dense, continuous and rich occupation history for all the archaeological periods of the  
99 Bronze Age, Iron Age and Antiquity (Lugand and Bermond, 2002; Ugolini, 2002; Gomez, 2011; Gascò,  
100 et al., 2012, 2015). Archaeological remains of these ancient settlements are sporadically detected in  
101 the Hérault catchment and on the rocky volcanic promontory of Agde. By contrast, our  
102 understanding of the settlement history of the lower Hérault plain is poor due to the significant  
103 sediment accumulations in these areas (Ambert *in* Lugand and Bermond, 2002; Ropiot, 2007; Gomez,  
104 2011; Gascò et al., 2012, 2015).

105

106 The aim of this paper is to investigate the Holocene geomorphological evolution of the Lower Hérault  
107 valley, in order to establish a dynamic model for coastal changes since 10 000 y. BP. The Lower  
108 Hérault valley and the Agde area constitute interesting case studies to probe coastal changes in and  
109 around archaeological contexts (Garcia, 1995). It could be used as a model for the Holocene  
110 morphogenesis and human-society co-evolution.

111

112 To refine the landscape evolution in the Hérault lower valley and improve our understanding of the  
113 environmental context of the site of La Motte, a multidisciplinary research project was initiated. The  
114 main objectives of this project were notably to determine the extension of the lagoonal-marine  
115 domain inside the palaeo-ria, the position of the coastal sandbars and barrier beaches, and the  
116 palaeogeography of the floodplain and palaeochannels of the Hérault River. This study is the first one  
117 to be undertaken in the Hérault valley, and complements previous research on western  
118 Mediterranean deltas and coastal geosystems during the Holocene (Dubar and Anthony, 1995;  
119 Blanchemanche et al., 2002; Dubar, 2004; Arnaud-Fassetta, 2003, 2004; Vella et al., 2005; Devillers et  
120 al., 2007; Bertoncetto et al., 2014; Faisse et al., 2015; Dolez et al., 2015). The originality of this work is  
121 the highly detailed geomorphological evolution provided by numerous cores and the better  
122 understanding of the relation between societies and environment in Agde territory. This paper  
123 focuses on the palaeogeographical evolution of the lower Hérault valley and is based on the bio-  
124 sedimentological study of 36 sedimentary cores from the coastal plain.

125

## 126 **2 Study area, a Mediterranean coastal floodplain**

### 127 **2.1 Geomorphic setting**

128 The Hérault River is located on the Languedoc plain, in South of France. It is a Mediterranean coastal  
129 river and its source is Mount Aigoual in the Cevennes area. Its geomorphology begins at the end of

130 the Eocene. The Pyrenean-Alpine orogeny created the Villeveyrac syncline, north of the Etang de  
131 Thau, and the anticline of Castelnau-de-Guers, northeast of Nézignan-l'Evêque (Fig. 2), which forms  
132 the very large structure of the Hérault valley. After the Late Miocene, a regression associated with  
133 the Mediterranean Messinian salinity crisis (Clauzon et al., 1987; Ambert et al., 1998) incised the area  
134 between the current Orb (west of the Hérault valley) and Hérault rivers (Ambert et al., 1998; Larue,  
135 2009). The discordant Pliocene series shows a succession of marine sediments and continental  
136 deposits filling the deeply incised Messinian palaeovalley and exceeding it up to 100 m NGF.

137

138 Volcanic activity occurred in the lower Hérault valley from the late Lower Pleistocene to the early  
139 Middle Pleistocene (Berger et al., 1978; Féraud and Campredon, 1983; Gastaud et al., 1983). It was  
140 characterized by effusive, strombolian, and hydromagmatic eruptions that respectively created the  
141 basaltic plateaus of Agde and Saint-Thibéry, the scoria cones of Mount Saint-Loup and Mount Ramus,  
142 and the tuff-ring of Cape d'Agde. The creation of these volcanic landscapes associated with an  
143 eustatic lowstand sea level led to a new incision of the present course of the Orb and Hérault valleys.  
144 Thereafter, during Pleistocene times, a system of stepped alluvial terraces was deposited over the  
145 Pliocene sediments.

146

147 The Holocene sequence is spatially restricted to the coastal area and the active flood plain of the  
148 present rivers. Along its lower part beyond Saint-Thibéry, it flows in meanders on the plain. The slope  
149 of the river is low, leading to the formation of a low and flat coastal plain from Florensac, as well as a  
150 reduction in sediment grain-size (Berger et al., 1978). The low topography also contributes to the  
151 development of secondary networks located at the limit of the floodplain, such as the current  
152 Ardaillon River (Fig. 2). The Hérault River flows into the Mediterranean, and its watershed is around  
153 2550 km<sup>2</sup>. The present average river flow is ca. 50 m<sup>3</sup>/s, but the river witnesses strong rain storms  
154 (the so-called Cevenol events). These strong rainfall events lead to brutal flood events (up to  
155 1500m<sup>3</sup>/s) on the Hérault lower valley (SAGE, 2005). River flow has been significantly mediated by  
156 Holocene rapid climate changes (Degeai et al., 2017).

157

## 158 **Figure 2: Geological map of the lower Hérault region**

159

### 160 **2.2 Archaeological context and human occupation of the Hérault lower valley**

161 The west of the valley attests to the earliest documented Neolithic settlements in the western  
162 Mediterranean, dating to ca. 7600 BP. These sites provide evidence of the exploitation of the  
163 environment with new imported farming and crops technics (Manen and Guilaine, 2007; Briois et al.,  
164 2009). The impact of these Neolithic societies on the forest cover and soil erosion, consequently, on  
165 fluvial sediment supply is attested by pollen (Court-Picon et al., 2010) and geoarchaeological  
166 (Devillers and Provansal 2003) analysis. Furthermore, sites suggest the existence of docking and  
167 anchorage areas further inland, consistent with the maximum flooding stage of the Languedoc coast  
168 (Gascò et al., 2015). The coastal plain and the most fertile lands at this time occupied a small area  
169 because of the ending of the transgressive phase.

170 At the beginning of the Bronze Age (ca. 4250 cal yr BP), landscape clearance can be attributed to  
171 several small settlements. They probably benefited from the stabilization of mean sea level and the  
172 progradation phase which contributed to create a lagoonal system and alluvial plain. Nonetheless,

173 the paleogeography and the coastline, as well as the deltaic, lagoonal and fluvial (i.e. channels)  
174 systems are unclear.

175 Until 2011, underwater archaeological surveys undertaken by UMR5140 ASM and IBIS association in  
176 the Hérault riverbed led to the discovery of a protohistoric dwelling dating to the late Bronze Age  
177 (Bronze final IIIb, between ca. 3000 and 2700 cal yr BP). This archaeological site, called La Motte, is  
178 located north of Agde, in the middle part of the coastal plain, at -5 m NGF. The site comprises  
179 ceramics and organic deposits, wood-pile alignments and accumulations of basalt blocks, interpreted  
180 as a managed lagoon-river bank in the vicinity of the habitat (Gascò et al., 2015). This pile-dwelling  
181 settlement lies near lagoonal clay layers and river-mouth deposits, which demonstrate that this  
182 Bronze Age settlement was located between a palaeolagoon and a river mouth. Understanding the  
183 environmental evolution of deltaic plain is therefore key to contextualizing the archaeological data.  
184

185 Downstream, close to the sea, the Cap d'Agde harbour excavation has unearthed many metal objects  
186 consistent with human societies (Mazière, 2013). The populations of the end of the Bronze Age have  
187 invested the Hérault lower valley and the Mediterranean coastline.  
188

189 For the late 7th century BC, the excavation of the Peyrou Necropolis shows the presence of an  
190 indigenous community (Fig. 2-3) on the basaltic promontory of Agde. At that time, local people had  
191 already established contacts with the Mediterranean world (Ugolini, 2010), as demonstrated by the  
192 Greek vases from the necropolis of Peyrou (Nickels et al., 1981; Dedet and Schwaller, 2017). At about  
193 4.4 km from the current mouth of the Hérault River, a shipwreck cargo (Garcia, 2002) or more likely  
194 votive deposit (Gascó et al., 2012) dated to the 6th century BC was discovered and confirms maritime  
195 activity and long-distance trade in the Agatois area.  
196

197 The foundation of the ancient Greek city of Agde dates to 550-525 BC. It will remain active until  
198 about 50 AD (Nickels et al., 1989; Nickel, 1989; Ugolini, 2002). The city is installed on a volcanic  
199 promontory overlooking the left bank of the Hérault River. Lower draught shipwrecks went up the  
200 river to trade with the native populations. The location of the Greek harbour is still not known, due  
201 to the progradation and avulsions of the Hérault delta, and thus this work could greatly help to find  
202 it.  
203

204 During the early Roman Empire, Agde became a key town. Numerous sites were mentioned, and  
205 trade on the river, related to the export of wine, is attested (Lugand and Bermond, 2002). At this  
206 time, the progradation of the Hérault delta led to the infilling of lagoons and an extension of fertile  
207 land conducive to human activities. Nonetheless, the environment of the city of Agde is not known  
208 during this period.  
209

## 210 **Figure 2: Geological map of the lower Hérault region**

### 211 **3. Materials and methods**

#### 212 **3.1 Coring**

215 The Holocene palaeoenvironments of the Hérault lower valley have been reconstructed using  
216 sedimentological, palaeobiological and chronostratigraphic data. Thirty-four cores were drilled on  
217 the alluvial plain, all of them yielding precise stratigraphic information. The lithological, geochemical  
218 and biological content were analysed for ten stratigraphic cores. These cores formed a transversal  
219 transect to the deltaic plain (Fig. 3). This transect is particularly useful to reconstruct  
220 palaeoenvironments of the alluvial plain, and to spatially constrain the palaeo-channels of the  
221 Hérault River and its palaeocoastline. The coring campaign was undertaken in April and October 2014  
222 using an Atlas Copco Cobra TT percussion corer. The sampling interval depends on the nature of the  
223 sediment, and varied between 5 and 10 cm. The multiplication of coring is favored in this work  
224 compared to pollen or geophysical approaches for example. Indeed, the large number of coring is the  
225 better approach to reach the objective which is to better characterize the environments and the  
226 littoral morphology.

### 227 3.2 Lithological and sedimentological studies

228 In the ASM laboratory (UMR5140 Paul-Valéry Montpellier 3 University) and Geosciences laboratory  
229 (Montpellier University), the sediment texture was determined using wet sieving and laser grain  
230 sizing with a Beckman Coulter LS13320 Particle Size Analyser (Fig. 4). A Passega diagram was drawn  
231 to determine the hydrodynamic conditions of the depositional environments (Passega, 1964). To  
232 characterize the depositional environment in relation to the hydrodynamic conditions (i.e. fluvial,  
233 coastal, lagoonal environments), we used the grain-size limits observed in similar coastal  
234 environments on the Tiber delta (Salomon, 2013). The results are consistent with other  
235 palaeoenvironmental markers.

### 236 3.3. Biological studies

237 The palaeo-ecology of the different environments was probed using species determination of  
238 mollusc shells (macrofauna) present in the sedimentary fraction > 2 mm (Fig. 5-7) and ostracodes  
239 present in the dry sand fraction > 150  $\mu\text{m}$ . 47 samples were analyzed. 176 specimens of macrofauna  
240 covering 10 taxa were picked and identified using the following references: Clanzig (1987), D'Angelo  
241 and Garguillo (1978), Doneddu (2005). The ecological groups were defined according to Péres and  
242 Picard (1964), a molluscan classification system for Mediterranean species, and on the basis of the  
243 salinity gradient. For the ostracodes, 6081 specimens covering 10 taxa were picked and determined.  
244 For each sample we normalised the ostracoda density to a standard dry sample weight (10 g). The  
245 ecological groups are based on the salinity gradient between freshwater species and brackish species  
246 (Salel et al., 2016).

### 247 3.4 Mineralogical analyses

248 Optical mineralogical analyses of the sand fraction were performed on nine samples of an E-W core  
249 transect. The objective was to determine the influence of the Hérault River on depositional  
250 environments. Minerals of biotite and muscovite along with clasts of carbonates and Permian  
251 sandstones are indicators of the Hérault watershed, whereas quartz, feldspars, pyroxenes,  
252 amphiboles, olivines and lithic fragments of granite and metamorphic rocks are more widespread  
253 minerals or clasts.

254 3.5 Geochronology

255 The chronological framework is provided by 61 radiocarbon dates performed at Poznan (Poland) and  
256 Saclay (France). Dates performed on charcoal and organic matter have been corrected for  
257 atmospheric <sup>14</sup>C variations using the calibration curve IntCal13 (Reimer et al., 2013) (Table 1). Marine  
258 shells were calibrated using the Marine13 calibration curve (Reimer et al., 2013). For lagoonal species  
259 a Δr correction of 245 years was applied (Degeai et al., 2015). Sixty AMS <sup>14</sup>C were produced. Dated  
260 samples were rejected in three cases: (i) if a dated coastal shell was collected from sediment of a  
261 fluvial or continental environment (which has been determined with post-dating analysis); (ii) if the  
262 <sup>14</sup>C result of a marine material was significantly higher than the expected sea level at the time of  
263 deposition, indeed a marine organism collected substantially above the sea level of its time can only  
264 be reworked; and (iii) if a single date departed significantly from the age-depth model made up of a  
265 large group of reliable dating. We assume that these precautions associated with the large number of  
266 available dates is the only method to minimize error caused by reworking.

267

268 **Table 1 : AMS 14C radiocarbon date**

269

270 3.6 Facies catalogue

271 The palaeogeographic results are based on two different methods. Different facies were studied in  
272 detail in cores A4 and A8 and subsequently extrapolated to other cores in the valley. On the basis of  
273 these results, the other cores are summarized and presented on the basis of the depositional  
274 environments (Fig. 8). Palaeogeomorphological maps are based on these analyses, the radiocarbon  
275 chronology and the interpretation of present floodplain landforms revealed by Lidar DEM mapping  
276 (Fig. 3).

277 **4 Results**

278 **4.1 Facies study in the lower Hérault valley: cores A4 and A8**

279

280 Palaeobiological analyses were performed on three cores from the Zone C transect (A11, A4 and A8).  
281 A11 and A8 are located at the extremities of the lower valley, on either side of the Hérault river bank  
282 (Fig. 4, 5, 6, 7 and 8). The core A11 is also located on the right flank of the Ardaillon river.

283

284 **4.1.1 Core A8:**

285

286 Core A8 Unit A: Facies 1

287 The basal unit (Unit A) between 13 and 15 m depth consists of an accumulation of ca. 70% of brown  
288 sands (50% of medium and fine sands and 20% of coarse sands) in a clayey silt matrix. The gravels  
289 fraction is virtually absent (Fig. 4). However, the C/M Passega diagram indicates that these sediments  
290 were transported by bed load (at the base) to graded suspension with rolling (at the top) (Fig. 4). This  
291 depositional environment is characteristic of open high-energy environment. This interpretation is



292 consistent with the grain-size of the C/M image of Passega diagram limits used by Salomon (2013) to  
293 determine palaeoenvironments.

294  
295 **Figure 4 : Sedimentological analysis of the A1, A3, A4, A8, A11 and A16 cores**

296  
297

298 The sand fraction is composed of ca. 15% of minerals derived from the Hérault watershed (ca. 7% of  
299 Permian sandstone clasts, 5% of biotite and muscovite, and 3% of carbonates). 85% of sands  
300 correspond to minerals like quartz (78%) and to clasts of granite and metamorphic rocks (7%). The  
301 presence of minerals from the Hérault river watershed suggests fluvial inputs into this environment.  
302 The microfauna is dominated by euryhaline species such as *Loxoconcha elliptica* and *Cyprideis torosa*  
303 at very high faunal population densities (Fig. 5). This association is characteristic of lagoonal  
304 environments. This is confirmed by the presence of *Loxoconcha tamarindus*, which is present in the  
305 sandy silts of the Thau lagoon (Kurc, 1961). *Hydrobia ventrosa* is the only macrofauna species  
306 present, attesting to a brackish depositional environment.

307

308 This highly hydrodynamic environment is characterized by fluvial inputs from the Hérault River. The  
309 brackish water salinity indicates a distal connection of the lagoon to the sea. The different proxies are  
310 consistent with a riverbed in connection with a lagoon.

311

312 **Figure 5: Ostracod analyses of the core A8**

313

314 Core A8 unit B: Facies 2

315 Unit B is located between 13 and 11.8 m depth and is dated at the base to 7819 ±114 cal yr BP (Table  
316 1). The sedimentary texture corresponds to silty sands characterised by ca. 15% of medium and fine  
317 sands. Coarse sands are virtually absent (Fig. 4-5). The Passega diagram indicates a pure deposit  
318 related to uniform suspension transport and a mixed deposit due to uniform suspension with the  
319 injection of graded suspension (Fig. 4). This reduction in grain size is typical of a constant and  
320 progressive environmental protection. These grain size characteristics evoke the onset of a less  
321 hydrodynamic and more protected environment, with only minor inputs of fine sands (Fig. 4-5). Eight  
322 ostracoda species with relatively high faunal population densities were identified. The following  
323 lagoonal species are dominant: *Cyprideis torosa*, *Loxoconcha elliptica* and *Loxoconcha tamarindus*.  
324 These are found in association with the lagoonal species *Cytherois fischeri* and the littoral species  
325 *Leptocythere lacertosa* (Fig. 5). This suggests the onset of a calm lagoonal environment in distal  
326 connection with the sea. The presence of freshwater species at high faunal densities (*Candona*  
327 *neglecta*, *Heterocypris salina*, *Ilyocypris bradyi*; Fig. 5) attests to the presence of a river mouth in a  
328 deltaic context. This interpretation is confirmed by some coastal (*Rissoa ventricosa*) and lagoonal  
329 (*Hydrobia ventrosa* and *Scrobicularia plana*; Fig. 6) macrofauna. Charophyte gyrogonites are present  
330 in abundant quantities (Fig. 5 and 6). They are indicative of fresh to low salinity environments (Soulié-  
331 Märsche, 2007) and support the hypothesis of a river mouth with hydro-sedimentological injections  
332 in a protected lagoon.

333

334 Core A8 unit C: Facies 3

335 Unit C is located between 11.8 and 9.2 m depth. It consists of an accumulation of silty sand (ca. 20%  
336 of medium and fine sand and ca. 10% of coarse sand; Fig. 4-5). Between 11.6 and 10.3 m depth, the  
337 sediment comprises an alternation of greyish silty sand with whitish sandy-marls. The sand  
338 percentage is higher than in the rest of the unit (ca. 35%). Between 9.8 and 10.1 m depth, the  
339 sediment comprises an organic deposit. This peat deposit has been dated to  $7494 \pm 73$  cal yr BP  
340 (Table 1). The Passega diagram places the sandy-marl sub-unit in mixed deposit due to uniform  
341 suspension with the injection of rolling deposit (Fig. 4). The environment is calm and protected but  
342 records some sandy-marl injections. Lagoonal ostracods decrease in favour of freshwater ostracods  
343 dominated by *Candona neglecta* and *Heterocypris salina* (Fig. 4). The environment corresponds to a  
344 freshwater swamp or a frequently flooded fluvial plain. Macrofauna species point to a hydrodynamic  
345 environment (Fig. 6). The presence of *Radix peregra* and *Bithynia* sp. in the sandy-marly sub-unit  
346 indicates a running freshwater environment. The specie of *Planorbarius corneus* indicates a stagnant  
347 freshwater pond (Fig. 6). In light of these data, unit C comprises a fluvial environment, such as a  
348 floodplain or a riverbed margin.

349

350 Core A8 unit D: Facies 4

351 Unit D is located between 9.2 and 6.4 m depth. The sedimentary texture corresponds to silty sand  
352 characterised by ca. 15% of medium and fine sand and 5% of coarse sand (Fig. 4-5). The Passega  
353 diagram indicate pure uniform suspension deposits and some sedimentary lens corresponded to  
354 uniform suspension with injection of graded suspension (Fig. 4). The ostracod diversity is high and  
355 lagoonal species reappear with the dominance of *Cyprideis torosa* (Fig. 5). The environment  
356 corresponds to a lagoon. The permanence of freshwater ostracods indicates a closed deltaic mouth.  
357 The low salinity of this lagoonal environment is attested by Charophyte gyrogonites. *Cerastoderma*  
358 *glaucum* and *Scrobicularia plana* are euryhaline species that can tolerate low salinities (D'Angelo and  
359 Garguillo, 1978) (Fig. 6). The proxies from this unit are consistent with lagoonal conditions.

360

361 Core A8 units E and F: Facies 3bis

362 These two units show similar sedimentary textures consistent with the accumulation of silts. The  
363 medium and fine sand fractions are very low (ca. 10%) (Fig. 4). The Passega diagram shows a pelagic  
364 suspension for these two deposits consistent with decantation processes in a very protected  
365 environment typical of a filling-up lagoon or alluvial plain (Fig. 5-6). In unit E, the sand fraction  
366 comprises residual ostracodes from unit D. The environment is characterised by the same association  
367 as unit D but in very low abundance. The lagoonal environment is filled up and progressively  
368 transformed into an alluvial plain characterized by freshwater ostracods like *Candona neglecta* (Fig.  
369 4). The evolution into an alluvial plain is also marked by terrestrial macrofauna such as *Theba pisana*  
370 (Fig. 6). This facies is similar to unit 3. Here, however, this fluvial environment is more distal and  
371 decantation processes are dominant. The environment is characteristic of a floodplain.

372

### 373 **Figure 6: Benthic macrofauna analyses of cores A4 and A8**

374

#### 375 **4.1.2 Core A4:**

376 Core A4 Unit A: Facies 1

377 The basal unit (Unit A) is located between 10.2 and 11 m depth. Like unit A of core A8, it consists of  
378 an accumulation of sands (10% of coarse sand and 60 % of medium and fine sand) in a clayey matrix.

379 The main difference is the presence of a ballast fraction (15%) comprising gravels and small pebbles  
380 (Fig. 7). The Passega diagram indicates a rolling transport processes (Fig. 4) consistent with a very  
381 energetic depositional environment such as the bed load of a river channel. Ostracod faunal densities  
382 are low with species such as *Loxoconcha elliptica*, *Loxoconcha tamarindus* and *Leptocythere lacertosa*  
383 (Fig. 7). This association is typical of a lagoon in proximity to a fluvial mouth and connected to the  
384 sea. The presence of the macrofauna *Hydrobia ventrosa* confirms the existence of a lagoonal  
385 environment close to this riverbed (Fig. 7).

#### 386 387 **Figure 7: Ostracod analyses of the core A4** 388

##### 389 Core A4 unit B: Facies 4

390 Between 10.2 and 5.4 m depth, unit B is characterised by a medium and fine silty sand sedimentary  
391 texture. Coarse sand and ballast are absent. The base and the top of the unit are marked by an  
392 increase in the percentage of sands (ca. 20% vs. ca 10%; Fig. 4 and 6). The Passega diagram indicates  
393 a uniform suspension process for the deposition of this unit typical of a relatively calm and protected  
394 environment (Fig. 4). The ostracods are relatively diversified. Lagoonal species are present in high  
395 abundance. *Cyprideis torosa* is the dominant species, confirming the installation of a lagoonal  
396 environment. However, the freshwater species *Heterocypris salina* and the abundance of *Loxoconcha*  
397 *elliptica* indicate relatively distal fluvial inputs. The number of coastal species, such as *Leptocythere*  
398 *lacertosa*, decreases progressively. This is characteristic of the gradual disconnection of the  
399 environment from the sea. Variations in freshwater and lagoonal species (Fig. 6-7) indicate some  
400 lateral variations in fluvial inputs into the lagoon environment. Like unit A, *Hydrobia ventrosa*  
401 gastropods attest to a brackish lagoonal environment (Fig. 6).

##### 402 403 Core A4 unit C: Facies 2

404 Unit C is located between 5.4 and 4 m depth. It consists of pebbles (25%) and sands (55%) in a clayey  
405 silty matrix (Fig. 4 and 7). Like unit A, the Passega diagram indicates a very high-energy rolling  
406 transport processes typical of river channel bed load (Fig. 4). *Loxoconcha elliptica*, *L. tamarindus* and  
407 some secondary freshwater species like *Candona neglecta* and *Heterocypris salina* attest to a river  
408 mouth in a lagoonal environment (*Cyprideis torosa*) connected to the sea (*Leptocythere lacertosa*, *L.*  
409 *fabaeformis* and *Cytherois fisheri*). The river mouth hypothesis is also supported by the presence of  
410 Hérault River watershed minerals at 25%.

##### 411 412 Core A4 units D and E: Facies 3

413 Like units E and F of core A8, these two units are characterised by the accumulation of silts (90%)  
414 (Fig. 6). They correspond to alluvial plain environment and highlight the progradation of the Hérault  
415 river.

##### 416 417 **4.1.3 Core A33: Facies 5**

418 Core A33 is almost entirely composed of bedded sand, from coarse to fine grain size. Malacofauna  
419 fragments are present in the sand fraction. Gastropods and bivalves are represented by  
420 *Cerastoderma glaucum*, *Pavicardium* sp. and *Cerithium vulgatum*. They are consistent with the  
421 coastal and lagoonal zones. These layers were deposited in a high-energy coastal zone, such as a  
422 sand bar.

423

424 Mineralogical observations

425 Almost all optical mineralogical counts of sand grains indicate a clear origin from the Hérault  
426 watershed (Fig. 8). Granite clasts, pyroxene, amphibole, olivine, quartz and feldspar are characteristic  
427 minerals and lithic fragments of the area, but Permian sandstone, biotite, muscovite and carbonate  
428 grains can clearly be attributed to the mid and upper Hérault valley. A marine origin for these sands  
429 can be excluded. Nonetheless, in the lower part of the core A11 (riverbed facies), mineralogical  
430 markers from the Hérault watershed are absent. We suggest that this is consistent with sediment  
431 deriving from the western tributary of the Hérault.

432

#### 433 **4.1.4 Facies model of the lower Hérault valley sedimentological records**

434 The study of these new cores allows us to build a facies model for the lower Hérault valley (Fig. 8).  
435 Facies 1 is composed of coarse sand and gravel and it is related to the fluvial channel. Silts and fine  
436 sands are sometimes interbedded in the facies. Facies 2 contains mixed lagoonal and freshwater  
437 fauna consistent with a lagoon near a rivermouth or a rivermouth in a lagoonal environment. Facies 3  
438 comprises brown silts associated with continental malacofauna and is indicative of a floodplain.  
439 Facies 4 is characterized by dark clays and loams associated with coastal and lagoonal macrofauna  
440 related to a lagoonal deposit. Facies 5 is made-up of shelly sands that we interpret as a shoreline or  
441 beachridge. All these facies compose the cores of this study (figure 8). This allows us to elucidate the  
442 geomorphological evolution of the Hérault ria since 8000 years.

443

### 444 **5 Geomorphological evolution of the lower Hérault valley**

445

#### 446 **5.1 Complex transgressive dynamics**

447 Until ca. 5500 BP, transgressive dynamics are predominant and large lagoonal areas are elucidated in  
448 all zones (Fig. 8). In the northern part of the valley, cores A13, A14 and A35 record a relatively stable  
449 lagoonal environment between 8500 and <7200 cal yr BP. East of the valley, a fluvial wetland rich in  
450 organic deposits began accreting around 8000 cal yr BP. The river mouth moved to the west from  
451 8000 to 7000 cal yr BP, as shown by cores A8, A16 and A7 cores (Fig. 8-9). During this general  
452 transgressive period in the Hérault valley, delta-like progradation occurred, mediated by the position  
453 of the river mouth. These progradation dynamics (Fig. 9) were very restricted, mobile and transitory  
454 (ephemeral and successive river-mouth). Remnants of these channels can still be perceived by a  
455 linear morphology only revealed by a geomorphological analysis of LIDAR data (Fig. 3).

456

457 These successive fluvial environments were submerged (cores A8, A16, A7, A1, etc.) thereafter,  
458 during the maximal flooding period between 7000 and 5000 cal yr BP. (Fig. 8-9). Lagoonal sediments  
459 are present in almost all cores (Fig. 8). The lagoonal deposits furthest from the current shoreline are  
460 found in cores A19 and A21 (zone A, Fig. 7-8), 11.2 km inland. These constitute the farthest coastal  
461 environments known nowadays in the valley and it show the maximum extension of the Hérault  
462 palaeolagoonal system. No dates are available for the core A19, but if we assume that the first  
463 lagoonal deposits (6 m bsl) are in direct relation with sea-level rise at this depth, this maximum  
464 extension could be roughly dated to between 7000-6500 cal yr BP, according to regional sea-level  
465 curves (Vella and Provansal, 2005; Vacchi et al., 2016). The main progradation phase began after 6500  
466 cal yr BP in the middle of the valley. Beachridges and/or sandbars developed inside the lagoon, due

467 to a slowdown in sea-level rise and the sedimentary inputs from the Hérault River and its tributaries.  
468 Until this period, the general morphological shape of this inner delta was concave, even if the river  
469 mouth could temporally prograde by siltation into small areas along the sides of the valley, where  
470 shallow depths could be more easily infilled.

471

472 Downstream, between the present-day cities of Agde and Vias, a large sandy barrier was elucidated  
473 during field surveys and mapped using the LIDAR digital elevation model (Fig. 3). The core A33,  
474 undertaken on this beach and dune ridge, is 9 m deep and composed almost entirely of sand. After  
475 7500 cal yr BP, the aquatic environments inside the ria were brackish and therefore separated from  
476 the sea by a sandy barrier. These data demonstrate that the inner sandy barrier was in place until  
477 7500 cal yr BP, between Agde and Vias. This barrier seems to be dynamic and discontinuous.  
478 Furthermore, it is known that a beachridge was present on the coast during the last 8000 years at  
479 least, located approximately on the current coastline (Court-Picon et al., 2000; Tessier et al., 2000;  
480 Raynal et al., 2009; Degeai et al., 2015). Once again, core BSS002KQQF (available online at:  
481 <http://infoterre.brgm.fr>) comprises 30 m of sand accumulation and reveals the presence of this  
482 beachridge. The beachridge was probably not continuous at this time (Court-Picon et al., 2000;  
483 Degeai et al., 2015). These natural barriers were conducive to navigation in a sheltered environment  
484 and thus promoted the appearance and dissemination of Neolithic culture in the Western  
485 Mediterranean. The Peiro Signado and Pont de Roque-Haute archaeological sites, near Vias, are the  
486 oldest Neolithic settlements in the region (Guilaine et al., 2007; Briois and Manen, 2009).

487

## 488 **5.2 Deltaic progradation**

489 The western route of the Hérault fluvial channel, visible in cores A4 and A3, was gradually or  
490 suddenly abandoned for a new channel to the east. Until 3000 cal yr BP, sedimentation from the  
491 Hérault river began to build a large floodplain on the western part of the valley (Fig. 8-9), then  
492 continued to the east of La Motte, a Bronze Age archaeological site (Gascó et al., 2015). These  
493 landscape dynamics isolated a small sub-lagoon in the eastern part of the valley. This large and fertile  
494 floodplain was attractive to human activities (navigation, agriculture, fishing) (Gascó et al., 2015) and  
495 helps to explain the importance and the long duration of La Motte settlement during this period.

496

497 From 3000 to ca. 1000 cal yr BP, the ria continued to be infilled by alluvial sediments in a lagoonal  
498 environment. Progradation dynamics were more rapid on either side of the valley, and driven by the  
499 Hérault River on the eastern side and, more slowly, by the Ardaillon tributary on the western side.  
500 Cores A30, A32 and the Lidar data (Fig. 3) show the general chronology and morphology of this  
501 lagoon, which is on the way to be filled. This lagoon, never described in previous studies, is of  
502 significant archaeological importance. Agde promontory is known to have accommodated an Iron  
503 Age Greek colony (Nickels et al., 1989; Ugolini *in* Lugand and Bermond, 2002) and such a lagoon  
504 would have been key for harbour activities and maritime trade. At this time, the Hérault valley was a  
505 major commercial route for the exportation of agricultural products throughout the Western  
506 Mediterranean (Garcia, 1995; Mauné, 2002; Ropiot, 2009; Mauné, 2016). Archaeological remains  
507 have been mapped around Agde, although no harbour structures have been formally identified  
508 (Lugand et Bermond, 2002). Scholars have suggested that the Roman harbour could be close to Luno  
509 Pond, Rochelongue beach or near the present Hérault river mouth. This could be reconsidered with  
510 the knowledge of new data presented here.

511

512 The silting and infilling dynamics continued during the last evolutionary stage of the lower Hérault  
513 valley. Cores A32 and A28 suggest that the lagoon was infilled between 1000 cal yr BP (age of the last  
514 lagoonal deposit) and 500 cal yr BP (riverbed dated near Agde). Further downstream, the LIDAR DEM  
515 shows a relict depression and abandoned river channel just behind the present coastline (Fig. 3).  
516 These landforms are clearly discernible in 18<sup>th</sup> century maps (Garipuy, 1774; Bourgoïn et al., 1777).  
517 Likewise, the river mouth and the Grau are also mapped, supported by the geological map of the  
518 area (Berger et al., 1978) and field surveys.

519

## 520 **6 Discussion**

521 The chronostratigraphic record of the lower Hérault valley provides evidence for 7000 years of a  
522 deltaic evolution. The numerous cores have helped to elucidate a detailed image of past coastlines  
523 and lagoon morphology. Until the end of the transgressive phase, corresponding to the sea-level rise  
524 slowdown, the wave-dominated morphology led to the expansion of lagoonal systems. But this  
525 period was also characterized by the formation of several narrow deltaic lobes, which were  
526 subsequently submerged in the eastern part of the valley. Coastline are very dynamics, asymmetric  
527 and more complex than suggested in previous study or expected by models (Dubar and Anthony,  
528 1995; Devillers, 2008; Devillers et al., 2007; 2015; Marriner et al., 2012; Ghilardi et al., 2008; Giaime  
529 et al., 2019).

530

531 During the progradation phase, deltaic lobes developed in the middle of the valley from west to east.  
532 This was probably because of the difference in sedimentation between this part of the valley, which  
533 was a little bit lower in elevation at this time, and the eastern part of the valley, which had already  
534 gone through a long phase of fluvial sedimentation. The inner delta lagoon systems were gradually  
535 infilled. The palaeoriver channel visible on ancient maps and located in the ancient lagoon is  
536 consistent with this evolution.

537

538 Beach ridges are present until at least 7000 cal yr BP and could have two origins. The first is more  
539 inland, directly connected to the river system. In this case, the beach ridges could be linked to the  
540 displacement of the Hérault river sediments, which were reworked in the lagoon system by floods,  
541 currents and wave actions. Gravels found in core A30 support this explanation. Studies have shown  
542 that reworked sediment can form beach ridges and/or lagoonal sandbars (Brückner et al., 2017). The  
543 second explanation is linked to longshore dynamics as attested along much of the Languedoc coast  
544 (Certain et al., 2005; Raynal et al., 2009; Court-Picon et al., 2010).

545

546 These steps in ria evolution were mediated by sea-level change dynamics and sedimentary inputs,  
547 which were not linear in space or time. The successive morphological legacies make these  
548 geomorphological system dynamics not strictly reversible. The weight of each factor is difficult to  
549 quantify precisely. Indeed, each core and its associated proxies yield only a partial image of  
550 landscape changes as a whole. Nonetheless, we tentatively quantify the evolution of the surface area  
551 of the coastal plain surface inside the lower Hérault valley (Fig. 10a). From the maximum  
552 transgressive surface to the present landscape, the coastal plain extends from 5.6 to 43 km<sup>2</sup>. Before  
553 6000 cal yr BP, the submerged (or eroded) surface was about 0.7 ha/yr. Thereafter, during the  
554 ensuing 6000 years, coastal progradation expanded the plain by around 0.7 ha/yr. This rate was

555 relatively regular except during the Roman period and late antiquity, when it was at 1 ha/yr. At  
556 present, it is not possible to compare our results with very high-resolution palaeoclimate data or the  
557 detailed land use history of the Hérault watershed. However, several key periods emerge from the  
558 data. Deceleration of sea-level rise, between 8000 and 6000 cal yr BP (Stanley, 1995; Flemmings et  
559 al., 1998; Vacchi et al., 2016), led to deltaic formation (Stanley and Warne, 1994) around 6000 cal yr  
560 BP. The progradation phase in the Hérault valley began slightly earlier, i.e. after 7000 cal yr BP. Very  
561 early Neolithization of the area is attested by Peiro Signado and Pont de Roque-Haute archaeological  
562 sites, which are the earliest Neolithic settlements known for the Western Mediterranean (Guilaine,  
563 2003; Guilaine et al., 2007; Manen and Guilaine, 2007; Briois and Manen, 2009). This early  
564 progradation phase could have resulted from accelerated erosion (Devillers and Provansal, 2003)  
565 through Neolithic landscape clearing and agriculture. The progradation phase was mainly controlled  
566 by sea-level variations and accelerated by human impacts on local sediment budgets. Moreover, the  
567 rapid development of the coastal plain could have contributed to the successful development of the  
568 local Neolithic settlements. Another regional high-quality paper have also shown the important  
569 relationships between shoreline evolution and archaeological evolution during prehistory (Brisset et  
570 al. 2018).

571

#### 572 **Figure 10: Coastal evolution compared to sea-level and archaeological remains**

573

574 A further interesting trend in the data is the acceleration of the progradation phase around 2000 cal  
575 yr BP. During the Roman period, strong economic and agricultural development is attested in the  
576 Hérault valley (Mauné, 2002, 2016; Ropiot, 2009). This development can be measured by an increase  
577 in archaeological sites in the area (Fig. 10c) and an increase in sediment supply resulting from  
578 human-induced erosion in the middle Hérault valley (Devillers and Provansal, 2003). At long time  
579 scales, an acceleration in progradation was a corollary of watershed agricultural pressures and  
580 erosion.

581

#### 582 **7 Conclusion**

583 This work provides detailed insights into Holocene coastal evolution using chronostratigraphic data  
584 and Lidar mapping. The Hérault palaeodeltaic lobes, in both retrogradational or progradational  
585 phases, were deposited in a relatively small geographic area. This is in contrast to large deltaic  
586 systems such as the Rhone delta where the fossilized coastal forms are more spread out, visible and  
587 more easily mapped, and therefore better understood (Aloisi et al., 1978; Panin et al., 1983; Coleman  
588 et al., 1980, 1998; Amorosi et al., 2001). This methodological aspect may explain why small  
589 morphosedimentary systems in coastal areas have received less research attention. New techniques  
590 and approaches (LIDAR, multiplication of coring, high resolution geophysical investigation, etc.) must  
591 be used to fill this knowledge gap in the coming decades. To understand Holocene landscape  
592 dynamics, we stress the importance of a multidisciplinary approach associating (bio)stratigraphy,  
593 geomorphology and archaeology.

594

595 The large number of cores undertaken within the framework of this project has allowed us to  
596 elucidate the different stages of Holocene coastal metamorphosis. Until the late Holocene, local  
597 deltaic systems were submerged in the eastern part of the valley. The Holocene history of the  
598 landscape in the Hérault valley began with a maximum flooding surface around 12 km inland ca. 7000

599 years ago. Its infilling began in the western part of the valley and shifted eastwards until Late Bronze  
600 Age at least (ca. 3000 cal yr BP). The non-linearity of coastal landscape evolution inside the ria is  
601 confirmed by field data and could be taken into account in future numerical models (Dubar, 2004).

602

603 This landscape evolution must be taken in account to understand the archaeological history of the  
604 lower Hérault valley: (i) from a taphonomic point of view; (ii) because of the evolution of the most  
605 fertile agricultural lands in relation to coastal retrogradation and progradation from the Neolithic to  
606 Roman periods; (iii) for the environmental potentialities of harbours and trade routes through time;  
607 (iv) for the changing nature of environmental risks for human societies; and (v) for the relationships  
608 between economic systems and changing environments. For these reasons, the lower Hérault valley  
609 and the region of Agde is an interesting laboratory to study Holocene human-environment  
610 relationships over the long time on sensible coastal geosystems.

611

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625

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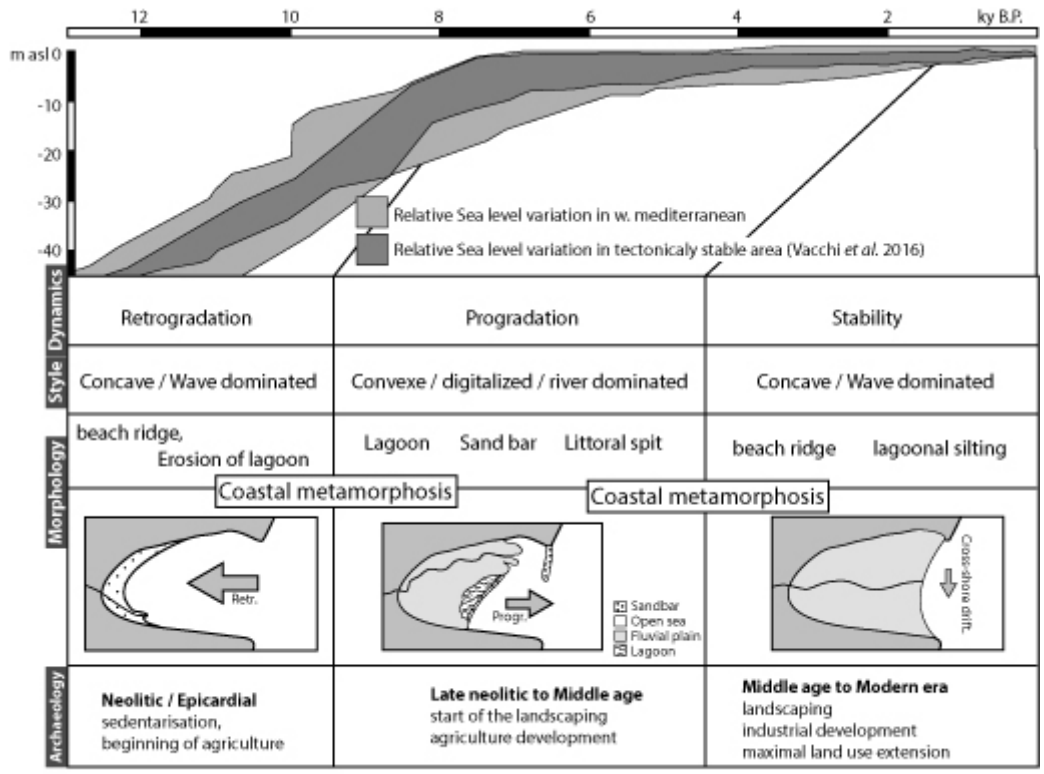
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## 882 **Figures**

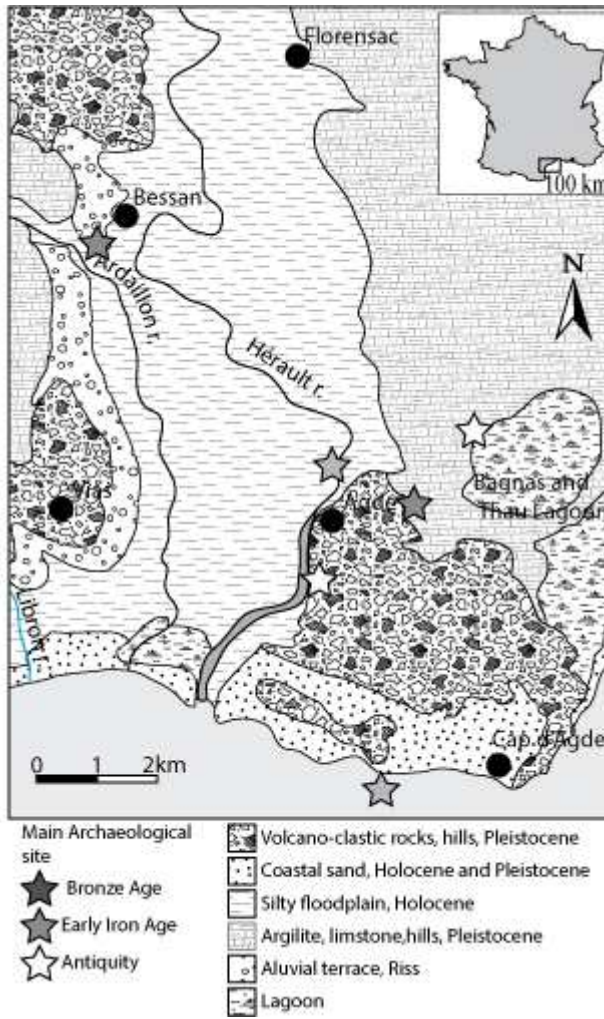
883 Figure 1: Coastal metamorphosis during the Holocene



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887 Figure 2: Geological map of the lower Hérault region

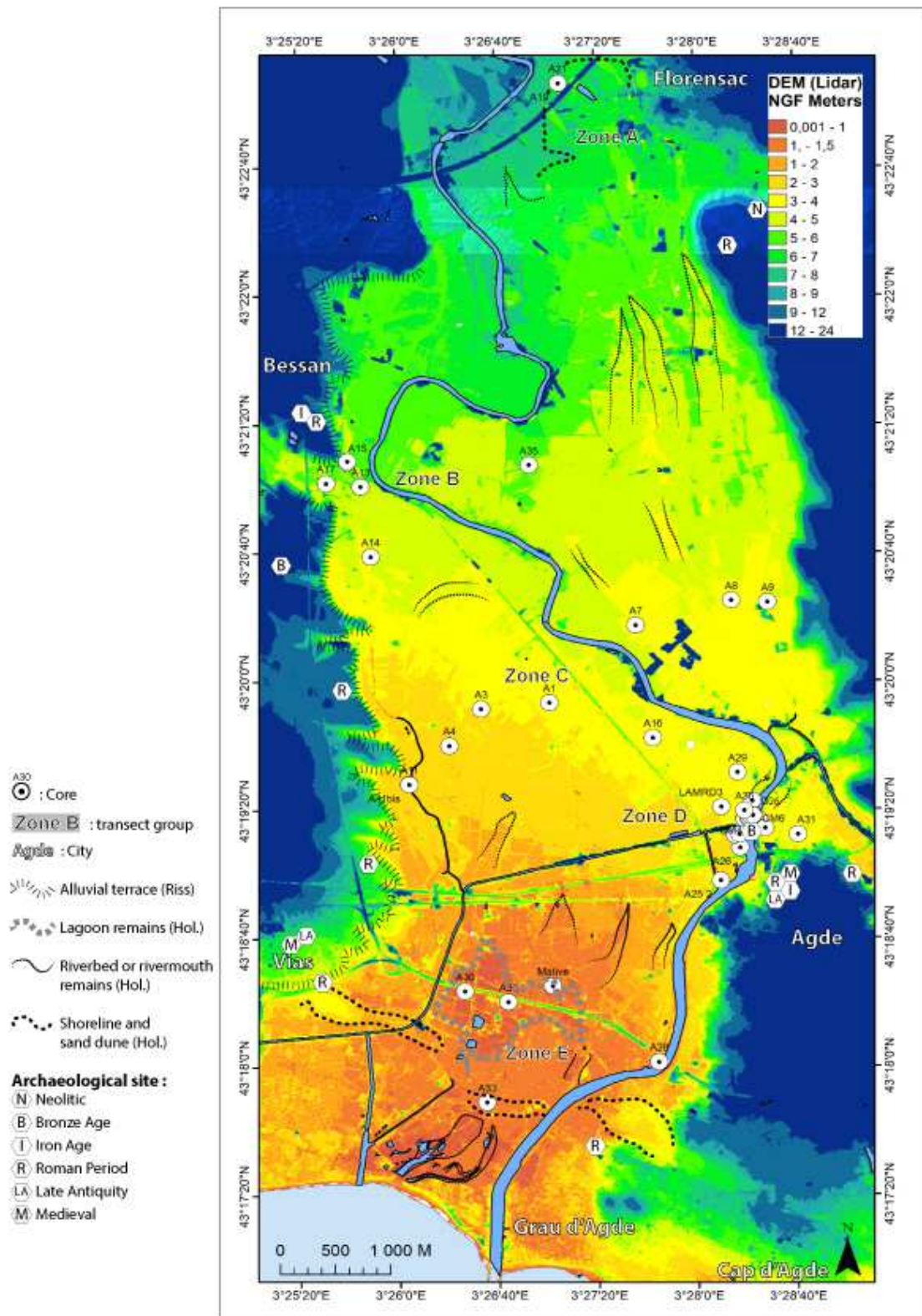


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891 Figure 3: Lidar, morphological and archaeological map of the lower Hérault valley

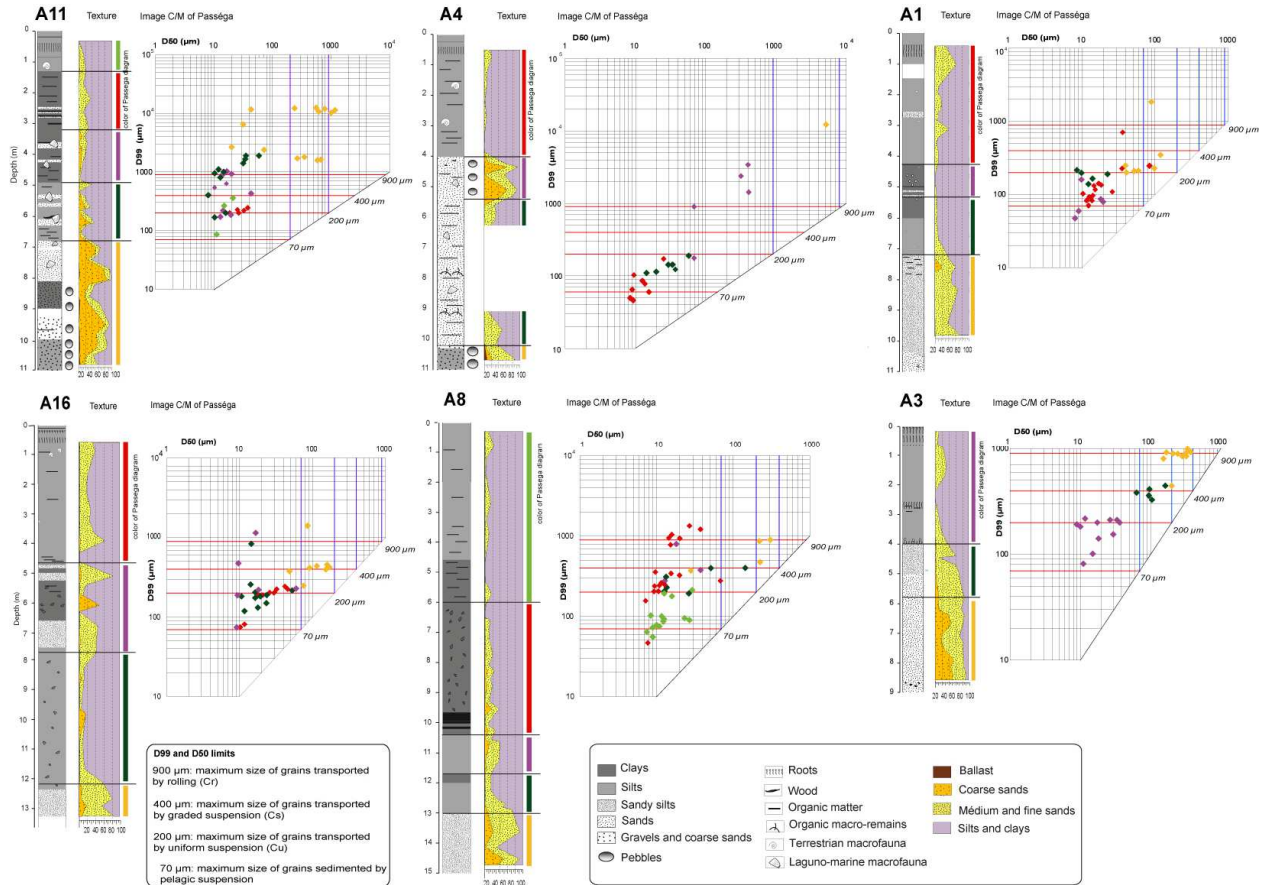


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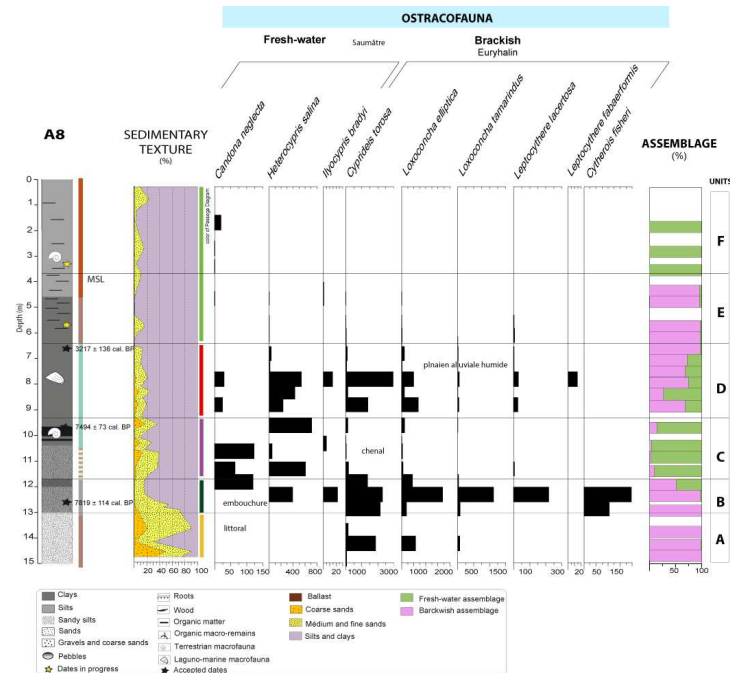


894 Figure 4: Sedimentological analysis of the A1, A3, A4, A8, A11 and A16 cores



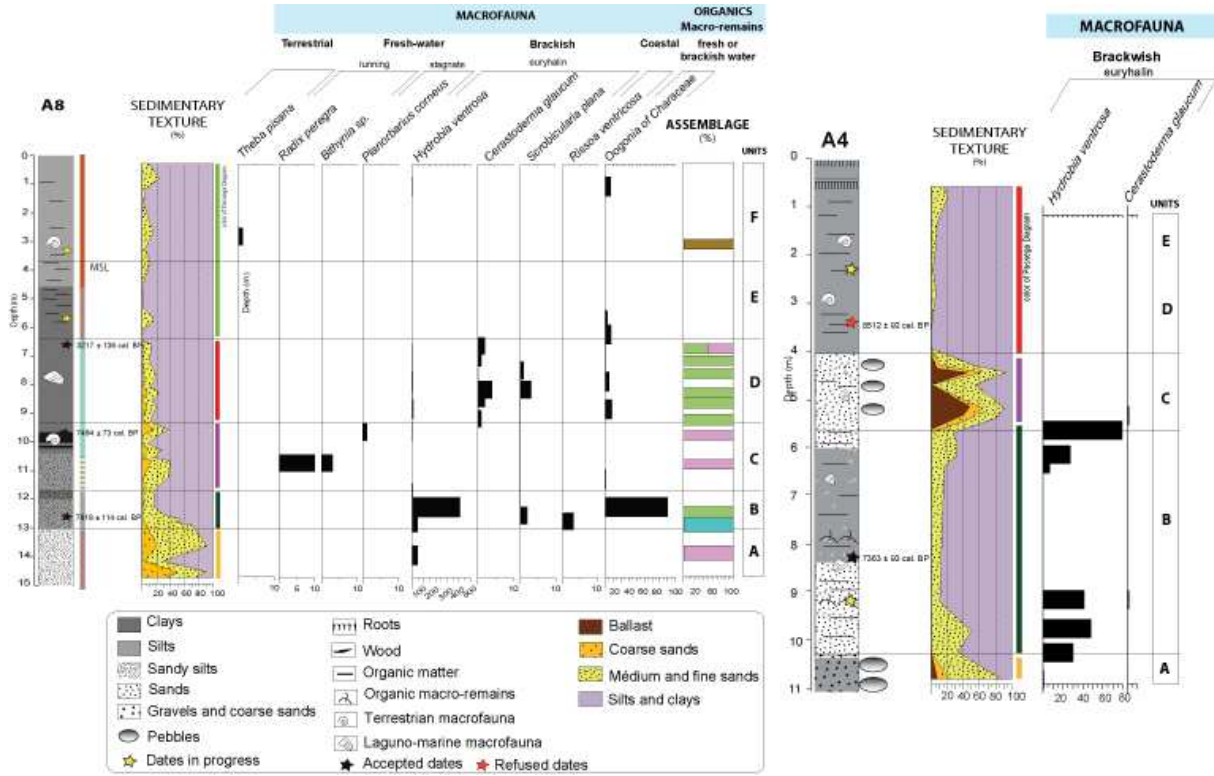
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Figure 5: Ostracod analyses of the core A8



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902 Figure 6: Benthic macrofauna analyses of cores A4 and A8



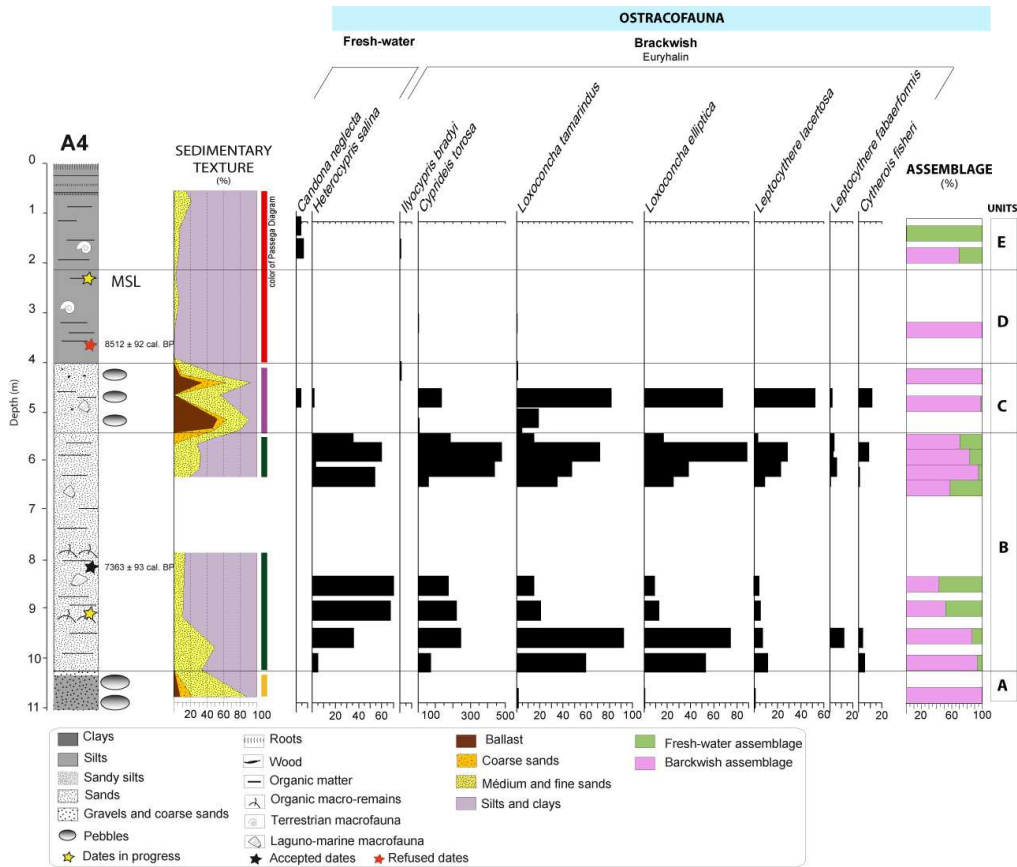
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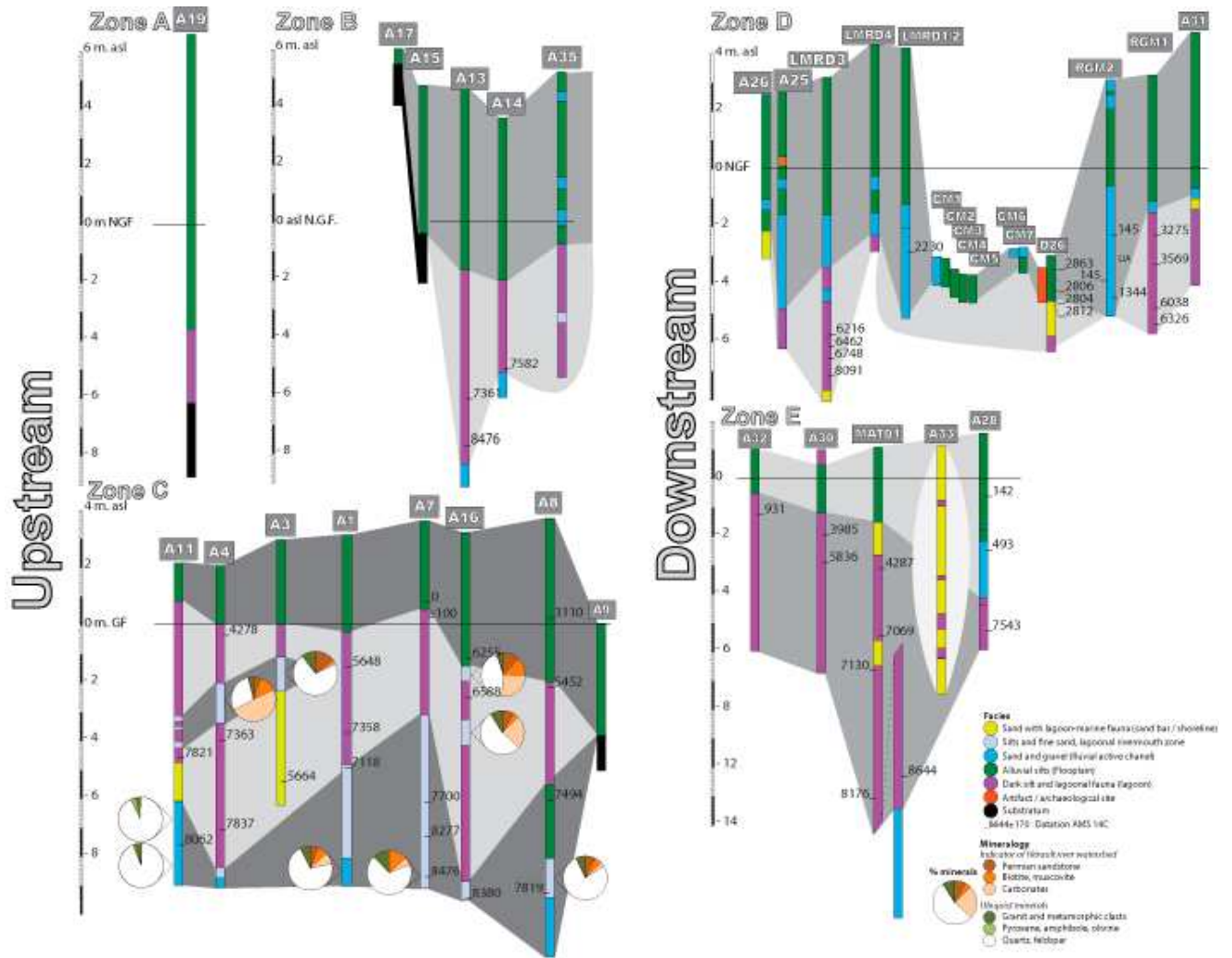
Figure 7: Ostracod analyses of the core A4



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909 Figure 8: Facies distribution of the Hérault's fluvio-lagoonal sedimentary body

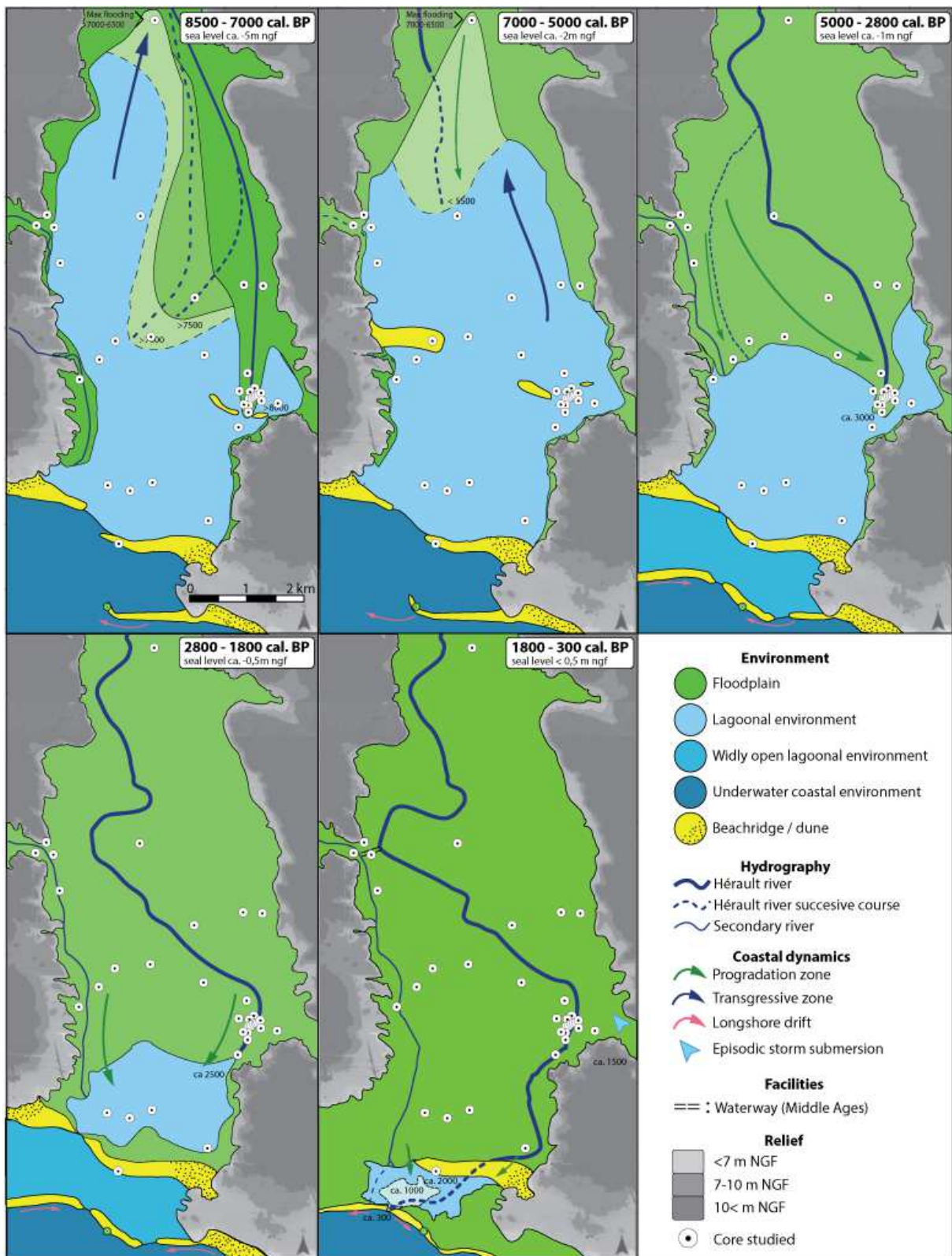


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913 Figure 9: Holocene geomorphological evolution of the lower Hérault valley

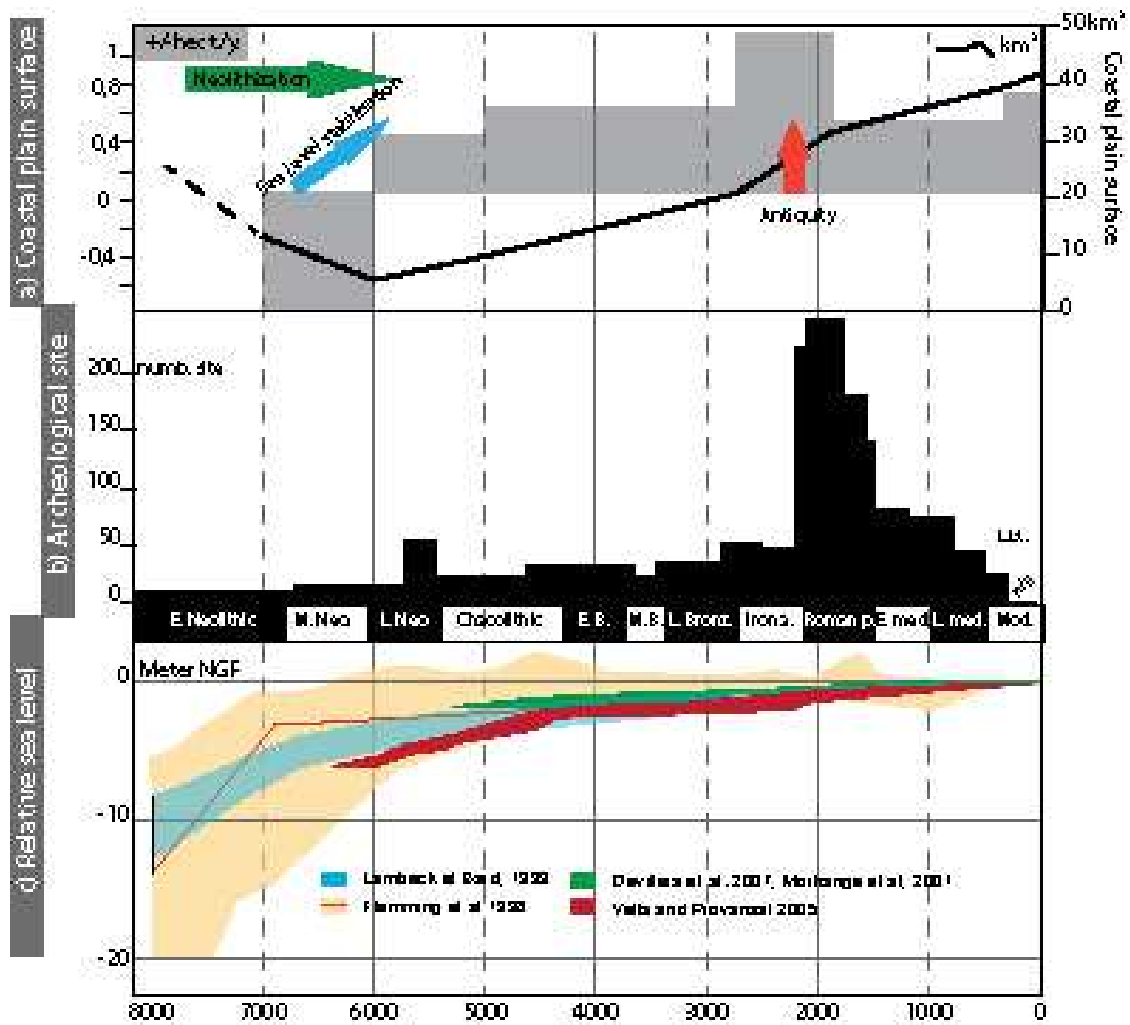


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917 Figure 10: Coastal evolution compared to sea-level and archaeological remains



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